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Outdoor Air Pollution and Mortality: the Evidence From the Czech Republic

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Abstract: Outdoor air pollution is generally recognized as a serious environmental risk factor of premature mortality. The main aim of this thesis is to examine how changes in fine particulate air pollution ($PM_{2.5}$) account for changes in selected mortality indicators, using empirical evidence from 45 districts in the Czech Republic. Besides the impact on changes in life expectancy, a special emphasis was placed on changes in age-specific and cause-specific mortality. First-difference models were used for empirical testing. While no statistically significant effects were found for changes in life expectancy at birth (and at the age of 65) and for changes in mortality during the first year of life as well as at the age of 65+, the reduction in fine particulate air pollution affected significantly the distribution of deaths by selected causes. More specifically, a 10% drop in the concentration of $PM_{2.5}$ was estimated to decrease the share of deaths on cardiovascular diseases by 0.9 percentage points. On the other hand, with the same reduction in fine particulate air pollution, the share of deaths on respiratory diseases and lung cancer was predicted to increase by 0.4 percentage points and 0.1 percentage points, respectively. With the exception of changes in the share of deaths on respiratory diseases, there was no evidence that the effect of fine particulate air pollution or returns to its reduction differs between districts with improved air quality and those whose air conditions deteriorated.

Key words: Air pollution, fine particulate matter, mortality, Czech Republic

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Table of Content

List of Figures

List of Tables

Chapter 1

Introduction

Although outdoor air pollution significantly affects the quality of everyone's life, its negative health impacts used to be highly underestimated in the past. However, the number of related deaths is so high that it is now considered the most important environmental risk factor for human health. In fact, it is estimated that the presence of air pollutants caused the death of 3.7 million[1] people in 2012, both in developed and developing countries (WHO, 2011).

Given its increasing significance, the topic of air pollution and its impacts on human health has attracted the attention of numerous scientists from across disciplines. Epidemiological studies typically conclude that living in more polluted areas is associated with increased mortality on cardiovascular diseases, respiratory diseases, and lung cancer both in short-term and long-term (Künzli et al., 2000; Swartz, 1994; Dockery et al., 1993). Empirical findings suggest that these premature deaths could be theoretically avoided by improving air quality. Moreover, Künzli et al. (2000) emphasize that a reduction in air pollution could bring economic benefits because the costs of medical treatment would be reduced and both production and consumption might increase.

For all these reasons, the main aim of this study is to investigate how changes in fine particulate air pollution ($PM_{2.5}$) account for changes in mortality and life expectancy, using empirical evidence from the Czech Republic. Data come from two different time periods, 2000-2002 and 2010-2012, for which it is possible to combine information on fine particulate

[1] For illustration, mortality attributed to the exposure to ambient air pollution is higher than mortality on AIDS (1.7 million) and Malaria (0.66 million) combined (WHO, 2014).

air pollution and mortality in individual districts with additional indicators derived from population censuses. By following the methodology used by Pope, Ezzati and Dockery (2009), this thesis attempts not only to make a contribution to the existing literature, but also to provide insights into the recent development in the Czech Republic.

There are two main reasons why the Czech Republic is chosen for the empirical analysis. Firstly, some of its districts belong to the most polluted areas in the whole European Union (European Enviromental Agency, 2013), which means that air pollution might significantly hinder improvements in life expectancy. Secondly, while outdoor air pollution has been mostly stagnating on the national level in the last decade (Puklová et al., 2013, p.9), there are districts where it has been changing dramatically (Český hydrometeorologický úřad, 2013a). This implies that districts where outdoor air pollution improved as well as those where it deteriorated will be included in the empirical analysis. This is important because the study by Pope, Ezzati and Dockery (2009) identified the absence of districts with worsening air conditions as one of its main limitations.

Altogether, four different research questions are addressed in this study in order to examine whether and how population can benefit from outdoor air pollution reduction. Are greater life expectancy gains achieved in districts where the concentration of $PM_{2.5}$ is reduced more? Is the impact of changes in air pollution on mortality distributed in all age groups equally? How do changes in air quality alter the distribution of main causes of deaths? And finally, are the the effect and returns of changes in fine particulate air pollution similar in districts with decreasing and in those with increasing concentration of $PM_{2.5}$?

This paper is structured into five chapters. The second chapter introduces the theoretical framework which illustrates that mortality in each district may be determined by several factors besides air pollution, such as age, sex, income, education, medical care, life style etc. This fact has to be considered because the effects of the changes in other risk and protective factors have to be separated from the effect of the changes in fine particulate air pollution (Schwartz, 1994). In the third chapter, the dataset under study as well as first-difference regression models used for hypotheses testing are described in more detail. The fourth chapter is dedicated to the interpretation and discussion of results, and it also addresses several problems and limitations of the empirical analysis. Finally, the last chapter summarizes main findings obtained in the empirical part of the thesis and provides some suggestions for future research.

Chapter 2

Theoretical Framework

From the demographic point of view, mortality represents one of the two fundamental components of human reproduction. Together with fertility, it ensures population renewal over time as dying people are continuously replaced by live-born children. Moreover, the size of new-born cohorts is gradually decreasing until they extinct in the highest ages. Therefore, understanding the determinants of mortality appears to be as crucial as awareness of fertility patterns in terms of population dynamics (Pavlík, Rychtaříková & Šubrtová, 1986).

Although life would not be possible without air, the air people breathe is contaminated with a large number of pollutants whose occurrence is directly linked to numerous adverse health outcomes (Pope, 2000). In fact, everybody on Earth is more or less unwillingly exposed to air pollution, albeit to a different degree. In contrast to smoking, which mostly depends on each individual's free choice, the exposure to air pollutants can be merely reduced by migrating to a less polluted area, but never completely prevented (WHO, 2011).

Epidemiological studies that investigate the relationship between mortality and air pollution typically assess the risk of death related to the prevalence of main pollutants in a certain area. These include nitrogen oxides, ozone, sulfur dioxide and suspended matter, of which the concentration of particulate matter (PM) reveals to be the most important risk factor for human health according to WHO (2011). In addition, a high level of PM concentration remains one of the main problems related to the topic of air pollution in the Czech Republic (Český hydrometeorologický úřad, 2013a). For all these reasons, the impact of air pollution is predominantly discussed with respect to this specific pollutant in the remaining parts of this thesis. However, it is important to keep in mind that population is exposed to other air pollutants at the same time as well.

Particulate matter consists of a mixture of both solid and liquid particles which are dispersed in the air and have diverse physical and chemical attributes. Their origin can be both organic (volcanic eruptions, pollens, etc.) and man-made (combustion, construction, etc.). A part of these particles is emitted directly to the atmosphere while the rest arises in the atmosphere as a result of liquefaction of emission gasses (Český hydrometeorologický úřad, 2013a). Their presence in air is measured in micrograms per cubic meter and they are typically divided into five major categories based on their size (see Tab.2.1).

Tab.2.1: Particulate matter by size of particles

	Size
Total Suspended Matter (TSP)	no size limits
Coarse Particulate Matter (PM_{10})	< 10.0 µm
Fine Particulate Matter ($PM_{2.5}$)	< 2.5 µm
Ultra Fine Particulate Matter (PM_1)	< 1.0 µm

Source: according to Pope (2000, p.713)

Most measurement stations keep tracking the concentration of PM_{10} despite the fact that WHO (2006, p.10) recommends using $PM_{2.5}$ for epidemiologic studies which deal with the effects of air pollution on human health. A similar suggestion is provided by Pope (2000) who emphasizes that fine particles can more easily penetrate human organism and tend to settle more deeply in lungs. Another important characteristic of fine particles is a longer settlement period as they can be transported up to 1,000 km far away from their source thanks to their light weight (Mechler, Amann & Schöpp, 2002).

The proportion of fine particles within PM_{10} depends on the characteristics of the specific location, but it usually ranges from 50 % to 80 % in developed countries (WHO, 2006, p.10). The interest in measuring the share of ultra fine particles has been gradually increasing in the last years, but the amount of available data remains rather limited. One of the reasons why they are usually not being tracked is their short lifetime, as they tend to agglutinate into bigger particles (Pope, 2000, p.713).

2.1. Health Consequences of Fine Particulate Air Pollution

Regarding the health effects, fine particulate matter can affect human health chronically as well as acutely already in low concentrations. In addition, a safe lower threshold has not been identified yet (Lepeule et al., 2012). Despite this fact, WHO (2006) sets guidline limits for daily and yearly concentrations which individual countries should reach or at least advance towards. These limits are summarized in Tab.2.2.

Tab.2.2: WHO Air quality guidline limits for PM concentrations and limits set in the Czech Republic in 2012

	WHO		Czech Republic (2012)	
Limits	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**
Annual mean concentration (in $\mu g/m^3$)	10	20	25	40
24-hour mean concentration (in $\mu g/m^3$)	25	50	---	50

Source: WHO (2006, p.9), Český hydrometeorologický úřad, 2013a

Apart from the WHO limits, Tab.2.2 also shows the air pollution limits set in the Czech Republic by law. If these limits are exceeded, several regulatory measures can be implemented in order to reduce the pollution; for example, traffic or industrial production can be partly restricted[2] (Parlament České Republiky, 2012). While the annual limits are twice higher in the Czech Republic than the values recommended by WHO, the daily limits are equal. However, it is important to emphasize that the WHO limits have only a recommendatory character. Reaching them in urban areas should lead to a substantial reduction in health risks (WHO, 2006). According to the estimations of WHO (2011), a decrease in the concentration of PM_{10} from 70 $\mu g/m^3$ to the recommended value should lead to a 15% drop in total mortality.

It is estimated that ambient air pollution caused 3.7 million premature deaths globally in 2012, of which 80 % were related to cardiovascular diseases, 14 % to respiratory diseases and 6 % to lung cancer (WHO, 2011). Although the estimated increase in risk of death reveals to be higher for respiratory diseases (Pope, 2000), the numbers presented above indicate that cardiovascular diseases represent the most common cause of death related to air pollution. However, it is important to keep in mind that the relative risk of dying due to particulate air pollution remains relatively low compared to other causes (Künzli et al., 2000).

[2] In case of $PM_{2.5}$, the daily limits have to be exceeded for 35 days (Český hydrometeorologický ústav, 2013a).

Despite adverse health outcomes, it is still unclear how exactly particulate matter influences the health of an individual. Some of the possible biological consequences involve a reduced lung function, changes in heartbeat, inflammation of the respiratory system or decreased immunity (Pope, 2000; Český hydrometeorologický úřad, 2013a).

Lepeule et al. (2012) argue that the relationship between the concentration of particulate matter in the air and mortality is characterized by a linear relationship. This means that an increase in the concentration of PM causes a proportionally equal increase in mortality disregarding the initial level of pollution. In contrast to this conclusion, a study conducted in twelve European cities discovered that the relationship between the concentration of PM and mortality is significantly weaker in the countries of Eastern Europe, where the initial level of air pollution was considerably higher, compared to Western Europe (Katsouyani et al., 1997). On the other hand, Peters et al. (2000) did not confirm this finding and states that the effect recorded for example in the Czech Republic is comparable with the effect recorded in Western Europe and the USA.

When studying the relationship between mortality and air pollution, it is necessary to consider the fact that different age groups are not likely to be impacted in the same way. An increase in the risk of death depends to a large extent on the amount of time over which the individuals are exposed to the increased level of air pollution and also on their initial health status. From this point of view, children, elderly and chronically ill individuals are perceived as the most endangered population groups as they are highly sensitive to changes in external conditions (Pope, 2000).

For instance, a logistic regression analysis conducted for the Czech Republic on the level of individual districts confirmed that there is a statistically significant negative impact of air pollution on infant mortality. The risk of death was constantly growing from the lowest to the highest quintile. In addition, it was dramatically higher for respiratory diseases especially in the postnatal period. This corresponds with the fact that children under the age of 1 year typically die of other causes than respiratory diseases shortly after birth (Bobak & Leon, 1992). In contrast to an increased infant mortality, Gouveia and Fletcher (2000) show that the relationship between air pollution and under-five mortality is not significant. These findings suggest that infants represent the most sensitive group among children.

Air pollution does not always directly threaten the live of an individual, but it may lead to increased morbidity instead. This effect is especially important in terms of higher age groups because it can be expected that the impact of higher sickness rate during working age can translate into higher death rates in elderly. In other words, individuals may reach a high age even if they live in polluted regions, however, the quality of their lives and resistance against diseases are likely to be considerably lower (Pope, 2000). This conclusion is also confirmed by Gouveia and Fletcher (2000) who indicate that the effect of air pollution is most severe for people older than 65 years and that it represented a 6% increase in mortality on cardiovascular diseases in this age group.

Time delay is one of the main problems of epidemiological studies which track the relationship between mortality and recent level of particulate air pollution. As a result, these studies typically tend to underestimate the effect of air pollution since people who die after the study is conducted are not included in the analysis (Mechler, Amann & Schöpp, 2002). Moreover, Pope (2000) emphasizes that there may be a large number of chronically ill or otherwise weakened individuals whose death was merely accelerated by an increased level of air pollution. Despite all these pitfalls, epidemiological studies can still offer valuable insights into the problematic.

2.2. Literature Review

A turning point in the attitude of both general and expert public towards the topic of air pollution was the so called *Great Smog of '52 in London* in December 1952. Based on an analysis of daily time series, it was discovered that the enormous increase in concentrations of dust particles and sulfur dioxide was followed by a dramatic rise in mortality with a delay of only one day (Schwarz, 1994). In addition, a more recent study reveals that the number of deaths caused by this smog crisis might be around 12,000 instead of previously estimated 4,000, if the mortality rates of the following two months are considered as well (Bell, Davis & Fletcher, 2004, p.8).

A similar approach was chosen for analyzing the impacts of the smog crisis in the Czech city Ostrava during the winter months of 2010. This smog situation was extreme not only with respect to the length of duration, but also regarding the values[3] of air pollution measured. In

[3] Maximum values of PM_{10} concentration reached up to 552,6 μg/m^3 (Tomášková et al. 2011, p.7).

comparison to the same months of the previous year, the number of deaths and illnesses caused by an increased concentration of PM_{10} was twice higher in 2010, and it represented 4.3 % of all deaths recorded during this specific period (Tomášková et al., 2011).

Besides daily time-series, cohort studies are another option which researchers choose to study the relationship between air pollution and mortality. As they observe selected individuals over a longer period of time, they can be used to investigate how mortality changes with respect to the duration of exposure to air pollution. Their results offer a more complex insight into this problematic because they also include individuals who die because of air pollution with a longer time delay. Moreover, they allow controlling for other individual risk factors as well (Mechler, Amann & Schöpp, 2002). However, they are relatively difficult to conduct because they require not only more time, but also more detailed data.

Beginning in 1974, the so called *Harvard Six Cities Study* tracked 8,100 adults living in six different American cities for 14 to 16 years (Dockery et al., 1993). After the data were adjusted of other risk factors, it was discovered that the ratio of the mortality rates in the most and the least polluted areas equaled 1.26. An increased risk of death was confirmed for cardiopulmonary diseases and lung cancer, while the effect remained insignificant for other causes of death. Moreover, these estimations appeared to be robust when other risk factors were considered, including smoking.

One of the most extensive cohort studies was conducted in the USA between the years 1982 and 1989. Over these eight years, a group of 550,000 Americans living in 151 different metropolitan areas was followed. Interestingly, the results of this study reveal to be similar to the results of the *six cities* mentioned in the previous paragraph, as the adjusted mortality rate-ratio between the most polluted and the least polluted areas was estimated to 1.17. Regarding the causes of death, cardiopulmonary diseases and lung cancer were dominating again (Pope et al., 1995).

One of the most important cohort studies, which were related to the topic of mortality and air pollution, conducted in the Czech Republic was the so called *Program Teplice*. This research project was launched by the Czech government together with the USA in 1991 with the aim to confirm the concerns about the negative implications of air pollution for human health. These concerns originated in the 1980s when the economic development in the Czech Republic was coupled with intense coal mining and massive energy production. In the framework of this program, the situation in two districts was compared: in district *Teplice* where the values of air pollution were comparably high, and in district *Prachatice* which served as a reference district. The results of this cohort study show that children had a higher probability of being born prematurely in the more polluted area and that their birth weight was on average lower as well. Moreover, pupils who were exposed to a higher level of air pollution had a higher chance of suffering from serious breathing problems and reduced lung function (Šrám et al., 1996).

Several authors also examine panel data on regions in order to investigate the impact of different rates of air pollution reduction. In this concept, regional differences can be regarded as a special form of a quasi-natural experiment since they are out of individual control. In fact, this perception is supported by the robustness of the estimations of these studies when socio-economic variables are included (Pope, Ezzati & Dockery, 2009).

An analysis performed for 217 counties in the USA shows that a reduction in the concentration of $PM_{2.5}$ between the 1980s and 1990s was on average associated with an extensions of human life by 0.77 years. This represents approximately one fifth of the total increase in life expectancy over the period under study (Pope, Ezzati & Dockery, 2009). However, it is possible that the extension of life expectancy was underestimated to a certain extent because authors used mortality on lung cancer and chronic obstructive pulmonary disease as a proxy for smoking and some of these deaths might be attributed to air pollution as well (WHO, 2011). Despite this discrepancy, authors of this study point out that the size of the effect is comparable with the results obtained from cohort studies (Pope, Ezzati & Dockery, 2009).

The positive relationship between a decrease in the concentration of $PM_{2.5}$ and life expectancy was also confirmed by Correira et al. (2013) who conducted an analysis of the data from 545 American counties for the years between 2000 and 2007 using the same methodology as Pope, Ezzati and Dockery (2009). Over this time period, a decrease of $PM_{2.5}$ by 10 $\mu g/m^3$ was associated with a gain in life expectancy of 0.35 years. In other words, the positive effect remained observable, although it was weaker in absolute numbers. Nevertheless, one of the possible explanations of this difference can be the choice of a shorter time period, but also the fact that the growth of life expectancy has been generally decreasing in the last years (Wilmoth, 2000).

Regarding the specific situation in the Czech Republic, Lubas (2014) analyzed the data from 55 Czech districts and concluded that the concentration of PM_{10} in the air contributed to the death of 4,013 people in 2011, which represents 6.5 % of all deaths in that year. Moreover, an increase in the concentration on PM_{10} by 10 $\mu g/m^3$ during the eight years under study was associated with a 2.4% rise in mortality. Paradoxically, his results also suggest that an increase in fine particulate air pollution in the last two years was coupled with a lower mortality on cardiovascular and respiratory diseases, and lung cancer. As the author admits, the most likely explanation of this illogical finding is the omission of one or more important variables in the regression model.

Despite the limitations of the study conducted by Lubas (2004), the analysis of Puklová et al. (2013) reached very similar results with regard to the impact of air pollution on the overall mortality. This study found out that the concentration of PM_{10} in the air contributed to 6.9 % of all deaths recorded in 2010.

2.3. Other Determinants of Mortality

Although the aim of this paper is to offer an in-depth analysis of the impact of fine particulate air pollution, other potential determinants of mortality have to be considered as well. As emphasized by Pope, Ezzati and Dockery (2009), the relationship between mortality and air pollution in individual regions might be confounded or altered due the presence of other risk and protective factors. For better illustration, these others factors are divided into five major groups and the mechanisms how they may influence human health and impact the relationship between air pollution and mortality is described more into depth in respective sections. A special attention is devoted to the situation in the Czech Republic.

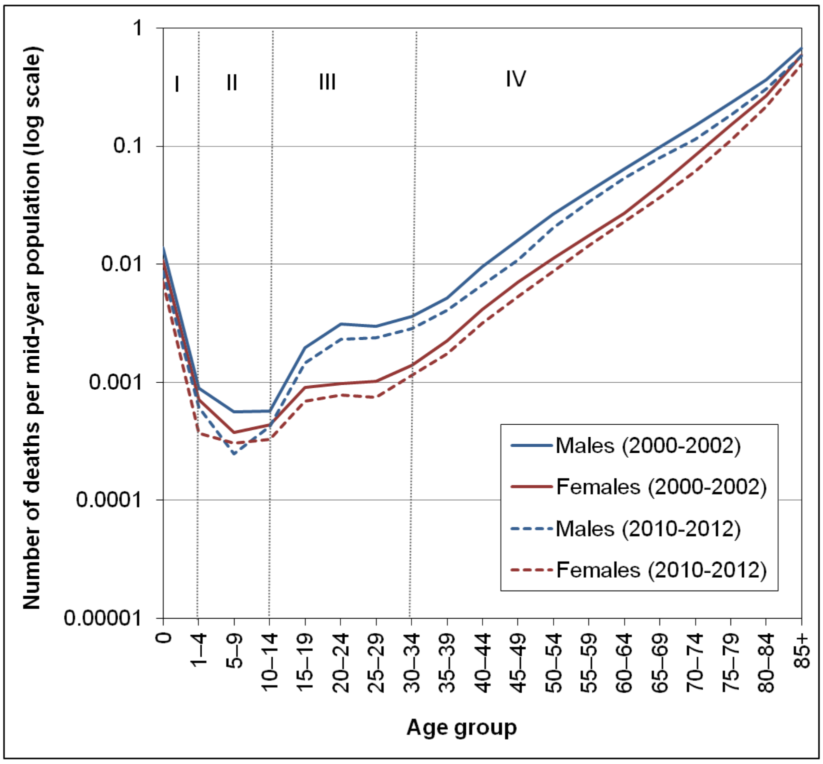
2.3.1. Demographic Determinants of Mortality

When studying mortality, demographers predominantly focus on regularities based on age and sex. In addition to these two factors, distribution of mortality by main causes of death represents another important part of demographic analysis.

2.3.1.1. Age and Prevailing Causes of Death

The risk of death depends on individual aging and, with the exception of postnatal period, it grows with increasing age (Weeks, 2008, pp.159-164). In order to illustrate how this fact applies to the situation in the Czech Republic, Fig.2.1 captures the age-specific death rates, separately for males and females, during the periods 2000-2002 and 2010-2012. While there is an observable horizontal downward shift of the mortality curves for both genders, which corresponds with the reduction in mortality between the periods under study, the shape of the curves stays relatively constant over time and reflects four phases of the development of human organism (labeled with roman numerals in Fig.2.1).

Fig.2.1: Age-specific death rates, Czech Republic, 2000-2002 and 2010-2012



Data source: Český statistický úřad, 2013a, author's calculations

An increased risk of death traditionally occurs directly after birth when the newborn has to adapt to the new environment (phase I). Afterwards, the risk of death drops to its minimum for the time before the beginning of adolescence (phase II). The transition to adolescence translates into an increased mortality which is related to a higher probability of dying on external causes, especially with relation to traffic accidents (Pavlík, Rychtaříková & Šubrtová, 1986, p.221). After this initial rise, mortality remains relatively constant until the age of approximately 35 years (phase III). Having reached this threshold, mortality starts to increase exponentially keeping the same growth rate for the next fifty years (phase IV). Although it is not depicted in Fig.2.1 due to unavailability of detailed data for the oldest age group, the growth rate typically decreases and the risk of death even starts to decline after turning the age of 90 years. One of the possible explanations of this phenomenon is the fact that people who reach such a high age are typically in a much better health state than the rest of the population, which grants them a certain degree of resistance (Horiuchi & Wilmoth, 1998).

Similarly as in other developed countries, the current age distribution of deaths in the Czech Republic is regarded to be a direct consequence of a finished epidemiological transition (Omran, 1971). In accordance with Omran's findings, the fatality of more and less infectious diseases (measles, cholera, tuberculosis,…) has significantly decreased over time while civilization and degenerative diseases (cardiovascular diseases, neoplasm, Alzheimer's diseases,…) have become the most common causes of death. In 2012, mortality on cardiovascular diseases and neoplasm made up 74.3 % of all deaths in the Czech Republic, while infectious diseases were reported as the main cause of the death in only 1.5 % of cases (Ústav zdravotnických informací, 2013, p.107).

Tab.2.3: Share of deaths by main age groups, Czech Republic, 2000-2002 and 2010-2012

	Share of deaths in the age group (percentage of total deaths)			
Time period	0-14	15-64	65+	85+
2000-2002	0.61	24.01	75.38	20.94
2010-2012	0.45	22.29	77.26	25.34

Data source: Český statistický úřad [Czech Statistical Office], 2013a, author's calculations

The infant mortality rate in the Czech Republic belongs to the lowest ones in the world as only 2.6 children out of 1,000 live-borns died before turning the age of one year in 2012. Compared to the past development, when most deaths during the first year of life were attributed to exogenous causes, such as infections or diseases of respiratory system and digestive tract, the most common causes of infant mortality are the endogenous ones today. In other words, infants typically die due to diseases which originate from the time of pregnancy or congenital genetic predispositions (Ústav zdravotnických informací, 2013).

Despite the continuous improvement of infant mortality rate, it is possible to conclude that an important role has been played by mortality reduction in advanced age in the Czech Republic in the last two decades. This assumption is also supported by the percentage share of deaths by main age groups in years 2000-2002 and 2010-2012 (see Tab.2.3). More than three quarters of them are concentrated in the age group of 65 and more years. Although the most dramatic relative drop was still recorded for the youngest age group (0-14), the percentage share of deaths of the age group 85+ increased by more than one fifth compared to the previous state.

2.3.1.2. Sex

Another important factor of mortality is its differentiation based on sex. In this respect, it is possible to observe an increased risk of dying for males in all age groups (see Fig.2.1). However, it is expected that this difference will gradually narrow down in the following decades (Burcin & Kučera, 2010).

One of the possible explanations of male excess mortality can be different genetic predispositions of men and women. For instance, it was found out that female sex hormones offer a more efficient protection against ischemic heart diseases during the fertility period than male sex hormones (Waldron, 1995 cited in Gjonça, Tomassini & Vaupel, 1999).

However, biological factors alone cannot sufficiently explain why the difference between the mortality rates of males and females vary across countries. For this reason, several authors claim that socioeconomic conditions and different life styles of men and women are far more important than biological predispositions (Rogers et al., 2010). Their main argument is that men tend to prefer a more risky life style, both with respect to their attitude towards personal health and also in form of a higher alcohol and cigarettes consumption. This conclusion is also supported by a handful of studies conducted in the Czech Republic which discovered that not only the prevalence, but also the intensity of smoking is higher for men than for women (Czémy & Sovinová, 2003, p.8). Moreover, alcohol consumption contributed to the death of 10 % men and only 2 % women who died in the Czech Republic in 2010 (Kohoutová, 2013b).

Last but not least, different job preferences between males and females may also play an important role, because they lead to different job-related illnesses (Messing, 1997). However, this difference is slowly disappearing as the proportion of people working in the tertiary sphere is increasing and as women are starting to get jobs which were rather reserved for men in the past.

2.3.1.3. Marital Status

A positive relationship between marriage and longevity has been repeatedly confirmed in the literature. For example, Gardner and Oswald (2004) pointed out that the positive effect of being married for males was strong enough to reverse the negative consequences of smoking. Although males can profit from marriage more, the positive effect revealed to be significant for females as well. Similarly, a recent study conducted in the Czech Republic concluded that married individuals live on average longer and that their mortality advantage even increases in time. In 2010, married men lived approximately 10 years longer than their unmarried counterparts. A slightly worse outcome was discovered for Czech women who lived, on average, seven years longer when married (Pechholdová & Šamanová, 2013).

Despite these empirical findings, the exact mechanism how marriage reduces the risk of death remains rather unclear. One of the possible explanations of excess mortality of unmarried population might be the fact that marriage often translates into material and also psychical stability and security for both partners. Apart from a higher household income, a married couple reaches time savings thanks to a more efficient allocation of household duties. In case of illness, the second partner can provide necessary care, which leads to a faster recovery, and the household budget is not as endangered as in case of an unmarried individual (Becker, 1981). Another positive consequence of marriage is the social contact between the partners which has a positive effect on psychological health of the individuals. Its importance rises especially in advanced age when the risk of social isolation increases (Gove, 1973). Moreover, some authors argue that married individuals tend to choose a healthier life style because of the long-term commitment which they gave to their partners (Gardner & Oswald, 2004). Divorce or death of one of the partners is then perceived as such a traumatic event that it instantly translates into a worse health status (Metsä-Simola & Martikainen, 2013).

However, the protective effects of marriage discussed above are often difficult to isolate from positive selection in the marriage market. This term refers to the fact that healthy individuals tend to enter marriage much more often than their unhealthy counterparts. Consequently, they reach a higher age thanks to their better health status (Goldman, 1993). On the other hand, it is possible that unhealthy individuals have a stronger motivation to enter into marriages if they are fully aware of its positive effects in order to reduce their original health disadvantage. In other words, adverse selection might occur in this case (Lillard & Panis, 1996).

2.3.1.3. Selective Migration

Although it is not possible to completely avoid the exposure to air pollution (WHO, 2011), Lipfert (1994, p.66) emphasizes that selective migration has to be considered when assessing the risk related to air pollution in different regions. From this point of view, it is possible that people who decide to migrate from more polluted areas to less polluted areas might be simply in better health than the non-migrating population. As a result, the mortality level will decrease in a receiving district while it will rise in the sending district.

2.3.2. Socio-Economic Determinants of Mortality

Although demographic determinants seem to be essential for explaining mortality differences, the influence of socio-economic factors cannot be neglected. Therefore, this section discusses why and how income, unemployment and educational attainment might influence the risk of dying.

2.3.2.1. Income and Unemployement

Empirical studies which analyze both time and cross-sectional data confirm that people who live in wealthier countries reach on average higher age. This positive correlation can be found not only on the level of countries, but also within the population of one country (Cuttler, Deaton & Lleras-Muney, 2006).

The curve describing the relationship between income and mortality is believed to follow a logarithmic shape, which means that the mortality advantage of wealthy people decreases with growing income. This shows that lower-income groups are more exposed to the risk of death and that even a slight decrease in income may have a dramatic impact on their living conditions (Ecob & Smith, 1999).

Despite these findings, the exact direction of causality between mortality and income remains a subject of scientific debate. On the one hand, unhealthy individuals with a higher risk of death can earn less, simply because of their lower productivity and more frequent absences from work (Weil, 2006). The supporters of the opposite approach claim that wealthier people have a better control over their health because they are able to make greater financial investments into it. In addition, they are able to profit from an improved health status more while being ill is more costly for them. Thus, they tend to treat their own health with more responsibility, which is reflected for example by choosing groceries of a higher quality or taking advantage of medical and health-care services (Soares, 2007).

Another way how income may influence mortality on regional level is through increased spending on infrastructure. Additional financial resources can be used to improve the existing infrastructure or to develop new infrastructure one in a specific region. For example, the network of medical and health-care centers can be extended and made more available. This is especially important with regard to the control and prevention of diseases (Pritchett & Summers, 1999).

While the economic situation used to be perceived as one of the most important determinants of mortality in the past (Pritchett & Summers, 1999), Preston (2007) objects that mortality rates do not depend on the level of disposable financial resources so strongly anymore. This conclusion is also supported by Soares (2007) who states that human lives were extending also when the level of income stayed constant. He explains this development mostly by the diffusion of new knowledge and technologies, which made the prevention of diseases more efficient across regions independently of their economic situation.

In the context of mortality differentiation by income, it is interesting to observe how the risk of death changes with respect to loss of employment. A study from six developed countries shows that a higher neighborhood unemployment rate is associated with an increased risk of premature death (Van Lenthe et al., 2004). There are various channels through which poor economic conditions may affect the level of mortality. A restricted access to high-quality food and health care provides a plausible explanation. Moreover, the health of an unemployed individual can be negatively influenced by a reduced frequency of social contact with other people. Unemployment can also lead to the feelings of personal failure which, together with chronic stress, may increase the prevalence of risk behavior (Jin, Shah & Svoboda, 1995).

2.3.2.2. Educational Attainment

In academic literature, education belongs to the most commonly mentioned factors influencing the probability of premature death. Interestingly, mortality differentiation based on education in the Czech Republic is one of the greatest in Europe. For illustration, a 30 years old man with university education lived on average 17 years longer in 2010 than a man who had been educated only in an elementary school. For women, this difference is less striking, as it made up only 4.6 years in 2010 (Kohoutová, 2013a, p.2). Another recent study shows that the risk of suffering from cardiovascular diseases is 3.2 times higher for a Czech with only elementary education compared to a person with a university degree. (Lustigová, 2013, p.8).

Similarly as other socioeconomic factors mentioned in this section, education influences mortality in a rather indirect way. One of the possible explanations of this relationship is that university graduates have a better access to information regarding health in general, and that they can make a better use of this information as well. Furthermore, they tend to spend more time looking after their personal health. As a result, they are able to communicate with doctors in a more efficient way than the rest of the population, and they are also more willing to accept new technologies and knowledge in the field of medical treatment and prevention (Pampel, Krueger & Denney, 2011).

Another important factor which may play a crucial role is the choice of life-style. For example, the percentage of regular smokers is significantly higher among Czechs with only elementary education compared to university graduates. Moreover, a recent survey shows that smoking is being increasingly disapproved by university graduates. Compared to the rest of the population, they favor a complete ban on smoking inside restaurants more often (Csémy, Sadílek & Sovinová, 2012, pp.19, 41). A similar indirect relationship can be also found between alcohol consumption and education in the Czech Republic, especially in case of Czech male population. Men who reached only elementary education drink on average 4.6 liters of pure alcohol more than male university graduates per year (Csémy & Sovinová, 2003, p.37).

It is important to take into consideration that the effect of education will be captured also by the income level and vice versa. University graduates are more likely to get jobs with higher salary and better working conditions after they finish their studies. This means that the jobs occupied by them are not only paid better, but also involve less physical efforts. Consequently, the probability of suffering from job-related illnesses is lower for university graduates than for the other parts of the population (Kohoutová, 2013a).

2.3.3. Quality and Availability of Medical and Health Care Services

Since the end of the 19th century, the quality of medical care has been one of the most important determinants of mortality in developed countries. In this regard, decreasing risk of premature death is mainly a consequence of the development of new drugs and medical technologies, which have improved the efficiency of disease prevention (for example through mandatory vaccination), and of treatment of already diagnosed diseases (Easterlin, 1999). Furthermore, Cuttler, Deaton and Lleras-Muney (2006) point out that there are no indications of a slow-down in this area. This means that improvements in quality and availability of medical care are likely to play an important role in the future as well.

Concernig the situation in the Czech Republic, mortality remained relatively constant between mid-1960s and mid-1980s as a result of a stagnating level of medical care. The lack of financial resources and isolation of the centralized economy caused that the Czech Republic started to lag behind the countries of Western Europe. When the borders opened up in 1990, an increase in available financial resources together with import of new technologies contributed significantly to a fast growth of life expectancy (Burcin & Kučera, 2009). Although the recent development of mortality in the Czech Republic belongs to the most favorable ones in former communist countries, there is still a noticeable difference when comparing it with the countries of Western Europe (Rychtaříková, 2004).

In the Czech Republic, the medical and health-care system is financed mainly through a compulsory health insurance which covers around three quarters of its costs (Daňková et al., 2010, p.43). Although the height of direct co-financing, another source of income of the medical system, has been increasing in the last years, only 0.3 % of the citizens of the Czech Republic found medical care financially unavailable in 2009 (Český statistický úřad, 2012, p.47).

One of the indicators showing that the quality of the Czech health-care system has been improving since 1990 is the continual drop in deaths caused by curable or preventable diseases. For illustration, between the years 1990 and 2006, the intensity of ‘avoidable mortality’ decreased by 38 % for men and by 40 % for women. This significant improvement was mainly achieved by reducing mortality on ischemic heart diseases (Burcin & Kučera, 2009, pp.68-70).

2.3.4. Life Style

In 1971, Omran (1971) suggested that the final phase of 'epidemiological transition' was represented by a period of degenerative and civilization diseases. At the time when this theory was formulated, a further decline in mortality seemed to be impossible. In reality, however, the period of *cardiovascular revolution* followed, in which further gains in life expectancy were achieved by reducing mortality on this particular cause. In context of this development, the importance of personal health-care started to grow and healthy life style became an important topic of the all-society debate (Burcin & Kučera, 2010).

On the other hand, the quality of nutrition was identified as an important determinant of mortality already in the study by McKeown, Brown and Record (1972). The authors noticed that mortality on infectious diseases had been decreasing already before the end of the 19th century despite the fact that the knowledge of appropriate medical treatment had not been available yet. They explained this development by pointing out the progress in agricultural production and increasing food import which had secured enough food for growing population.

Paradoxically, the increased supply of food has led to an increased risk of death on degenerative and civilization diseases in developed countries because they are often associated with a higher prevalence of obesity. This trend has been mainly supported by improper changes in diet and a lower intensity of physical activities (Popkin, 1993). Despite minor improvements in recent years, the composition of food consumed in the Czech Republic is far from ideal, especially with respect to the consumption of fruits and vegetable (Rychtaříková, 2004). Moreover, current statistics reveal that around 17 % of the population suffers from obesity (Daňková et al., 2010, p.24).

Another important factor of life style which contributes to premature mortality in the Czech Republic is the prevalence of smoking and excessive consumption of alcohol. Both these unhealthy habits are typically associated with a higher risk of cardiovascular diseases, neoplasm and developmental defects in fetus (Csémy & Sovinová, 2003). A recent study shows that the share of smokers in the population has remained relatively constant in the last 15 years – every fifth citizen of the Czech Republic consumes at least one cigarette per day (Csémy, Sadílek & Sovinová, 2012, p.13). Compared to this development, the alcohol consumption has been slightly rising since 1994 (Kohoutová, 2013b).

2.3.5. Urbanization and Industrialization

At the beginning, migration to urban areas was associated with an increase in mortality. Although cities represented the centers of economic activity, they were not able to accommodate the great influx of population from rural areas and, consequently, did not offer satisfying living conditions to all newcomers. Moreover, the prevalence of infectious diseases was higher in densely populated areas because they could spread more easily (Easterlin, 1999).

Nevertheless, the relationship between mortality and urbanization has reversed mainly as a consequence of the improvement of transportation and health-care infrastructure. Due to time reasons, people had to live close to factories they worked at in the past. However, newly constructed roads enabled them to move to more distant residential districts with better living conditions. Excess mortality in cities was further reduced by introducing public sanitation, developing greater awareness of disease prevention and constructing a dense system of medical facilities (Weeks, 2008, p.189; Easterlin, 1999).

On the other hand, increasing motor-vehicle traffic and related higher level of air pollution could, to a large extent, slow down the favorable trend in mortality reduction achieved in cities. However, a study conducted in the Czech Republic in 2002 and 2003 surprisingly shows that particulate air pollution in small municipalities reaches on average the same levels as in large cities (Kotlík et al., 2005). Although it seems that the concentration of dust particles does not significantly differ between rural and urban areas, the risk of dying attributed to air pollution might still be higher in cities because their inhabitants are better protected against other causes (Gouveia & Fletcher, 2000).

2.4. Hypotheses

Based on the mechanisms discussed in this chapter, fine particulate air pollution as well as its reduction is expected to have the same impact on districts with improving and those with deteriorating air quality. Moreover, it is possible to assume that higher gains in life expectancy will be detected in regions where the concentration of fine particles decreased between the periods 2000-2002 and 2010-2012 more. On the contrary, regions where air pollution increased most are likely to reach the smallest gains in life expectancy.

In addition, changes in concentrations of fine particulate matter are likely to affect mainly the intensity of mortality of infants and people older than 65 years. The reason for formulating such an assumption is that these age groups offer more room for improvements of mortality than other age groups in general (Wilmoth, 2000). Old people and children under the age of one might be also more sensitive to deteriorating living conditions, including the environmental aspects of their surroundings (Gouveia & Fletcher, 2000). Furthermore, it is possible to expect that people at these age groups have been exposed to air pollution levels in respective districts because their migration rates are significantly lower compared to the rest of population (Burcin Kučera, 2010, p.9).

Regarding the causes of death, a reduction in the concentration of $PM_{2.5}$ is expected to decrease mainly the share of deaths on respiratory and cardiovascular diseases. However, it is important to take into consideration that a lower risk of death on a certain cause does not necessarily imply a reduction in total mortality. In fact, a decreasing risk of death on one cause automatically leads to an increasing risk of death on other ones. This means that mortality on these other causes increases, although their incidence might remain constant. Thus, competing risks cannot be ignored since the overall impact on mortality remains unclear (Nevalainen & Pekkanen, 1998).

Chapter 2

Data Description and Methodology

In this chapter, the construction of individual pollution and mortality indicators using raw data derived from the databases of Český hydrometeorologický ústav and Český statistický úřad is described. Afterwards, relevant descriptive statistics for each variable are summarized, which offers an insight into the distribution of the data. In addition, regional as well as time comparability of the data is discussed.

In case of the Czech Republic, the analyzed territorial units are districts which correspond with the LAU1 level (formerly labeled as NUTS 4). Compared to higher territorial units, districts have an indisputable advantage – their borders have been relatively stable over time[4] (Český statistický úřad, 2013b). For every district, the average values of all selected indicators in the three-year periods 2000-2002 and 2010-2012 are calculated. The main reason for choosing time periods longer than one year and calculating the averages for the whole periods is the risk of choosing a year marked by an abnormal variation, which could lead to significant distortions (Český statistický úřad, 1997).

As indicated in the theoretical framework, the relationship between air pollution and mortality can be influenced by different risk or protective factors which are present in a certain location. In other words, it is necessary to separate the effect of the reduction or increase in fine

[4] Between the years 2000 and 2012, the borders of regions changed only once on 1st January 2007 (Český statistický úřad, 2013b).

particulare air pollution from the effects of other determinants of mortality in order to test the hypotheses stated in the section 2.4. Therefore, the description of other explanatory variables selected for the empirical analysis is provided as well. At the end of this chapter, the first-difference model and its theoretical assumptions are formally introduced.

3.1. Outdoor Air Pollution Data

Ccollection of air pollution data has a relatively long tradition in the Czech Republic, as the first measuring stations were constructed as early as at the beginning of the 1970s. Although the concentration of suspended particulate matter was already measured at that time, the size of individual particles was not differentiated. The breakthrough came first in the 1990s when the network of automated measuring stations was established. While the concentration of particles smaller than 10µm has been tracked since 1994, the measurement of $PM_{2.5}$ was initiated ten years later and has been gradually extending to more areas ever since (Macoun, 2009).

In 2012, the quality of air was analyzed by 202 measuring stations in the Czech Republic, of which 104 measured the concentration of PM_{10} and 43 tracked also the concentration of $PM_{2.5}$ (Český hydrometeorologický ústav, 2013b). The data obtained from these stations are gathered and archived by the information system ISKO which publishes them in tabular yearbooks every year (the data for the years after 1997 are available online as well). For purpose of this study, six of these yearbooks (Fiala et al., 2001; Fiala et al., 2002; Fiala et al., 2003; Český hydrometeorologický ústav, 2011; Český hydrometeorologický ústav, 2012; Český hydrometeorologický ústav, 2013b) are the source of data on air pollution in individual regions. The correctness of these data is assured by both physical controls of the measuring stations performed by official authorities and regular revisions not only on the regional, but also on the national level (Fiala et al., 2003).

3.1.1. Fine Particulate Matter ($PM_{2.5}$)

Although the network of stations measuring the concentration of $PM_{2.5}$ has been gradually extending (Macoun, 2009), the data are not available for the period of 2000-2010. For this reason, this indicator is calculated indirectly as a fraction of the concentration of PM_{10}. For the sake of consistency and because the same measuring stations[5] have to be observed in both periods, this approach was applied to the period of 2010-2012 as well. The calculation method is based on a long-term parallel measurement of the concentrations of PM_{10} and $PM_{2.5}$ on the territory of the Czech Republic. Using the data from the time period of 2006-2012, it was discovered that, on average, $PM_{2.5}$ makes up 75 % of PM_{10} (Státní zdravotní ústav, 2013, p.15). Therefore, the concentration of PM_{10} can be multiplied by 0.75 in order to obtain the concentration of $PM_{2.5}$. Although it is a generally accepted calculation method resulting from the recommendations of the WHO, it is possible that significant regional differences in the proportion of fine particles within PM_{10} may result into a certain distortion of the results for some regions.

Regarding the actual calculation, firstly, the average of monthly values was calculated for the years 2000, 2001, 2002, 2010, 2011, and 2012 for every measuring station which conducted valid measurements of the concentration of PM_{10} at least in six months of each of these years. Consequently, the yearly values were averaged for the three-year periods 2000-2002 and 2012-2012. Finally, the results were multiplied by 0.75 in order to obtain the average concentration of $PM_{2.5}$ in all locations in the selected time periods, as discussed in the previous paragraph.

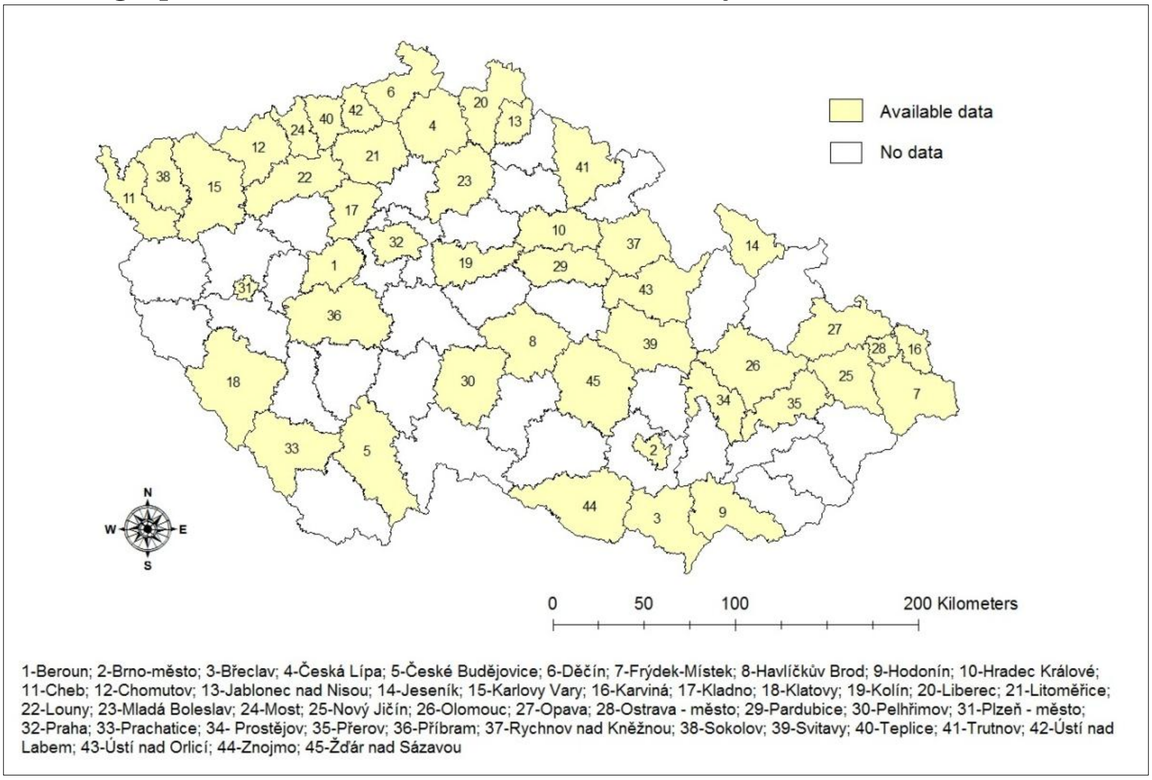
In general, only those measuring stations which were in operation in both periods under study were considered. When there were more measuring stations in one district, the average value for each station was calculated first, and then the values were averaged for the whole district. By following this procedure, data on the concentration of $PM_{2.5}$ were obtained for 45 different districts, whose geographical location is depicted by Fig.3.1.

It is also important to note that the change of district borders in 2007 does not affect the analysis in any way, because relevant measuring stations stayed in the same districts. On the other hand, it has to be taken into account that the selection of the districts was not based on a random choice from all 77 districts[6] of the Czech Republic. Therefore, it is possible that the measuring stations were mainly installed in the districts where a severe decrease in air quality was expected or where certain projects aiming at the reduction of the concentration of particulate matter were launched (Bobak & Leon, 1992). Although neither of these cases

[5] The concentration of $PM_{2.5}$ is not always measured by the same station as the concentration of PM_{10}.
[6] including Prague

would threaten the internal validity of the results, their external validity would be reduced (Angrist & Pischke, 2009).

Fig.3.1: Geographical distribution of districts under study



Source: author

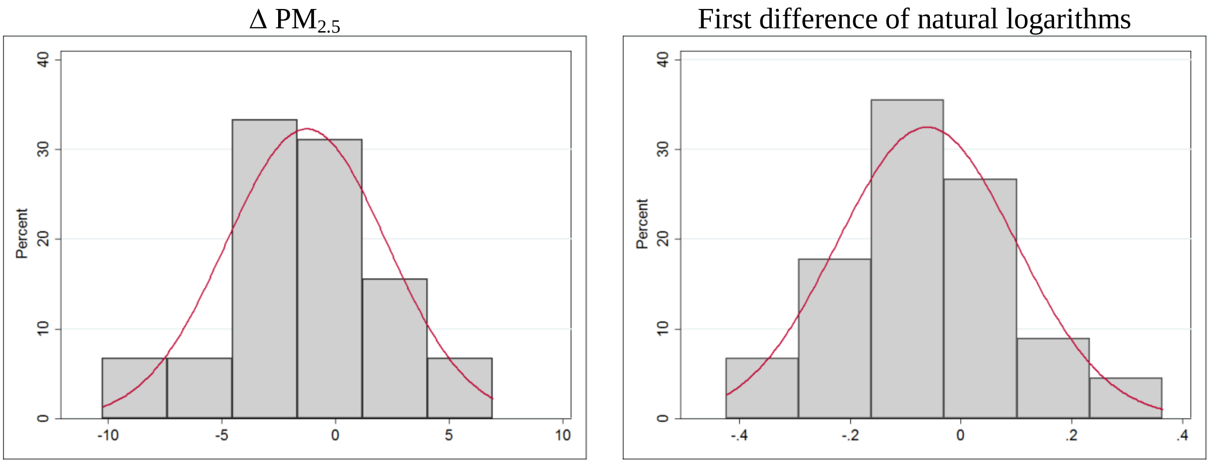
Tab.3.1: Descriptive statistics of variables related to fine particulate matter

Variable	Mean	Std. dev.	Min	Max	Obs
$PM_{2.5}$ ($\mu g/m^3$)					
2000–2002	20.990	6.336	6.909	37.552	45
2010–2012	19.721	6.278	5.763	44.499	45
Change	-1.269	3.538	-10.247	6.948	45
$PM_{2.5}$ ($\mu g/m^3$), logged					
2000–2002	2.995	0.330	1.933	3.626	45
2010–2012	2.993	0.323	1.751	3.795	45
Change	-0.062	0.161	-0.424	0.365	45

Source: author's calculations based on data from Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

Tab.3.1 summarizes the descriptive statistics of the fine particulate matter concentration in all 45 districts under study in selected time periods. The change is calculated as the difference between the values of the second period (2010-2012) and the values of the first period (2000-2002). This means that a lower negative value implies a higher reduction in air pollution while a higher positive values means that the concentration of fine particulate matter increased more.

Fig.3.2: Histrograms of Δ $PM_{2.5}$ and Δ $PM_{2.5}$ after logarithmic transformation of the data



Source: author’s calculations based on data from Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

It is possible to observe that average values were similar in both periods, which corresponds with the fact that the concentration of fine particulate matter has been rather stagnating on the national level in the last years (Český hydrometeorologický ústav, 2013a). On average, the concentration of $PM_{2.5}$ decreased merely by 1.27 $\mu g/m^3$ between the periods. However, the standard deviation is approximately three times bigger than the mean, which implies a flat distribution of values around the mean value. In addition, it indicates that there might be outliers in the dataset. Since large variability is caused rather by properly measured extreme values than by faulty observations, there is no logical reason for dropping extreme observations from the dataset. Instead, a sensitivity analysis of results will be performed.

Furthermore, logarithmic transformation of the data using a natural logarithm is applied and the resulting variable is used in the following sections of this paper. More specifically, the natural logarithm of the concentrations of $PM_{2.5}$ in individual periods is taken, which is possible as all values are positive and natural logarithm is for all of them defined. Then, the difference between the logarithm of the values for 2010-2013 and for 2000-2002 is calculated.

$$\Delta\, ln\,(PM_{2.5}) = ln\,(PM_{2.5}^{2010-2012}) - ln(PM_{2.5}^{2000-2002})$$

This approach leads not only to a compression of the values (see Fig.3.2), but it also allows interpreting the resulting estimations as growth rates (Wooldridge, 2009, p.393).

In both periods under study, 43 out of 45 districts were exceeding the limits recommended by the WHO and 12 of them were even above the limits set by Czech regulations. Both the negative (in orange and red colors) and positive (in green color) relative changes can be observed on a cartogram (see Fig.A1 in the appendix). Overall, the development seems to be geographically scattered with no clearly observable trend. The greatest relative drop in air quality took place in the districts of *Cheb* and *Mladá Boleslav*, while the greatest improvements were recorded in *Kladno, Beroun, Ústí nad Labem* and *Znojmo*. Contrary to the expectation, the situation in the northwestern borderland, which is traditionally associated with a higher rate of air pollution due to intensive coal mining and electricity generation (Šrám, 1996), did not worsen between the periods. On the other hand, in the northeastern part of Moravia, an area strongly affected by industrial production (Tomášková et al., 2011), all five regions recorded an increase in the concentration of $PM_{2.5}$ between the periods.

3.2. Mortality Data

Mortality data related to the Czech Republic are collected on regular basis and gathered by Český statistický úřad [Czech Statistical Office]. The main sources for this study are two demographic yearbooks which summarize the data on the district level for the periods 1999-2012 (Český statistický úřad, 2009), and 2003-2012 (Český statistický úřad, 2013b).

The information on the death of every individual is processed by statistical authorities immediately after its occurrence. An attendant doctor is obliged to fill in the so called “List o prohlídce mrtvého” form with the information on the deceased person which is consequently processed by local register office. Registers are required to inform Český statistický úřad once a month in order to update the vital statistics. This requirement persists even in the months when nobody dies. In this case, the register sends a negative report. This practice ensures that the evidence stays practically complete at all times (Ústav zdravotnických informací, n.d.).

Mortality data were obtained from the yearbooks only for those 45 districts which were identified in the section on air pollution (see Fig.3.1). The raw data consisted of deaths by sex and by age groups and of the total population by sex and by age groups at the end of each calendar year. Based on these data, abridged life tables were calculated separately for the period 2000-2002 and 2010-2012 using the methodology suggested by Pavlík, Rychtaříková and Šubrtová (1986, pp. 171-214).

Apart from the advantages presented in previous sections, using three-year intervals also allows controlling for possible random fluctuations in regional mortality caused by an overall low number of deceased people in these territorial units (Český statistický úřad, 1997). Another clear upside of the intervals chosen for this study is the fact that all data are recalculated for the territorial structure valid at the time of the publications of the respective yearbook, i.e. for 2009 and 2013 (Český statistický úřad, 2013b; Český statistický úřad, 2009). This means that the change of borders of individual districts in 2007 is taken into account and that the indicators are fully comparable.

Tab.3.3 summarizes the descriptive statistics of all indicators related to mortality (seven in total) which will be used subsequently as dependent variables in the regression models. Their further characteristics are described in the following subsections.

3.2.1 Life Expectancy at Birth and Life Expectancy at Age 65

Life expectancy at birth and at age 65 was derived from the life tables calculated in the previous steps. These theoretical indicators show how long a person born (resp. 65 years old) would on average live if he or she was exposed to the age-specific mortality rates recorded in the year of birth (resp. attaining 65 years) throughout the rest of his or her life (Weeks, 2008). One of the main benefits of using these indicators is the fact that they account for different age structures across individual districts (Pavlík, Rychtaříková & Šubrtová, 1986, p.201). On the other hand, it is possible that the theoretical life expectancy may underestimate the real gains in life expectancy because of an ongoing reduction in mortality observable in all age groups (Wilmoth, 2000).

Life expectancy at birth increased in all districts under study between the selected time periods and individuals born in 2010-2012 are expected to live on average 2.5 years longer than the ones who were born in 2000-2002. Life expectancy at age 65 also increased, namely by 1.64 years, which corresponds with the fact that older age groups form a substantial part of the overall gain in life expectancy. Moreover, the low value of standard deviation implies that data are distributed relatively close to the mean in both cases, and visual inspection does not suggest the presence of outliers (see Tab.3.3). However, for the purpose of regression analysis, using life expectancies in logged form is preferred because no increasing returns to air pollution reduction are expected. Moreover, the distribution of life expectancy at the age of 65 is positively skewed and logarithmic transformation makes it more symmetric. For updated descriptive statistics see Tab.A.1 in the appendix.

The cartogram (see Fig.A2 in the appendix) shows that the greatest relative gains in life expectancy at birth were predominantly achieved in districts in the north of the country and in the eastern part of Moravia. Surprisingly, quality of air significantly decreased between the periods in some of these districts.

Compared to life expectancy at birth, life expectancy at age 65 shows a slightly different development. The greatest gains were achieved mainly by districts in the northwestern borderland in which the concentration of fine particulate matter was reduced. On the other hand, it is possible to observe that all northeastern districts of Moravia, where the level of air pollution increased, attained rather small gains in life expectancy at age 65 (Fig. A3 in the appendix).

3.2.2 Age-specific Mortality Indicators

Based on the theoretical framework, it is possible to expect that the change in air pollution which occurred over the ten-year period affects different age groups differently. For this reason, the age-specific mortality rates at older age (65+) and infant mortality rates were calculated for both periods under study. The definitions of these indicators are summarized in Tab.3.2.

Tab.3.2: Definitions of indicators related to age-specific mortality

Indicator	**Definition**
Infant mortality	number of deaths before turning the age of one per 1,000 live births
Mortality at the old age	number of deaths at the age 65+ per 100,000 population aged 65+

Source: author based on Weeks (2008)

Concerning the age-specific mortality rates at old age, mortality, on average, decreased by 856 deaths per 100,000 population. Infant mortality decreased, on average, by 1.2 children per 1,000 births, which represents a decline of one third of the already low values recorded in the initial period. Moreover, this indicator shows a higher level of variability across individual districts compared to other mortality indicators (see Tab.3.3). This corresponds with the fact that the number of deceased infants is very low in individual districts (also in three-year intervals), which means that even a slight variation can cause a substantial fluctuation of the infant mortality rate.

Tab.3.3: Descriptive statistics of variables related to mortality

Variable	Mean	Std. dev.	Min	Max	Obs
Life expectancy at birth (yr)					
2000–2002	74.921	1.099	72.801	77.009	45
2010–2012	77.424	1.062	75.136	79.345	45
Change	2.503	0.394	1.673	3.574	45
Life expectancy at the age of 65 (yr)					
2000–2002	15.511	0.642	14.123	16.828	45
2010–2012	17.153	0.615	15.710	18.470	45
Change	1.642	0.290	1.112	2.404	45
Infant mortality rate[1)]					
2000–2002	4.169	1.579	0.873	7.578	45
2010–2012	2.975	1.261	1.103	6.117	45
Change	-1.193	1.691	-4.540	2.698	45
Mortality at old-age (65+)					
2000–2002	5,877.541	348.863	5,215.209	6,748.440	45
2010–2012	5,021.070	261.414	4,540.574	5,844.562	45
Change	-856.471	232.331	-1393.431	-375.127	45
Mortality on cardiovascular diseases					
2000–2002	0.52408	0.03381	0.44403	0.60037	45
2010–2012	0.49245	0.02613	0.43076	0.54281	45
Change	-0.03116	0.02823	-0.09409	0.03756	45
Mortality on respiratory diseases					
2000–2002	0.04523	0.01162	0.02217	0.08549	45
2010–2012	0.05631	0.00996	0.03690	0.07689	45
Change	0.01107	0.01359	-0.03875	0.03566	45
Mortality on lung cancer					
2000–2002	0.05456	0.00992	0.03746	0.08619	45
2010–2012	0.05447	0.00997	0.03688	0.07813	45
Change	-0.00009	0.00551	-0.01349	0.01964	45

Source: author's calculations based on data from Český statistický úřad (2009) and Český statistický úřad (2013b)

For the purpose of regression analysis, all these indicators were transformed using natural logarithm. Again, the main reason is that line-log model would change the character of the relationship and that using first differences of logged form is more convenient when interpreting the estimates. Updated descriptive statistics can be found in Tab.A.1 in the appendix.

When observing individual cartograms (Fig.A4-A5 in the appendix), it is interesting to notice the infant mortality rates did not only improve but they also deteriorated in some districts. However, the districts with increasing infant mortality are considerably scattered across the country, and so it is not possible to claim that they copy the trend of the changes in the concentration of fine particulate matter. Surprisingly, relatively big improvements in infant mortality were achieved in northeastern districts of Moravia where the concentration of fine particulate matter increased (see Fig.A4). The cartogram capturing changes in age-specific mortality rates at old age (Fig.A5) shows that this indicator improved in all districts between the two periods.

3.2.3 Cause-specific Mortality Indicators

As discussed in the theoretical framework, the changes in air pollution might also impact the shares of individual causes of death. In the Czech Republic, deaths are classified according to the primary cause of death and for the purpose of statistical evidence, the International Classification of Diseases and Related Health Problems is used. Since 1994, its 10^{th} revision (ICD-10) has been used, which guarantees that the coding system is the same in both periods under study (Ústav zdravotnických informací, n.d.). As discussed previously, the concentration of fine particulate matter is typically associated with an increased mortality on three causes: cardiovascular diseases (I00-I99), respiratory diseases (J00-J99) and lung cancer (C34). For this reason, three indicators were constructed which capture the proportion of deaths caused by these causes of the overall number of deaths recorded over the periods under study.

When observing individual cartograms (Fig.A6-A8 in the appendix), it is possible to notice that the proportion of cardiovascular diseases increased only in five regions, of which in four the concentration of $PM_{2.5}$ rose significantly. On the contrary, the regions with the greatest improvements of air quality seem to record a slight decrease in the proportion of this cause (see Fig.A6). Surprisingly, the situation is completely opposite for the proportion of respiratory diseases, as it decreased in the regions with the greatest increase in $PM_{2.5}$ concentration. The only exception is region *Beroun* where both the proportion and air pollution decreased (see Fig.A7). Finally, there is also a cartogram depicting the development of the proportion of deaths caused by lung cancer (Fig.A8). In contrast to the previous two cases, the geographical distribution of regions where this proportion develops unambiguously is scattered around the whole country, and it does not seem to be visually associated with changes in the concentration of fine particulate matter.

Cardiovascular and respiratory diseases were the primary cause of death of every fifth resident of the Czech Republic and the proportion of these two causes combined decreased, on average, by two percentage points between the periods under study. While the proportion of cardiovascular diseases dropped by 3.1 %, the proportion of respiratory diseases rose by 1.1 %. The proportion of people who died of lung cancer remained relatively constant over time and represented approximately 5.4 % of all deaths (for details see Tab.3.3).

3.3. Other Explanatory Variables

Apart from an indicator capturing the percentage change in $PM_{2.5}$ concentration, individual regression models include also other variables which could confound or bias the effect of changes in fine particulate air pollution. The mechanisms how these factors impact mortality were closely examined in section 2.3. of the theoretical framework. In reality, however, controlling for all discussed variables reveals to be highly complicated due to unavailability of data on the level of individual districts (smoking) or with respect to a relatively small sample size[7]. Tab.3.4 summarizes the descriptive statistics of selected additional explanatory variables included in the regression analysis. When not stated differently, all indicators were calculated or directly derived from the results of the population censuses which took place in 2001 and 2011 (Český statistický úřad, 2003; Český statistický úřad, 2013c).

Different age structure of the population is captured by *mean age*. In fact, it is a weighted arithmetical average of the number of years which people lived in a respective district in a given year (Pavlík, Rychtaříková & Šubrtová, 1986, p.120). The advantage of this indicator is that it, unlike the dependency ratio or the proportion of population above a certain age limit, uses the values of the whole sample (Burcin & Kučera, 2010). On the other hand, mean age can be influenced by extreme values (Pavlík, Rychtaříková & Šubrtová, 1986). In general, population of the districts under study became on average 2.6 years older between the two periods (Tab.3.4).

[7] A higher number of included explanatory variables reduces the probability of detecting statistically significant effects (Wooldridge, 2009, p.97).

Tab.3.4: Descriptive statistics of other explanatory variables

Variable	Mean	Std. dev.	Min	Max	Obs
Mean age (yr)					
2001	38.369	1.002	36.300	41.100	45
2011	40.929	0.817	38.800	43.400	45
Change	2.560	0.661	0.900	3.900	45
Males (proportion)					
2001	0.489	0.005	0.474	0.499	45
2011	0.490	0.004	0.480	0.502	45
Change	0.002	0.003	-0.006	0.010	45
University graduates (proportion)					
2001	0.073	0.030	0.040	0.188	45
2011	0.102	0.038	0.053	0.237	45
Change	0.029	0.009	0.011	0.058	45
Number of doctors (per 1,000 population)					
2001	3.578	1.185	2.600	7.600	45
2011	4.140	1.522	2.700	8.900	45
Change	0.562	0.479	-0.200	1.900	45
Unemployment rate					
2001	0.692	0.166	0.409	1.000	45
2011	0.686	0.159	0.417	1.000	45
Change	-0.006	0.027	-0.069	0.061	45
Natives (proportion)					
2001	0.504	0.058	0.400	0.618	45
2011	0.461	0.051	0.373	0.563	45
Change	-0.042	0.021	-0.110	-0.006	45
Urban (proportion)					
2001	0.692	0.166	0.409	1.000	45
2011	0.686	0.159	0.417	1.000	45
Change	-0.006	0.027	-0.069	0.061	45
Married (proportion)					
2001	0.298	0.128	0.124	0.576	45
2011	0.191	0.081	0.086	0.385	45
Change	-0.107	0.050	-0.221	-0.038	45

Source: author’s calculations based on data from Český statistický úřad (2003), Český statistický úřad (2013c) and Český statistický úřad (2014)

Regarding the sex structure of the population, the development of the *proportion of males* in the population of the districts in 2001 and 2011 is tracked. The proportion of males appears to be relatively stable over time, as it increased only by 0.2 % between the periods (Tab.3.4).

Socio-economic differences between districts are represented by the *proportion of university graduates* in population older than 15 years. Despite the fact that the income level might offer some interesting insights into the problematic, educational attainment is preferred when analyzing mortality differentiation. The main reason for that is the fact that the level of education attained can be obtained for the whole population while the income level is, by definition, available only for the economically active part of the population (Kitagava & Hauser, 1973 in Rychtaříková & Sobotík, 1992, p.97). Moreover, it is obvious that the income level depends to a large extent on the educational attainment. The level of education should also capture the effect of different life-styles and attitudes towards personal health across the districts. On average, the proportion of university graduates increased by 0.3 percentage points between the periods under study (Tab.3.4).

Different economic conditions in the districts are reflected by the *unemployment rate*. This indicator is defined as the proportion of unemployed people within the economically active population. Data from population censuses in 2001 and 2011 are used for its calculation as they captured all people who declared to be unemployed disregarding whether or not they were registered at an employment bureau (Český statistický úřad, 2003; Český statistický úřad, 2013c). Therefore, these data offer a better idea about the real unemployment in the respective region than the data provided by employment bureaus. Although the unemployment rate did not change dramatically on average (decreased only by 0.6 percentage points), this indicator was highly variable across individual districts. These variations ranged from a decrease of 7 % to an increase of 3 % (Tab.3.4).

Measuring the quality and availability of medical care reveals to be rather complicated in practice. One of the possible indicators is the *number of doctors per 1,000 inhabitants* because a higher number of doctors implies that doctors can devote more time to each patients. This indicator was derived for the years 2001 and 2011 from regional time series published by Český statistický úřad (2014). On average, the number of doctors per 1,000 inhabitants rose by 0.5 doctors between the periods (Tab.3.4).

The *share of natives* living in the respective region in 2001 and 2011 helps capturing the process of selective migration to less polluted districts. In other words, it makes it possible to identify if the health status (and mortality) of the individuals who live in the respective district since their birth is better or worse than the health status of the rest of the population of the district. Between the time periods under study, the share of natives decreased on average by 5 percentage points (Tab.3.4).

Because air pollution as well as availability of medical care may be different in urban and rural areas, the *share of people living in urban areas* in individual districts in 2001 and 2011 is controlled for as well. However, the definition of urban areas may be slightly problematic. In the framework of population census, every municipality with a status of a city at the time of the census was considered as an urban area (Český statistický úřad, 2003; Český statistický úřad, 2013c). On average, the number of people living in urban areas decreased by 0.6 percentage points between the periods (Tab. 3.4).

The last indicator included in the model is the *proportion of married people* in the population of the districts in years 2001 and 2011. This indicator shows a dramatic decrease between the periods under study, as it dropped by 10 percentage points. However, it is important to take into account that this indicator does not include cohabitations, whose prevalence is increasing in time, which may be associated with the same effects as matrimonies.

3.4 Methodology

The final balanced panel dataset contains data on two time periods, 2000-2002 and 2010-2012 (t=2), for 45 districts (N=45). The basic linear model for this panel data can be transcribed as:

$$Y_{it} = \alpha + \delta \cdot log\ (PM)_{i1} + \boldsymbol{\beta} \cdot \boldsymbol{X_{it}} + \omega_i + \varepsilon_{it} \quad t = 1,2 \quad i = 1, \dots, 45$$

where the dependent variable Y_{it} represents the selected mortality indicator and X_{it} includes all explanatory variables apart from the one which captures the concentration of fine particulate matter in the air. For better illustration, this variable stands separately in the formula.

It is assumed that the error term, which reflects all unobserved factors, can be divided into two parts. While the first one changes in time (ε_{it}), the second one remains constant over time and is specific for each individual district (ω_i) (Wooldridge, 2009, p.457). Among others, the latter may include the effects of district's geographical location or attitudes towards air pollution that are likely to change slowly over time. However, all these unobserved factors are expected to be dependent on the values of explanatory variables included in the model during the two periods under study.

$$E[log\ (PM)_{i1}, log\ (PM)_{i2}, X_{i1}, \dots, X_{n2}] \neq 0$$

Therefore, fixed effect regression model can be employed. However, since only two time periods are analyzed, this estimation approach can be replaced by taking first-difference. These two methods provide equal results if only two time periods are observed (Angrist & Pischke, 2009, p.167).

If the relationship between the concentration of fine particulate matter and mortality was tested separately for each period, it would be possible to formulate the following cross-sectional regression models and estimate them using OLS:

(1) $Y_{i1} = \alpha + \delta \cdot log\ (PM)_{i1} + \boldsymbol{\beta} \cdot \boldsymbol{X_{i1}} + \omega_i + \varepsilon_{i1} \qquad t_1 = 2000 - 2002, i = 1, \dots, 45$

(2) $Y_{i2} = \alpha + \delta \cdot log\ (PM)_{i2} + \boldsymbol{\beta} \cdot \boldsymbol{X_{i2}} + \omega_i + \varepsilon_{i2} \qquad t_2 = 2010 - 2012, i = 1, \dots, 45$

where the set of explanatory variables includes demographic determinants of mortality (age[8], sex and marital status, natives), socioeconomic determinants (the proportion of university graduates, unemployment rate), indicators related to the availability of health-care (the number of doctors per 1,000 inhabitants) and environmental factors (urbanization). Although the choice of these specific variables is based on the insights discussed previously in the theoretical framework, controlling for all variables that could explain the mortality level and might be correlated with already included explanatory variables is not feasible in practice (Wooldridge, 2009).

On the other hand, it is possible to subtract the second model from the first one:

(3) $\Delta Y_i = \alpha + \delta \cdot [\log(PM)_{i2} - \log(PM)_{i1}] + \boldsymbol{\beta} \cdot \Delta \boldsymbol{X_i} + \Delta\varepsilon_i$

This means that the changes in a selected mortality indicator are regressed on the changes in the concentration of fine particulate matter while changes in all additional explanatory variables are held constant. Provided that the classical linear model assumptions are fulfilled, model (3) can be estimated using OLS method (Wooldridge, 2009, p.458).

In order to identify the first-differenced model, all explanatory variables included in the regression (3) have to be strictly exogenous. This means that the part of the error term which varies over time (ε_{it}) may not be dependent on the values of PM2.5 concentrations or on any other explanatory variables in any time period. In other words, there are no time-specific unobserved shocks that affect simultaneously air pollution level and health status of the

[8] Included only if the dependent variable is not already adjusted by the impact of different ageing across districts.

population. If the assumption of strict exogeneity is violated, estimates become inconsistent (Wooldridge, 2009, p.458).

The main advantage of using first-difference estimator is that all unobservable factors, which are constant over time, are differenced away. This helps to prevent a possible omitted variables bias which is likely to be present in models (1) and (2). From this point of view, the first differenced model is likely to predict values which are closer to the real effect which air pollution has on mortality than individual cross-sectional models. On the other hand, first-differenced model is more sensitive to measurement errors as it relies on within observations (Angrist & Pischke, 2009, p.167).

Overall, three different first-difference regression models are estimated for each mortality indicator. Firstly, the percentage change in fine particulate air pollution is regressed only on the selected indicator. For visual analysis of these relationships see Fig. A9 in the appendix. As next, several other determinants of mortality and possible confounders are added to the first model in order to assess the sensitivity of estimates. Finally, the third model includes also a dummy variable indicating whether the air quality deteriorated or not in a given district and an interaction term of this dummy variable with a variable representing percentage change in the concentration of PM2.5. This approach allows investigating whether the effect of changes in fine particulate air pollution significantly differs between districts with improving and worsening air quality. Each model is run twice, using the whole sample (n=45) and without potential outliers. After the estimation, several diagnostic tests of each model are run in order to see whether the classical linear model assumptions are fulfilled. The results of these tests are provided in the appendix (Tab.A6).

Chapter 4

Empirical Results and Discussion

In this chapter, the results of three first-difference regression models, which were closely described in the previous chapter, are summarized and discussed. Estimated coefficients related to fine particulate air pollution can be interpreted as predicted changes in a selected mortality indicator induced by a percentage change in the concentration of $PM_{2.5}$, holding changes in all other explanatory variables constant. It is important to keep in mind that a positive change in the variable representing fine particulate air pollution implies worse air quality. Therefore, estimated coefficients have to be multiplied by a negative number in order to obtain the effect of reduction in fine particulate air pollution. Due to a relatively small size of the sample, a higher probability of falsely rejecting the null hypothesis is perceived as acceptable. Thus, the 10 % level of significance is chosen for testing the hypotheses.

4.1. Life expectancy at birth and life expectancy at the age of 65

Firstly, the relationship between changes in fine particulate air pollution and increases in life expectancy at birth is examined. Derived estimates are summarized in Tab.4.1. The results of model (1) show that life expectancy at birth is expected to increase by 3 % even without any changes in fine particulate air pollution. Moreover, a reduction in the concentration of $PM_{2.5}$ of 10 % is associated with an increase in life expectancy at birth of 0.03 %. However, this effect reveals to be statistically insignificant. This means that a positive effect of decreasing concentration of fine particulate matter on changes in life expectancy was not proven for the given sample. Moreover, model (1), which includes only an indicator of changes in air quality, is able to explain just one percent of the overall variation in changes in life expectancy at birth.

Estimated coefficients of model (2) imply that the effect of decreasing fine particulate air pollution is robust to the inclusion of other mortality determinants as it does not change dramatically. A positive, albeit still statistically insignificant, impact is observed also after removing possible outliers from the sample (for details see Tab.A3 in the appendix). No significant differences in the size of this effect or in the returns to air pollution reduction between the districts with improving and the ones with deteriorating air quality were identified (model 3).

Regarding the results related to life expectancy at the age of 65, a positive intercept indicates that this indicator is expected to increase by 9.9% between the periods under study even if no change in fine particulate air pollution occur. Similarly as in case of life expectancy at birth, a positive effect of air pollution reduction is predicted. More specifically, a 10% reduction in $PM_{2.5}$ concentration is associated with an increase in life expectancy at 65 of 0.2 %. However, this effect reveals to be statistically insignificant again. Model (1) that contains only a variable related to changes in fine particulate air pollution explains 2% variation in changes in life expectancy at 65.

In addition, the size of the effect does not change when controlling for other explanatory variable, which shows the robustness of the results (model 2). The last model (3) indicates that the size of the effect and returns to air pollution reduction does not significantly differ between the regions with improving and worsening air quality. Furthermore, removing possible outliers from the model neither changes the size of the effect nor leads to its statistical significance. The difference between regions with improving and deteriorating air quality remains insignificant as well (Tab.A3 in the appendix).

4.2. Age-specific Mortality

As changes in fine particulate air pollution may affect individual age groups differently, the models are estimated again using infant mortality rate and mortality rate at the age of 65+ as dependent variables. As discussed before, these specific age groups are selected because they are often regarded as highly endangered by an increased level of fine particulate air pollution (for details see Theoretical Framework). Estimated coefficients are summarized in Tab.4.2.

Model (1) explains only 0.03% variation in change in the infant mortality rate and predicts that infant mortality decreases by 34 % when the level of fine particulate air pollution does not change. Surprisingly, a reduction in $PM_{2.5}$ concentration of 10 % is associated with an increase in infant mortality of 0.6 %. However, this effect reveals to be statistically insignificant and highly sensitive to inclusion of other mortality determinants. More specifically, model (2) predicts a decrease in infant mortality of 2.4 % when particulate matter pollution decreases by 10 %. Despite the fact that the direction of the effect becomes more logical, it still remains insignificant. Moreover, it is not possible to prove that there are statistically significant differences between the districts with improving and worsening air quality.

However, the model for infant mortality is also highly sensitive to the presence of potential outliers because the coefficient changes its sign again if the model is reestimated using the restricted sample. In fact, reduction in air pollution of 10 % is again associated with an increase in infant mortality, this time of 0.1 %. Nevertheless, this effect remains statistically insignificant (for details see Tab.A4 in the appendix).

Regarding the impact on mortality in elderly (65+), it is possible to claim that negative intercept reflects a decrease in mortality of 15.4 % when air pollution remains unchanged. If the concentration of $PM_{2.5}$ decreases by 10 %, mortality at old age is expected to drop by 0.4 %. However, this effect appears to be statistically insignificant again. Moreover, model (1) explains only 2% variation in changes in mortality in elderly and the estimated coefficient appears to be highly sensitive to including other determinants. In fact, model (2) indicates that mortality reduction is no longer associated with air pollution reduction when other explanatory variables are added to the model. On the contrary, a 0.3% increase in mortality is linked to a reduction in $PM_{2.5}$ concentration of 10 %. The difference between districts with an increase and those with a decrease in air pollution level reveals to be insignificant again. The sensitivity to outliers was identified mainly for the second model which predicts a 0.2% drop in mortality related to a 10% reduction of fine particulate air pollution in the restricted sample (for details see Tab.A4 in the appendix).

4.3. Cause-specific Mortality

Estimated coefficients related to the effect on cause-specific mortality are presented in Tab.4.3. In general, these models investigate how changes in fine particulate air pollution affect changes in the share of total deaths on selected diseases, holding changes in other explanatory variables fixed.

As expected, the relationship between changes in fine particulate air pollution and changes in the share of deaths on cardiovascular diseases reveals to be statistically different from zero at the 1% level of significance. In addition, model (1), which includes only a variable representing the change in fine particulate pollution, can explain 19% variation in the change in the share of deaths on cardiovascular diseases between the two periods under study. Even with no change in the concentration of fine particulate matter, the share of deaths on cardiovascular diseases is predicted to drop by 2.7 percentage points. If the concentration of PM2.5 is reduced by 10%, the proportion of population dying on cardiovascular diseases decreases by 0.8 percentage points.

This effect reveals to be statistically significant even at the 1% level of significance and it appears to be robust to the inclusion of various demographic and socio-economic indicators (model 2). Furthermore, no statistically significant difference in the effect between regions with improved and deteriorated air quality is proven at the 10 % level of significance (model 3). These estimated coefficients do not reveal to change if the presence of potential outliers is controlled for, as positive effect is detected in the restricted sample as well (see Tab. A5 in the appendix).

In case of respiratory diseases, the estimated positive intercept indicates that the share of deaths on these particular diseases is expected to increase by 0.9 percentage points between the periods under study when no changes in fine particulate air pollution occur. Model (1), which investigates only the effect of the percentage change in the concentration of $PM_{2.5}$, explains 14 % of variation in the change in the share of deaths on respiratory diseases. Surprisingly, the share of deaths on respiratory diseases is predicted to decrease by 0.3 percentage points if the concentration of $PM_{2.5}$ increases by 10 %. This effect is statistically significant even at 1% level of significance. Moreover, the magnitude and significance of the estimated coefficient does not seem to be sensitive to the inclusion of other demographic and socio-economic indicators (model 2).

Tab. 4.1: Estimated changes in life expectancy at birth and at the age of 65, whole sample

	Δ Logged life expectancy at birth			Δ Logged life expectancy at the age of 65		
Variable	(1)	(2)	(3)	(1)	(2)	(3)
Δ Logged $PM_{2.5}$ concentration	-0.003	-0.004	-0.001	-0.016	-0.014	0.002
	(0.005)	(0.005)	(0.010)	(0.017)	(0.016)	(0.032)
Deterioration (D=1 if Δ $PM_{2.5}$>0)	-----	-----	-0.001	-----	-----	0.000
			(0.003)			(0.010)
Deterioration#ΔLogged $PM_{2.5}$	-----	-----	0.005	-----	-----	-0.045
			(0.019)			(0.057)
Δ Males	-----	0.160	0.141	-----	1.082	0.885
		(0.326)	(0.346)		(1.019)	(1.073)
Δ Married		-0.152	-0.157		-0.472	-0.573
		(0.144)	(0.159)		(0.450)	(0.493)
Δ University graduates	-----	0.009	0.006	-----	-0.614	-0.697
		(0.125)	(0.137)		(0.392)	(0.425)
Δ Unemployed	-----	0.081**	0.079*	-----	0.201	0.204
		(0.038)	(0.041)		(0.116)	(0.127)
Δ Doctors	-----	-0.003	-0.003	-----	0.000	0.000
		(0.002)	(0.002)		(0.007)	(0.007)
Δ Natives	-----	0.052	0.046	-----	0.124	0.078
		(0.063)	(0.068)		(0.197)	(0.209)
Δ Urban	-----	-0.003	-0.002	-----	0.212*	0.227**
		(0.034)	(0.036)		(0.107)	(0.111)
Intercept	0.033***	0.029***	0.030***	0.099***	0.102***	0.101***
	(0.001)	(0.003)	(0.006)	(0.003)	(0.017)	(0.019)
Number of observations:	45	45	45	45	45	45
R^2	0.01	0.19	0.20	0.02	0.37	0.36

*** p<0.01; ** 0.01<p<0.05; * p<0.1

Source: author's calculations based on data from Český statistický úřad (2003), Český statistický úřad (2013c), Český statistický úřad (2014), Český statistický úřad (2009), Český statistický úřad (2013b), Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

Tab. 4.2: Estimated changes in the infant mortality and mortality at the old age (65+), whole sample

	Δ Logged infant mortality rate			Δ Logged mortality the age of 65		
Variable	(1)	(2)	(3)	(1)	(2)	(3)
Δ Logged $PM_{2.5}$ concentration	-0.062	0.243	-0.552	0.038	-0.033	-0.006
	(0.507)	(0.457)	(0.892)	(0.037)	(0.038)	(0.076)
Deterioration (D=1 if Δ $PM_{2.5}$>0)	-----	-----	-0.036	-----	-----	0.008
			(0.263)			(0.022)
Deterioration#ΔLogged $PM_{2.5}$	-----	-----	2.271	-----	-----	0.052
			(1.616)			(0.137)
Δ Males	-----	-41.290	-31.313	-----	-1.617	-1.423
		(28.679)	(29.597)		(2.734)	(2.508)
Δ Married		-23.492*	-18.712		0.926	0.952
		(12.665)	(13.605)		(1.048)	(1.153)
Δ University graduates	-----	-32.404*	-28.109**	-----	0.514	0.504
		(11.031)	(11.727)		(0.913)	(0.994)
Δ Unemployed	-----	2.174	2.010	-----	-0.447	-0.418
		(3.365)	(3.498)		(0.278)	(0.297)
Δ Doctors	-----	-0.445**	-0.446**	-----	0.007	0.007
		(0.191)	(0.191)		(0.016)	(0.016)
Δ Natives	-----	-8.517	-6.209	-----	-0.347	-0.291
		(5.548)	(5.781)		(0.459)	(0.490)
Δ Urban	-----	9.428***	8.668***	-----	-0.383	-0.390**
		(3.003)	(0.036)		(0.249)	(0.261)
Intercept	-0.338***	-0.841	0.030	-0.154***	-0.383***	-0.153***
	(0.087)	(0.500)	(0.006)	(0.006)	(0.249)	(0.045)
Number of observations:	45	45	45	45	45	45
R^2	0.00	0.40	0.43	0.02	0.27	0.27

*** p<0.01; ** 0.01<p<0.05; * p<0.1

Source: author's calculations based on data from Český statistický úřad (2003), Český statistický úřad (2013c), Český statistický úřad (2014), Český statistický úřad (2009), Český statistický úřad (2013b), Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

Tab. 4.3: Estimated changes in the share of deaths on selected diseases, whole sample

	Δ Share on cardiovascular diseases			Δ Share on respiratory diseases			Δ Share on lung cancer		
Variable	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
Δ Logged $PM_{2.5}$ concentration	0.077***	0.086***	0.076	-0.029**	-0.039***	-0.046**	-0.003	-0.002	-0.005
	(0.024)	(0.025)	(0.050)	(0.011)	(0.011)	(0.018)	(0.005)	(0.006)	(0.011)
Deterioration (D=1 if Δ $PM_{2.5}$>0)	-----	-----	-0.010	-----	-----	0.017***	-----	-----	-0.003
			(0.014)			(0.005)			(0.003)
Deterioration#ΔLogged $PM_{2.5}$	-----	-----	0.084	-----	-----	-0.086**	-----	-----	0.027
			(0.089)			(0.033)			(0.020)
Δ Average age	-----	-0.014*	-0.012	-----	0.007**	0.006*	-----	-0.002	-0.001
		(0.008)	(0.008)		(0.003)	(0.003)		(0.002)	(0.002)
Δ Males	-----	-2.828*	-2.367	-----	0.566	0.065	-----	0.415	0.563
		(1.555)	(1.641)		(0.682)	(0.611)		(0.355)	(0.369)
Δ Married		-0.420	-0.177		0.277	-0.051		0.018	0.096
		(0.711)	(0.756)		(0.312)	(0.282)		(0.163)	(0.170)
Δ University graduates	-----	-1.490**	-1.224*	-----	0.458*	0.125	-----	0.195	0.280*
		(0.613)	(0.670)		(0.269)	(0.249)		(0.140)	(0.150)
Δ Unemployed	-----	-0.319*	-0.350*	-----	0.139*	0.198***	-----	0.041	0.032
		(0.182)	(0.192)		(0.080)	(0.071)		(0.042)	(0.043)
Δ Doctors	-----	0.003	0.003	-----	-0.001	-0.001	-----	-0.001	-0.001
		(0.010)	(0.010)		(0.006)	(0.004)		(0.002)	(0.002)
Δ Natives	-----	-0.470	-0.390	-----	0.257*	0.179	-----	0.080	0.106
		(0.297)	(0.313)		(0.130)	(0.117)		(0.068)	(0.070)
Δ Urban	-----	0.247	0.200	-----	-0.192**	-0.135**	-----	-0.015	-0.030
		(0.165)	(0.173)		(0.072)	(0.064)		(0.038)	(0.039)
Intercept	-0.027***	0.022	0.022	0.009***	-0.004	-0.009	-0.000	0.003	0.003
	(0.004)	(0.043)	(0.045)	(0.002)	(0.019)	(0.017)	(0.001)	(0.010)	(0.010)
Number of observations:	45	45	45	45	45	45	45	45	45
R^2	0.19	0.40	0.42	0.14	0.44	0.61	0.01	0.18	0.23

*** p<0.01; ** 0.01<p<0.05; * p<0.1

Source: author's calculations based on data from Český statistický úřad (2003), Český statistický úřad (2013c), Český statistický úřad (2014), Český statistický úřad (2009), Český statistický úřad (2013b), Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

In addition, model (3) shows that while the share of deaths on respiratory diseases is expected to decrease by 0.9 percentage points in districts with improved air quality, it is predicted to increase by 0.8 percentage points in districts with deteriorating air conditions. The interaction term is also significant and implies that the returns of 10% decrease in fine particulate air pollution are associated with an increase in the share of deaths of 1.3 percentage points in districts with worse air quality. On the other hand, the same percentage in districts with improving air quality is related to an increase in the share of deaths on respiratory diseases of 0.5 percentage points. Furthermore, these different effects between districts with improving and deteriorating air quality remain jointly significant[9] even if the model is reestimated without potential outliers (see Tab.A5 in the appendix).

Finally, the estimated results show that the share of deaths on lung cancer is predicted to increase by 0.03 percentage points if the fine particulate air pollution is reduced by 10 %. However, this effect is not statistically different from zero at the 10 % level of significance, and thus, the model fails to prove that there is a relationship between reduction in the concentration of PM2.5 and the change in the share of deaths on lung cancer. Moreover, this particular impact seems to be highly influenced by the presence of potential outliers. If they are dropped from the sample, the effect reveals to be both statistically significant and higher. In the restricted sample, the reduction in fine particulate air pollution of 10 % is associated with an increase in the share of deaths on lung cancer by 0.1 percentage points (see Tab.A5 in the appendix). On the other hand, based on the estimates from the whole as well as restricted sample, no statistically significant differences in the relationship between the reduction in fine particulate air pollution and changes in the share of death on lung cancer are identified between districts with deteriorating and improving air quality.

4.4. Discussion

Although no statistically significant relationship between changes in life expectancy (both at birth and at 65) and changes in fine particulate air pollution is proven, it is still not possible to conclude that such a relationship does not exist in reality. Despite the fact that the results are insignificant, estimates are negative, which is in accordance with the expected direction of the effect. On the other hand, even if the estimated coefficients were statistically significant, the

[9] $F(2,33) = 7.16$ Prob > F = 0.0026

size of the effect would be rather small. This finding corresponds with the claim of Künzli et al. (2000) that the risk of death related to air pollution is considerably lower when compared to other risk factors. In other words, reduction in the concentration of $PM_{2.5}$, which is only one of the pollutants present in the air, cannot alone bring dramatic gains in life expectancy. Comparing the discovered size of the effect with the results presented in other studies (Pope, Ezzati & Dockery, 2009; Dockery et al., 1993), it is possible to conclude that the effect estimated in 45 districts of the Czech Republic is substantially smaller. If they were significant, the results obtained in this study would rather support authors who found out that the effect of air pollution reduction on the extension of human lives is smaller in the countries of Central and Eastern Europe compared to the countries of Western Europe and the USA (Katsouyani et al., 1997).

Moreover, Bobak and Leon (1992) argue that air pollution data obtained from individual measuring stations in each district might not provide sufficient information about the level of air pollution in the whole district as the presence of air pollutants is measured only in the surroundings of the station. This means that these data might not reflect adequately the real changes in air pollution which the population in each district was exposed to. As a result, the effect between reduction in fine particulate air pollution and the extension of human life can be weaker. An important role may also be played by the fact that mortality has been concentrated in the oldest age groups in the Czech Republic (Ústav zdravotnických informací, 2013) which generally offer smaller room for further improvements in life expectancy than the youngest ones (Wilmoth, 2000).

On the other hand, it is also possible that the insignificancy and small size of the estimated coefficients can be attributed to the deficiencies of the regression model itself. Because the limitations of the model apply to all results received in the empirical part of this thesis, they will be closely discussed at the end of this section.

Because life expectancy is an aggregated indicator and as such it cannot accurately differentiate changes in mortality in individual age groups (Pavlík, Rychtaříková & Šubrtová, 1986), the effect of air pollution on infant mortality and on mortality in elderly (65+ years) was examined separately as well. Nevertheless, neither of these effects revealed to be statistically significant. This means that it was not proven that a change in air pollution is associated with a change in mortality in these age groups. On the other hand, these findings do not imply that this effect can be dismissed.

In case of infant and old mortality, the models used for empirical testing appear to be considerably sensitive to the inclusion of other explanatory variables or removal of possible outliers. In fact, the results obtained suggest that the effect of reduction in fine particulate air pollution on infant mortality may be biased in model (1). It is important to keep in mind that, in contrast to the second model, the first one does not control for changes in other explanatory variables. A change in the unemployment rate can be chosen as an example demonstrating how bias can be introduced to the first model. This particular variable is negatively correlated with the change in $PM_{2.5}$ concentration (see Tab.A2 in the appendix) and, according to the estimated coefficient, it affects the level of mortality positively (see Tab.4.2). If the concentration of fine particulate matter in atmosphere decreases, the infant mortality rate should drop. However, at the same time, the unemployment rate increases as well as a result of the reduction in fine particulate air pollution. For example, a reduced industrial production might provide a plausible explanation for an increasing number of unemployed people. However, poorer economic condition will consequently increase the number of children dying before turning the age of one year. In other words, a reduction in air pollution may be, paradoxically, indirectly associated with an increase in infant mortality through unemployment. In fact, all other variables except marital status and education level seems to be operating in the similar way as indicated for the unemployment rate.

Although the coefficients estimated for the share of deaths related to individual causes are statistically significant, their interpretation is not as straightforward as for previous mortality indicators because the causes of death are mutually exclusive. In other words, a reduction in the share of deaths on one specific cause may take place not only as a result of a reduction in mortality on that cause, but also as a consequence of a higher number of deaths on another cause (Nevalainen & Pekkanen, 1998).

In the case of cardiovascular diseases, the relationship between the reduction in the concentration of $PM_{2.5}$ and the drop in mortality on this particular cause is found to be statistically significant and implies that the share of deaths on cardiovascular diseases decreases when fine particulate matter decreases. In addition, the estimated effect cannot be perceived as minor (decrease by 0.8 percentage points) if the overall decrease in the share of deaths on cardiovascular diseases (equal 3.1 percentage points) between the periods under study is taken into account (Tab 3.3). This corresponds with the findings of other authors who proved that a increased mortality on cardiovascular diseases is associated with deteriorating air quality (Gouveia & Fletcher, 2000; Dockery et al., 1993; Pope et al., 1995).

Surprisingly, in the case of respiratory diseases and lung cancer, the situation is reversed as air pollution reduction is related to an increase in the share of deaths on these two causes. However, the effect is significant for lung cancer only when potential outliers are removed from the sample. These results may seem to be illogical at first because higher mortality on both these diseases is traditionally linked to increased air pollution (WHO, 2011). However, it is important to understand that the dependent variable represents the change in the share of deaths on this cause. Thus, there are several explanation for increasing trend in these indicators despite the fact that air quality improves.

Firstly, a decrease in the share of cardiovascular diseases was proved, which means the share of other causes, which may include respiratory diseases and lung cancer, has to increase. In addition, it is also possible that improving air quality in Czech districts is associated also with a reduction in the share of deaths on other causes than only the cardiovascular ones. Due to competing risk, the share of respiratory diseases and lung cancer may increase in this case as well. Secondly, the fact that the share of respiratory diseases increased does not necessarily mean that the absolute number of people dying of them increased as well. Since the number of deaths caused by respiratory diseases and by lung cancer is considerably smaller compared to cardiovascular diseases (Ústav zdravotnických informací, 2013), an absolute decrease of deaths related to these causes might have only a very limited influence on the overall number of deaths. As a result, the relative share of these two causes may increase even if the absolute number of people dying of them dropped. Thirdly, it is possible that improvements of air quality may lead to a reduction in morbidity in a short-term period and would impact mortality in a longer time frame (Pope, 2000).

An interesting finding is that the effect of changes in $PM_{2.5}$ concentration on the share of respiratory diseases is different in regions with improving and the ones with deteriorating air quality, holding changes in other variables fixed. This effect revealed to be statistically significant also in a restricted sample which controlled for the presence of potential outliers. The estimated coefficients suggest that the share of deaths on this cause is expected to drop in districts with improving air quality, while it rises in districts where the concentration of $PM_{2.5}$ increases. Moreover, returns to reduction in fine particulate air pollution are twice higher in districts with worsening air quality. In other words, reduction in $PM_{2.5}$ leads to a twice higher increase in the number of deaths on respiratory diseases in these regions. This finding might reflect that the distribution of deaths by causes differ in the districts with improving and deteriorating air quality even before the changes in fine particulate air pollution take place.

4.4.1. Limitation of the Empirical Analysis

Based on the results of the regression analysis, it is not possible to conclude that changes in air pollution have a statistically significant impact on changes in life expectancy or on changes in infant mortality or mortality in elderly (65+). However, even if the effect was significant, its size would be considerably small. This can be caused by the fact that the regression model used in the analysis is likely to suffer from several methodological problems.

Firstly, first-difference models are in general very sensitive to possible measurement errors. In this case, the downward bias is considerably larger than in individual cross-sectional models (Angrist & Pischke, 2009, p.167). From this perspective, calculating concentration of fine particulate matter indirectly from PM_{10} might be problematic. Moreover, taking averages of the concentration measured by individual stations within one district could also distort the results. In both cases, the resulting changes in $PM_{2.5}$ concentration might not reflect sufficiently the real development of fine particulate air pollution in the whole district. Similarly, life expectancy underestimates the real extension of human life because it is just a theoretical indicator which does not account for general improvements of age-specific mortality rates during the lifetime of an individual (Wilmoth, 2000). Furthermore, it is possible that the real improvement of mortality rates proceeds unequally across districts, which would result into different levels of underestimation in individual districts. These measurement errors may biased the results downwards.

Another problem is that first-difference models rely generally on within variation between observations (Wooldridge, 2009, p.458). Although there are significant geographical differences in individual cross-sections, the rate of variability is considerably lower when differences are observed (Tab 3.3 in third chapter and Tab.A1 in the appendix). In this case, it is far more difficult to detect a significant effect of the variable under study. Theoretically, this issue can be solved by choosing more distant points in time for the analysis. However, this approach would be highly complicated to implement for Czech districts because of the insufficient measurement of particulate matter before 1994. Moreover, year 2001 is the first year when the data on particulate air pollution can be linked to the development of other determinants based on the data from population census. The second possibility is to observe the changes in the concentration of $PM_{2.5}$ in smaller territorial units (e.g. on the level of cities). However, this analysis requires more detailed data on both changes in mortality indicator and changes in fine particulate air pollution.

In fact, the last suggestion presented in the previous paragraph would be a suitable way to extent the analysis performed in this paper, also because it would increase the number of observations in the dataset. Small sample size can be another reason why most of the results reveal to be insignificant. Typically, smaller samples imply bigger standard errors, and so the significant relationship tend to be successfully detected only if the effect is relatively large (Wooldridge, 2009, p.136). Due to the small sample size, it is also difficult to include a higher number of explanatory variables. However, removing some of the additional explanatory variables from the model might introduce omitted bias as the variable excluded would become a part of the error term (Angrist & Pischke, 2009). As it is expected based on the theoretical that all selected determinants play an important role in explaining changes in mortality indicators and might affect the relationship between changes in fine particulate pollution and changes in mortlity level, all these variables are left in the model despite their insignificancy.

Another important limitation which is necessary to considered is that the omitted bias may be present even in the first-difference model because, in practice, it is infeasible to control for all possible determinants explaining changes in mortality that can be correlated with changes in air pollution. For instance, due to unavailability of detailed data on district level in the Czech Republic, the changes in the prevalence of smoking cannot be controlled for in the regression model. However, this factor has clearly negative implications for health and it also can amplify the negative consequences of fine particulate air pollution. In the analysis, changing patterns in smoking were controlled through other explanatory variables such as education, unemployment or marital status. However, the extent to which this approach succeeded remains questionable.

Chapter 5

Conclusion

Previous epidemiological studies, including those conducted in the Czech Republic, show that outdoor air pollution is associated with an increased risk of premature death (Lubas, 2014; Pope, 2000; Dockery et al., 1993). For this reason, attempts to decrease the concentration of air pollutants have taken place on international, national as well as regional level in the last decades. However, the question is if a drop in air pollution can really lead to significant improvements of the mortality rates in a certain area. Thus, selected aspects of the relationship between the changes in fine particulate air pollution and changes in mortality were chosen as the main topic of this thesis.

Although the air is contaminated with various pollutants, the focus of this study was narrowly restricted to the changes in the concentration of fine particulate matter ($PM_{2.5}$). The choice of this indicator was made with respect to the fact that it is most commonly associated with a higher prevalence of adverse health outcomes which may occur already at low concentrations (WHO, 2011). Moreover, in the Czech Republic, fine particulate pollution is perceived as one of the main problems related to air quality (Český hydrometeorologický ústav, 2003a).

Overall, 45 Czech districts were included into the analysis, for which it was possible to match the data on the concentration of fine particulate matter with mortality data in selected periods. More specifically, average values measured in 2000-2002 and 2010-2012 were compared.

Three-year intervals were preferred over one-year interval because they offer a higher protection against possible abnormal yearly variations in air pollution or mortality.

Individual hypotheses were tested using first-difference models and seven different mortality indicators were used as dependent variables. Thanks to this approach, not only the changes in life expectancy, but also in age-specific and cause-specific mortality indicators were observed. Firstly, the model was always estimated using only the variable representing the change in $PM_{2.5}$ concentration. Then, other explanatory variables which could have influenced the development of mortality in individual districts or which could have distort the relationship between air pollution reduction and mortality changes were added to the model. A set of control variables captured the changes in quality and availability of medical care (the number of doctors per 1,000 inhabitants) as well as changes in other selected demographic (age, sex, marital status, migration), socio-economic (education, unemployment) and environmental indicators (urbanization).

Regarding the effect of air pollution reduction on life expectancy, the model predicted gains in life expectancy when air quality improved, however the effect was relatively small and also statistically insignificant at the 10% level of significance. These results revealed to be robust to the inclusion of other explanatory variables as well as to potential outliers. Similarly, no significant implications were found for the changes in infant mortality or mortality in elderly (65+). The insignificancy of the results might be explained by the fact that the risk of premature death is relatively small compared to other risk factors and that the sample used for the analysis was also not extensive (n=45). Nevertheless, it is important to point out that the findings of this thesis do not imply that fine particulate air pollution reduction does not lead to improvements in life expectancy, infant mortality or mortality in elderly (65+). These relationships were just not proven for the specific sample used in the analysis. On the other hand, it was confirmed that the differences in the impact of changes in fine particulate air pollution on changes in these indicators in districts where air quality improved and those where it deteriorated are not statistically significant.

Contrary to life expectancy and age-specific mortality, the results for cause specific-mortality were revealed to be statistically significant at the 10% level of significance. More specifically, it was discovered that a reduction in $PM_{2.5}$ concentration of 10% is associated with a reduction in the share of deaths on cardiovascular diseases of 0.9 percentage points, while the same change is predicted to increase the share of deaths on respiratory diseases by 0.4 percentage points, holding changes in all other variables fixed. In case of lung cancer, an increase of 0.1 percentage points is estimated, but only when possible outliers are controlled for.

An increase in the share of deaths on cardiovascular diseases is a logical consequence of fine particulate air pollution reduction. On the other hand, the rise in the share of respiratory diseases and lung cancer might seem to be surprising at first. However, it is important to keep in mind that all these causes of death are mutually exclusive. Moreover, the absolute number of people dying of respiratory diseases and lung cancer is very small compared to cardiovascular diseases. Therefore, a relative increase in the share of one of these two causes does not necessarily mean that the absolute number of people dying of them increased as well.

Although no significant differences between districts with improving and worsening air quality were identified for lung cancer and cardiovascular diseases, the difference was significant for respiratory diseases on the 10% level of significance both for the size of the effect and returns to reduction in fine particulate air pollution. More specifically, it is was found out that the share of deaths on respiratory diseases decreased in regions with improving air quality and increased in regions with deteriorating air quality. This corresponds with an expected lower mortality on this cause in districts with improving air quality where individuals are more likely to die because of other factors than air pollution. It was also discovered that reduction in $PM_{2.5}$ leads to a twice higher increase in the share of deaths on respiratory diseases in regions with worsening air conditions. This may reflect the fact that with reduction in fine particulate matter mortality on other causes decreases in districts with worsening levels of air pollution more or that only morbidity is decreased, which cannot be observed through this mortality indicator.

Although a first-difference model reduces the omitted bias compared to a cross-sectional model, this bias cannot be removed completely (Wooldridge, 2009). From this point of view, the unavailability of data on several factors, such as the development of smoking in individual districts, can be perceived as problematic. On the other hand, the changing patterns in smoking should be, to a certain extent, captured by changes in other variables which were included, such as education, age or marital status.

The results of the empirical analysis might be also distorted because of several limitations of the regression model used in the empirical analysis. In general, first-difference models are greatly sensitive to measurement errors and variability within individual observations (Angrist & Pischke, 2009). It is also important to emphasize that the change in mortality is a result of parallel influences of many risk a protective factors and their mutual interactions. For this reason, the estimates of this study cannot be interpreted as causal.

To sum it up, the effect of air pollution on cause-specific mortality was confirmed. However, the coefficient of the effect on life expectancy as well as age-specific mortality revealed to be statistically insignificant. This could have been, to a certain extent, caused by methodological drawbacks of the model applied. The empirical analysis presented in this study could be further improved in the future by analyzing the effects of air pollution on the level of smaller territorial units, such as cities, which would increase the sample size as well as variability of data. This might help detect a statistically significant effect of $PM_{2.5}$ reduction on life expectancy or age-specific mortality in the Czech Republic.

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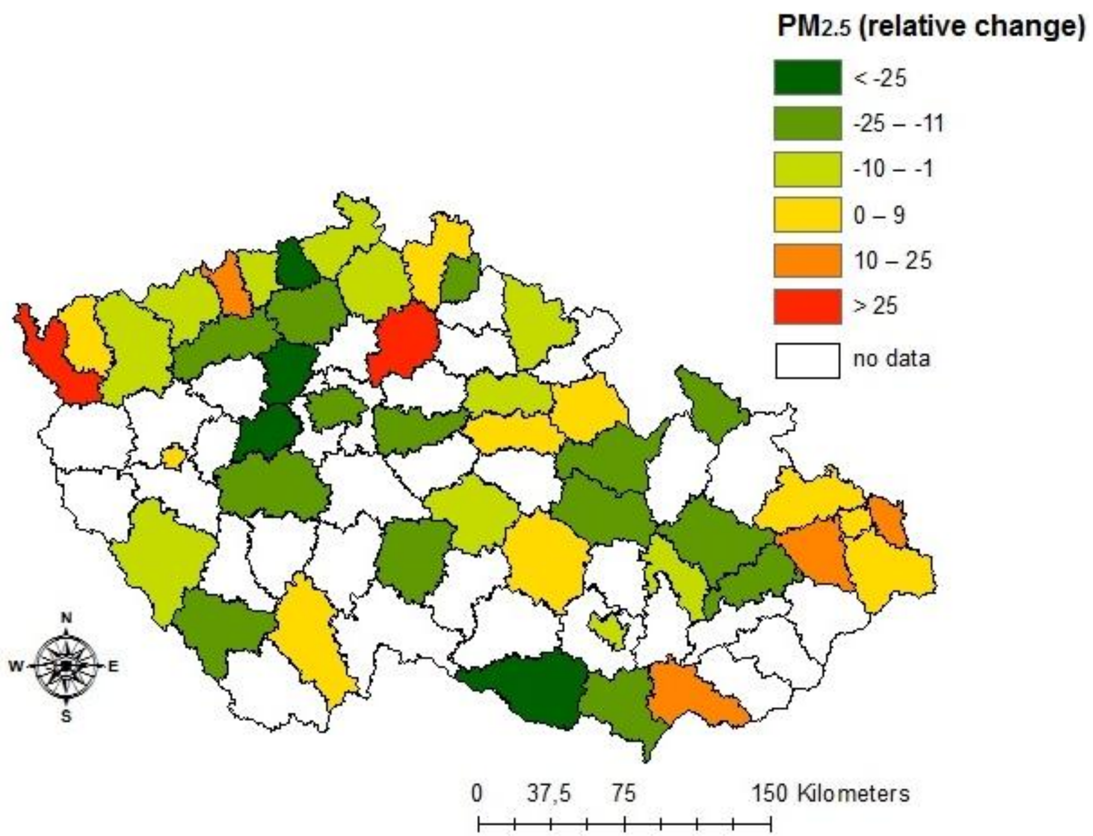
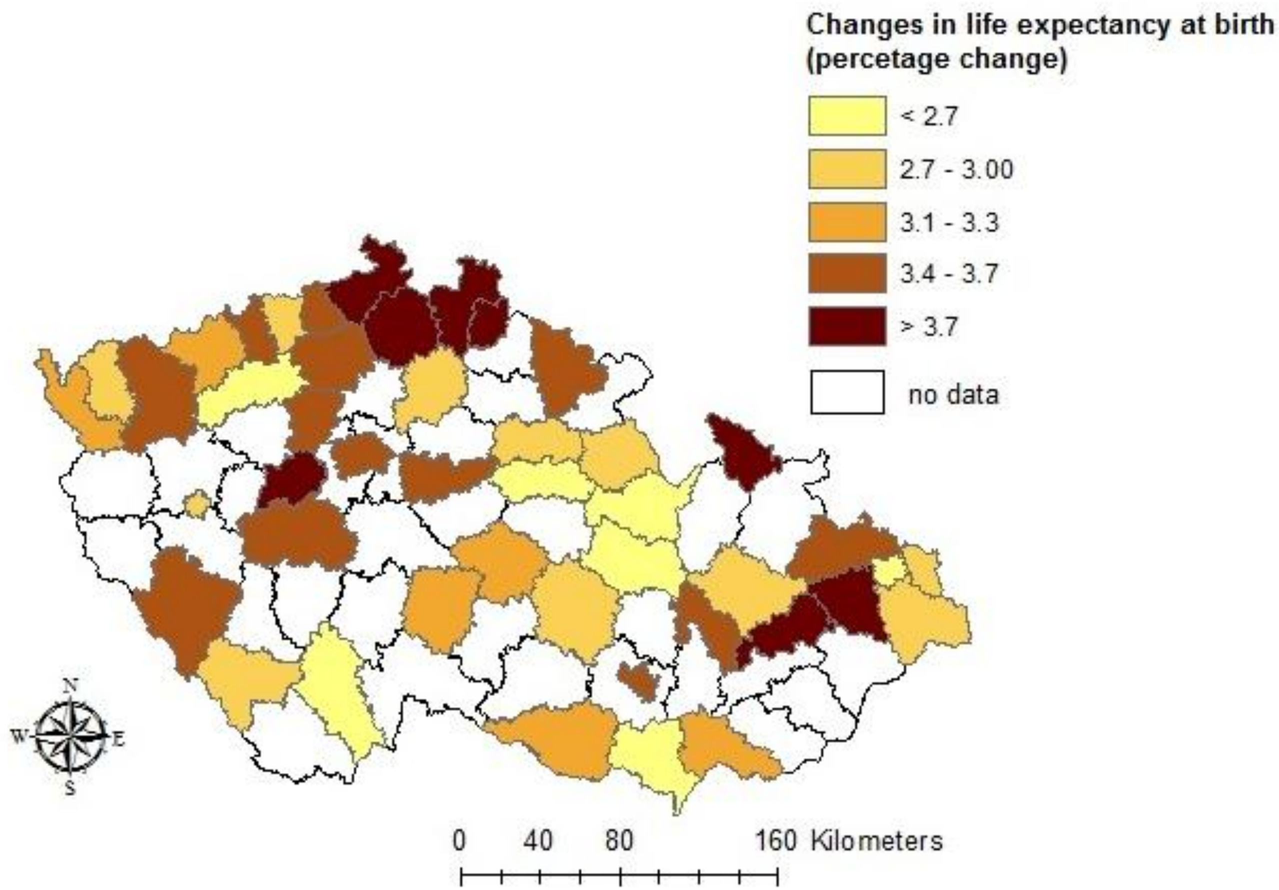
Appendix

Fig. A1: Relative change in the concentration of fine particulate matter ($PM_{2.5}$), Czech Republic, 45 districts, 2000-2002 vs 2010-2012



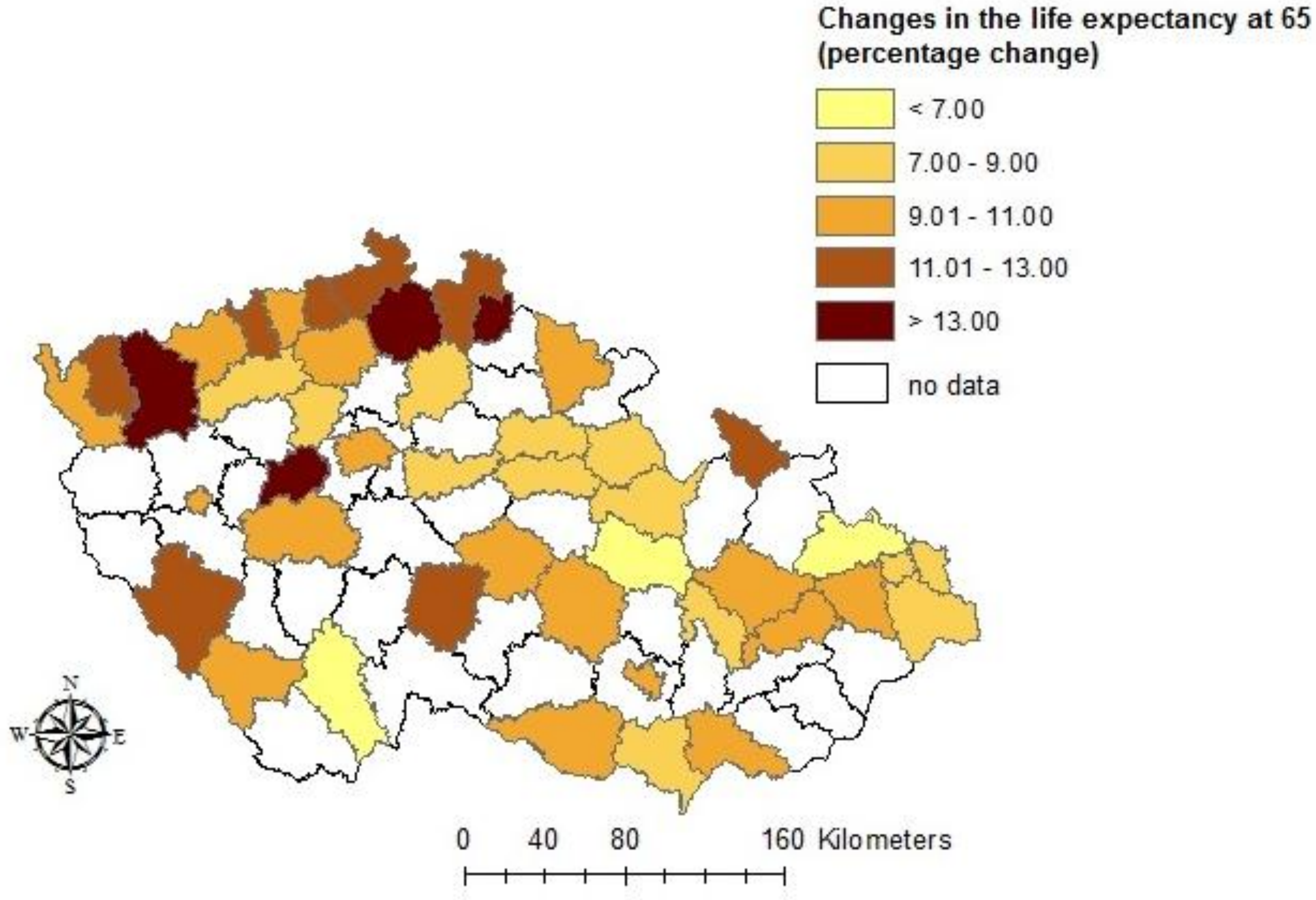
Source: author's calculations based on data from Fiala et al. (2001), Fiala et al. (2002), Fiala et al. (2003) for the time period 2000-2002 and from Český hydrometeorologický ústav [Czech Hydrometeorological Institute] (2011); Český hydrometeorologický ústav [Czech Hydrometeorological Institute] (2012); Český hydrometeorologický ústav [Czech hydrometeorological Institute] (2013) for the time period 2010-2012

Fig. A2: Relative change in the life expectancy at birth, Czech Republic, 45 districts, 2000-2002 vs 2010-2012



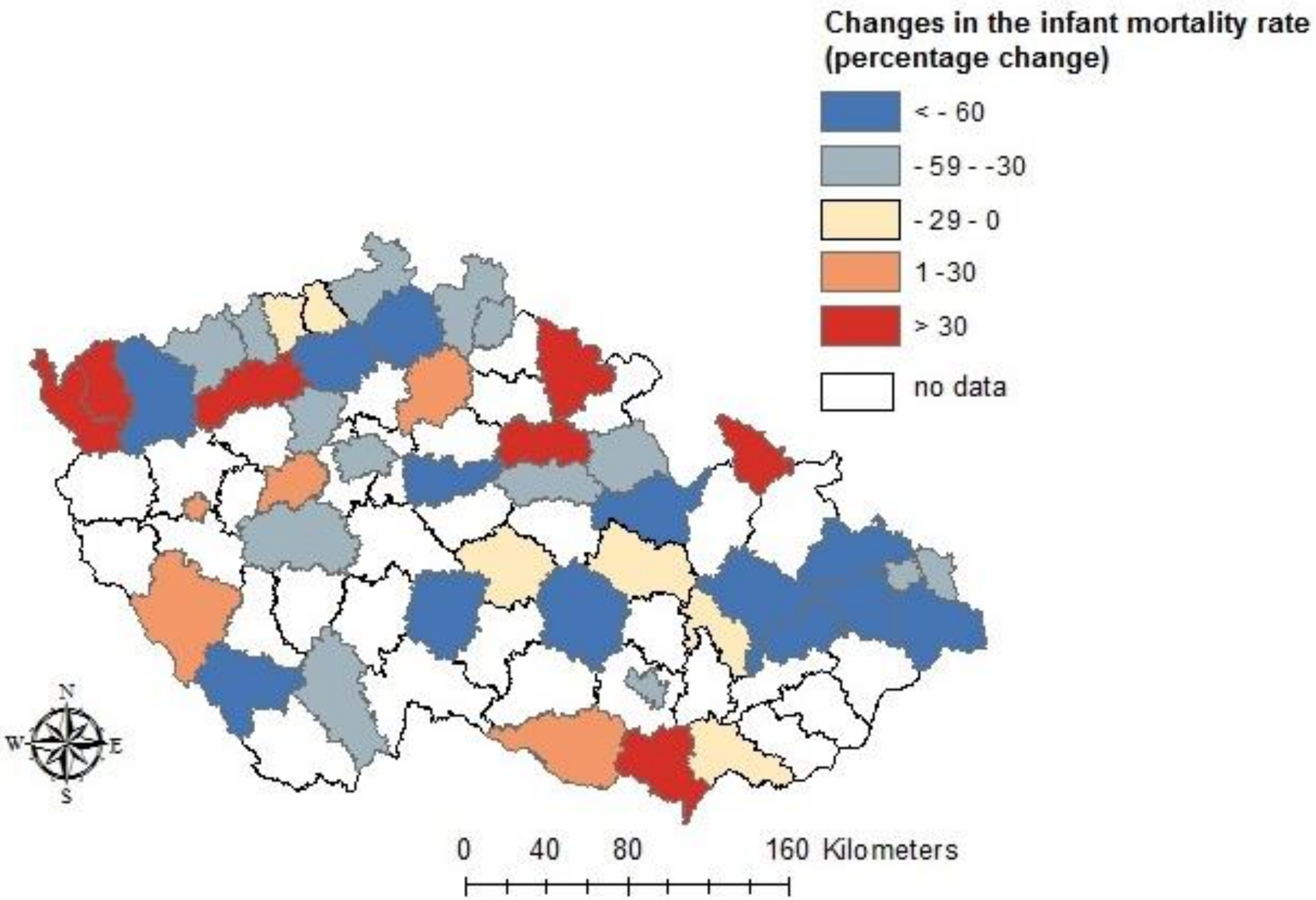
Source: author's calculations based on data from Český statistický úřad [Czech Statistical Office] (2009) for the time period 2000-2002 and from Český statistický úřad [Czech Statistical Office] (2013b) for the time period 2010-2012

Fig. A3: Relative change in the life expectancy at the age of 65, Czech Republic, 45 districts, 2000-2002 vs 2010-2012



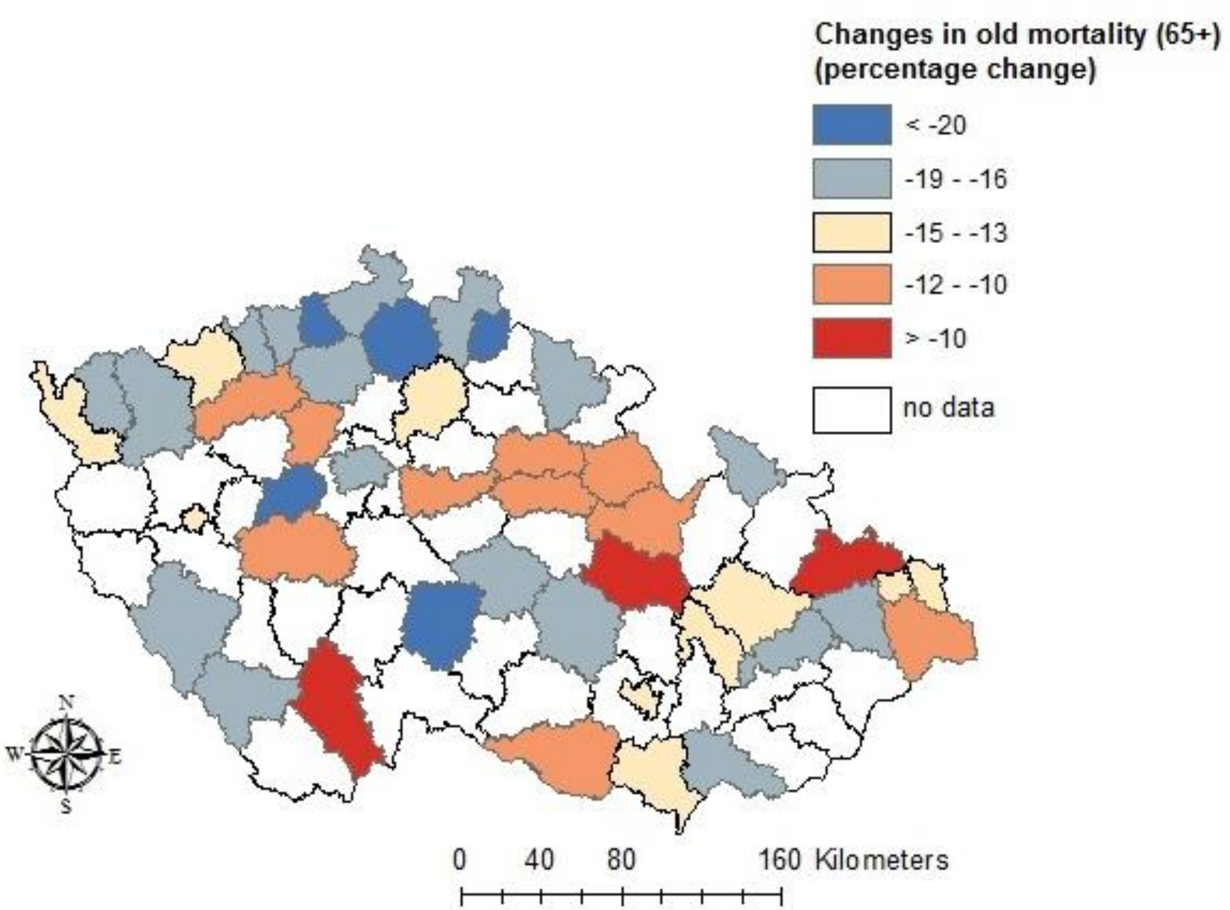
Source: author's calculations based on data from Český statistický úřad [Czech Statistical Office] (2009) for the time period 2000-2002 and from Český statistický úřad [Czech Statistical Office] (2013b) for the time period 2010-2012

Fig. A4: Relative change in the infant mortality rate, Czech Republic, 45 districts, 2000-2002 vs 2010-2012



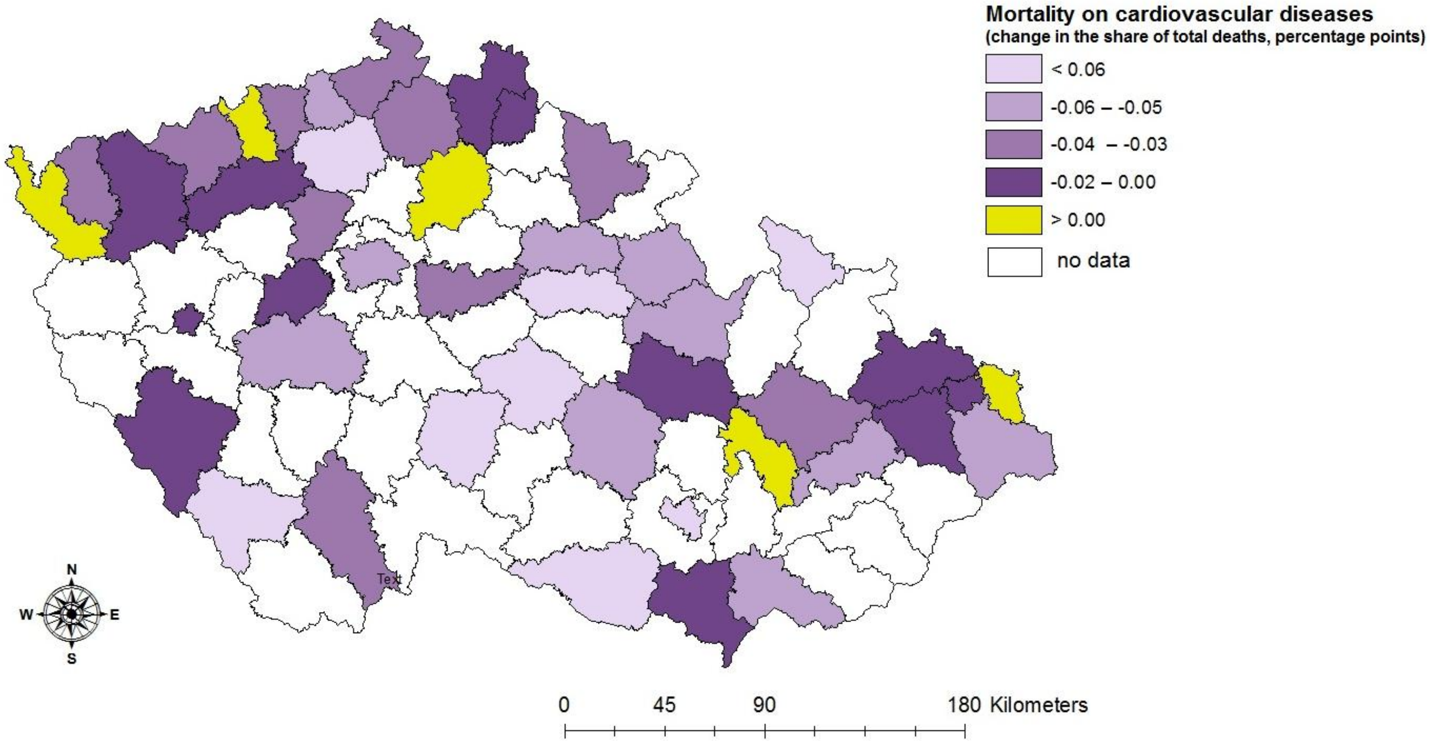
Source: author's calculations based on data from Český statistický úřad [Czech Statistical Office] (2009) for the time period 2000-2002 and from Český statistický úřad [Czech Statistical Office] (2013b) for the time period 2010-2012

Fig. A5: Relative change in the old mortality rates (65+), Czech Republic, 45 districts, 2000-2002 vs 2010-2012



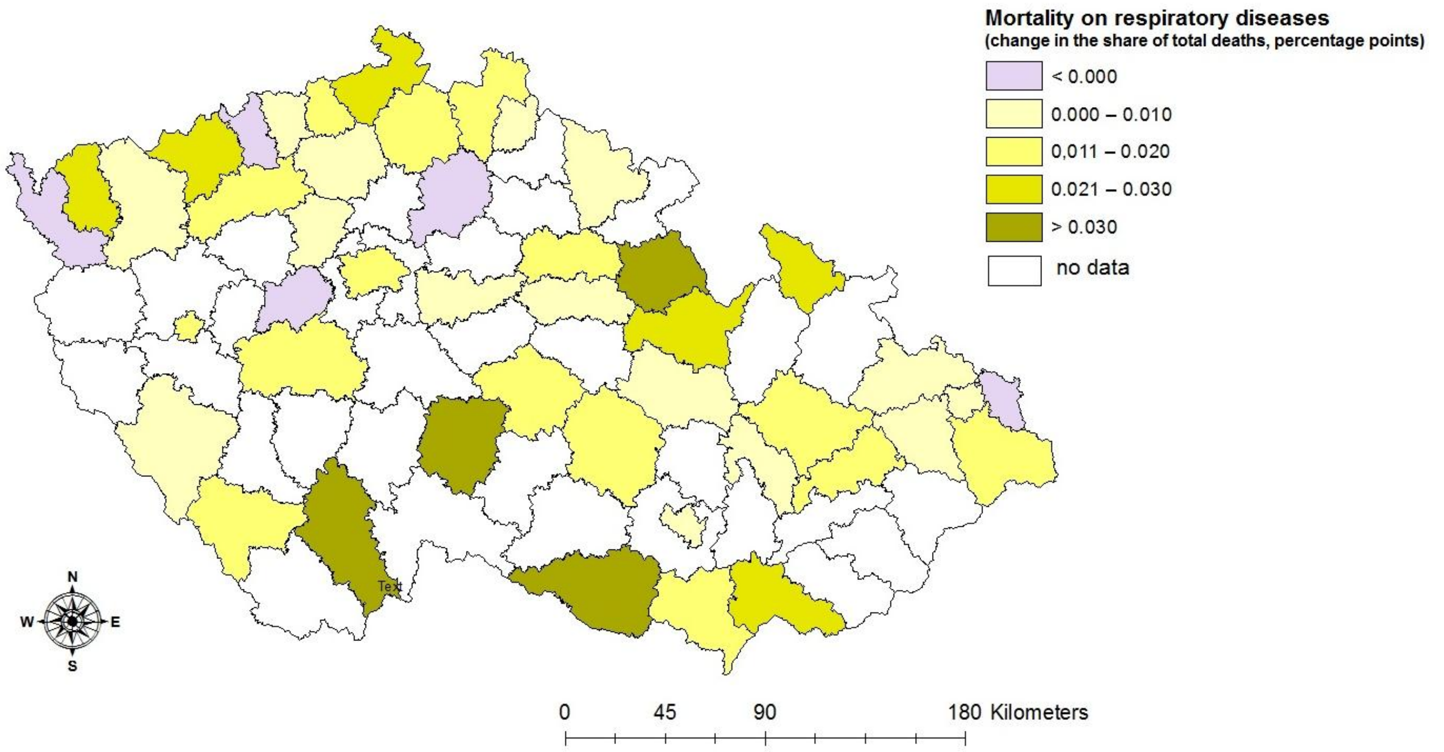
Source: author's calculations based on data from Český statistický úřad [Czech Statistical Office] (2009) for the time period 2000-2002 and from Český statistický úřad [Czech Statistical Office] (2013b) for the time period 2010-2012

Fig. A6: Change in the share of deaths on cardiovascular diseases, Czech Republic, 45 districts, 2000-2002 vs 2010-2012



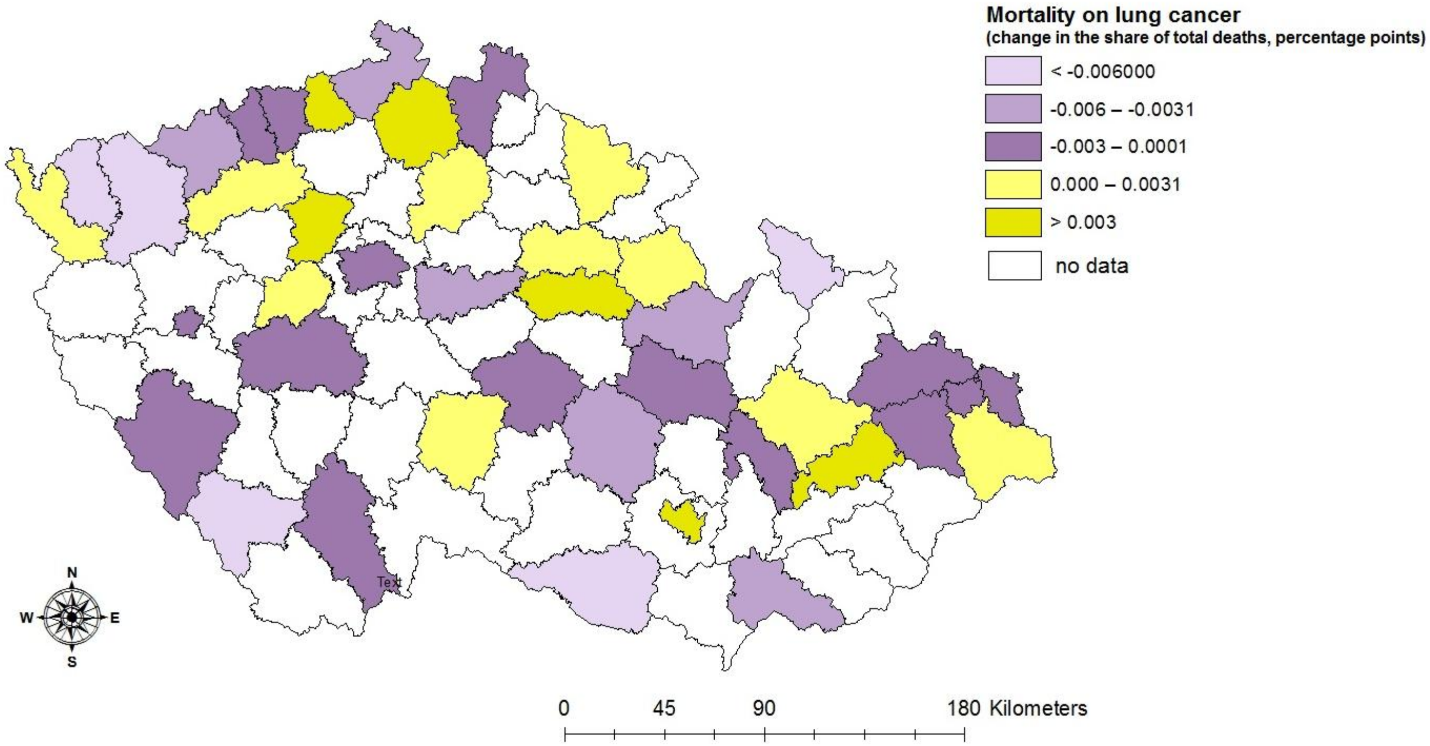
Source: author's calculations based on data from Český statistický úřad [Czech Statistical Office] (2009) for the time period 2000-2002 and from Český statistický úřad [Czech Statistical Office] (2013b) for the time period 2010-2012

Fig. A7: Change in the share of deaths on respiratory diseases, Czech Republic, 45 districts, 2000-2002 vs 2010-2012



Source: author's calculations based on data from Český statistický úřad [Czech Statistical Office] (2009) for the time period 2000-2002 and from Český statistický úřad [Czech Statistical Office] (2013b) for the time period 2010-2012

Fig. A8: Change in the share of deaths on lung cancer, Czech Republic, 45 districts, 2000-2002 vs 2010-2012



Source: author's calculations based on data from Český statistický úřad [Czech Statistical Office] (2009) for the time period 2000-2002 and from Český statistický úřad [Czech Statistical Office] (2013b) for the time period 2010-2012

Tab.A1: Descriptive statistics of indicators related to age-specific mortality, log transformation

Variable	Mean	Std. dev.	Min	Max	Obs
Life expectancy at birth, logged					
Change	0.033	0.005	0.022	0.048	45
Life expectancy at the age of 65, logged					
Change	0.101	0.019	0.069	0.145	45
Infant mortality rate, logged					
Change	-0.335	0.536	-1.249	0.802	45
Child mortality (1-14), logged					
Change	-0.459	0.466	-1.501	0.590	45
Mortality at working-age (15-64), logged					
Change	-0.083	0.063	-0.232	0.007	45
Mortality at old-age (65+), logged					
Change	-0.157	0.040	-0.261	-0.068	45
Mortality at oldest-age (85+), logged					
Change	-0.155	0.060	-0.273	-0.037	45

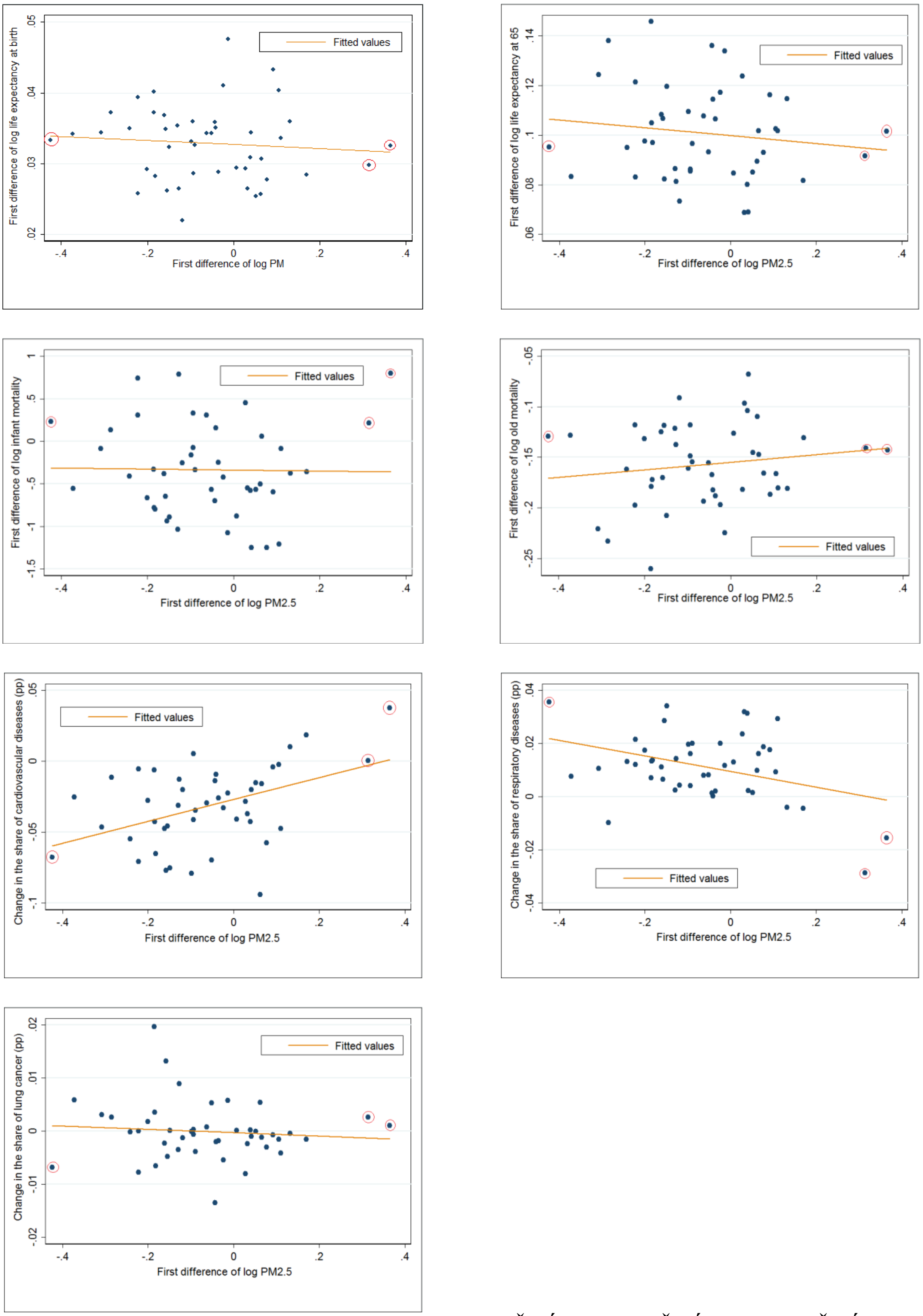
Source: author's calculations based on data from ČSÚ (2009) and ČSÚ (2013b)

Tab.A2: Correlation matrix of explanatory variables

	Δ Mean age	Δ Males	Δ Married	Δ Graduates	Δ Unemployed	ΔDoctors	Δ Natives	Δ Urban	Δ Logged PM
Δ Mean age	1.000								
Δ Males	-0.445	1.000							
Δ Married	0.478	-0.500	1.000						
Δ Graduates	-0.477	0.253	-0.355	1.000					
Δ Unemployed	-0.003	0.075	0.295	-0.201	1.000				
Δ Doctors	-0.324	0.376	-0.435	0.509	-0.118	1.000			
Δ Natives	0.490	-0.589	0.359	-0.617	-0.160	-0.415	1.000		
Δ Urban	0.286	-0.189	0.295	-0.229	0.233	-0.405	0.176	1.000	
Δ Logged PM	0.167	0.004	-0.060	-0.145	-0.081	-0.110	0.116	-0.218	1.000

Source: author's calculations based on data from ČSÚ (2014), ČSÚ (2013c) and ČSÚ (2003)

Fig.A9: Plotted changes in selected mortality indicators over changes in PM2.5 concentration



Source: author's calculations based on data from ČSÚ (2003), ČSÚ (2013c), ČSÚ (2014), ČSÚ (2009), ČSÚ (2013b), Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

Tab. A3: Estimated changes in life expectancy at birth and at the age of 65, controlling for potential outliers

	Δ Logged life expectancy at birth			Δ Logged life expectancy at the age of 65		
Variable	(1)	(2)	(3)	(1)	(2)	(3)
Δ Logged $PM_{2.5}$ concentration	-0.003	-0.000	0.001	-0.024	-0.004	-0.009
	(0.007)	(0.007)	(0.013)	(0.023)	(0.023)	(0.040)
Deterioration (D=1 if Δ $PM_{2.5}$>0)	-----	-----	-0.004	-----	-----	-0.005
			(0.004)			(0.012)
Deterioration#ΔLogged $PM_{2.5}$	-----	-----	0.040	-----	-----	0.081
			(0.040)			(0.123)
Δ Males	-----	0.092	0.201	-----	0.736	0.947
		(0.385)	(0.402)		(1.183)	(1.253)
Δ Married		-0.185	-0.104		-0.613	-0.469
		(0.167)	(0.183)		(0.509)	(0.569)
Δ University graduates	-----	-0.032	-0.017	-----	-0.823*	-0.810*
		(0.140)	(0.144)		(0.431)	(0.449)
Δ Unemployed	-----	0.086**	0.081*	-----	0.219*	0.216
		(0.040)	(0.042)		(0.124)	(0.131)
Δ Doctors	-----	-0.003	-0.002	-----	0.001	0.001
		(0.002)	(0.002)		(0.007)	(0.007)
Δ Natives	-----	0.028	0.021	-----	0.032	0.020
		(0.071)	(0.072)		(0.217)	(0.223)
Δ Urban	-----	0.003	-0.005	-----	0.230**	0.226*
		(0.036)	(0.037)		(0.113)	(0.117)
Intercept	0.033***	0.028***	0.032***	0.099***	0.101***	0.104***
	(0.001)	(0.006)	(0.007)	(0.003)	(0.019)	(0.021)
Number of observations:	42	42	42	42	42	42
R^2	0.00	0.20	0.24	0.03	0.37	0.41

Note: Δ Logged $PM_{2.5}$ concentration <0.2 & Δ Logged $PM_{2.5}$ concentration >-0.4 *** p<0.01; ** 0.01<p<0.05; * p<0.1

Source: author's calculations based on data from Český statistický úřad (2003), Český statistický úřad (2013c), Český statistický úřad (2014), Český statistický úřad (2009), Český statistický úřad (2013b), Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

Tab. A4: Estimated changes in the infant mortality and mortality at the old age (65+), controlling for potential outliers

	Δ Logged infant mortality rate			Δ Logged mortality the age of 65		
Variable	(1)	(2)	(3)	(1)	(2)	(3)
Δ Logged $PM_{2.5}$ concentration	-0.846	- 0.012	-0.020	0.059	0.023	0.038
	(0.607)	(0.623)	(1.084)	(0.049)	(0.053)	(0.090)
Deterioration (D=1 if Δ $PM_{2.5}$>0)	-----	-----	0.100	-----	-----	0.023
			(0.337)			(0.028)
Deterioration#ΔLogged $PM_{2.5}$	-----	-----	-1.125	-----	-----	-0.330
			(3.384)			(0.281)
Δ Males	-----	-42.523	-45.548	-----	-0.489	-1.352
		(32.308)	(34.348)		(2.736)	(2.853)
Δ Married		-24.014*	-26.255		1.341	0.740
		(13.895)	(15.607)		(1.171)	(1.295)
Δ University graduates	-----	-26.373**	-26.770**	-----	1.014	0.943
		(11.776)	(12.314)		(0.997)	(1.022)
Δ Unemployed	-----	1.997	2.129	-----	-0.486*	-0.465
		(3.391)	(3.600)		(0.287)	(0.299)
Δ Doctors	-----	-0.437**	-0.432**	-----	0.006	0.005
		(0.188)	(0.194)		(0.016)	(0.016)
Δ Natives	-----	-5.700	-5.483	-----	-0.170	-0.118
		(5.918)	(6.133)		(0.501)	(0.509)
Δ Urban	-----	9.335***	9.539***	-----	-0.419	-0.363
		(3.073)	(3.216)		(0.260)	(0.261)
Intercept	-0.449***	-0.946	-1.112*	-0.154***	-0.143***	-0.159***
	(0.089)	(0.522)	(0.577)	(0.007)	(0.044)	(0.048)
Number of observations:	42	42	42	42	42	42
R^2	0.05	0.36	0.43	0.03	0.30	0.33

Note: Δ Logged $PM_{2.5}$ concentration <0.2 & Δ Logged $PM_{2.5}$ concentration >-0.4 *** p<0.01; ** 0.01<p<0.05; * p<0.1

Source: author's calculations based on data from Český statistický úřad (2003), Český statistický úřad (2013c), Český statistický úřad (2014), Český statistický úřad (2009), Český statistický úřad (2013b), Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

Tab. A5: Estimated changes in the share of selected diseases, whole sample , controlling for potential outliers

	Δ Share on cardiovascular diseases			Δ Share onrespiratory diseases			Δ Share on lung cancer		
Variable	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
Δ Logged $PM_{2.5}$ concentration	0.048***	0.076*	0.068	0.003	-0.010	-0.033	-0.011*	-0.015*	-0.019
	(0.031)	(0.039)	(0.062)	(0.012)	(0.015)	(0.023)	(0.007)	(0.008)	(0.014)
Deterioration (D=1 if Δ $PM_{2.5}$>0)	-----	-----	-0.022	-----	-----	0.016**	-----	-----	-0.002
			(0.019)			(0.007)			(0.004)
Deterioration#ΔLogged $PM_{2.5}$	-----	-----	0.302	-----	-----	-0.110	-----	-----	0.043
			(0.185)			(0.068)			(0.040)
Δ Average age	-----	-0.013	-0.015*	-----	0.004	0.005*	-----	-0.000	-0.001
		(0.008)	(0.009)		(0.003)	(0.003)		(0.002)	(0.002)
Δ Males	-----	-2.713	-2.024	-----	0.599	0.346	-----	0.746*	0.844*
		(1.880)	(1.905)		(0.720)	(0.698)		(0.399)	(0.415)
Δ Married		-0.403	0.193		0.367	0.061		0.106	0.181
		(0.804)	(0.876)		(0.308)	(0.321)		(0.171)	(0.191)
Δ University graduates	-----	-1.421*	-1.411*	-----	0.256	0.209	-----	0.309*	0.305*
		(0.717)	(0.713)		(0.275)	(0.261)		(0.152)	(0.155)
Δ Unemployed	-----	-0.325*	-0.351*	-----	0.146*	0.182**	-----	0.028	0.028
		(0.190)	(0.197)		(0.074)	(0.072)		(0.041)	(0.043)
Δ Doctors	-----	0.003	0.005	-----	0.000	-0.001	-----	-0.002	-0.001
		(0.011)	(0.011)		(0.004)	(0.004)		(0.002)	(0.002)
Δ Natives	-----	-0.434	-0.492	-----	0.147	0.187	-----	0.131*	0.125*
		(0.336)	(0.335)		(0.129)	(0.123)		(0.071)	(0.073)
Δ Urban	-----	0.227	0.189	-----	-0.150**	-0.136**	-----	-0.045	-0.051
		(0.184)	(0.183)		(0.072)	(0.068)		(0.039)	(0.040)
Intercept	-0.030***	0.018	0.042	0.013***	0.012	-0.004	-0.008	0.000	0.002
	(0.005)	(0.047)	(0.050)	(0.002)	(0.018)	(0.018)	(0.001)	(0.010)	(0.011)
Number of observations:	42	42	42	42	42	42	42	42	42
R^2	0.06	0.25	0.31	0.00	0.28	0.40	0.06	0.27	0.29

Note: Δ Logged $PM_{2.5}$ concentration <0.2 & Δ Logged $PM_{2.5}$ concentration >-0.4 *** p<0.01; ** 0.01<p<0.05; * p<0.1

Source: author's calculations based on data from Český statistický úřad (2003), Český statistický úřad (2013c), Český statistický úřad (2014), Český statistický úřad (2009), Český statistický úřad (2013b), Fiala et al. (2001), Fiala et al. (2002), Fiala et al.(2003), Český hydrometeorologický ústav (2011), Český hydrometeorologický ústav (2012) and Český hydrometeorologický ústav (2013b)

Tab.A6: Diagnostic tests of individual regression models

	Δ Logged life expectancy at birth			Δ Logged life expectancy at the age of 65		
Test	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
Multicollinearity						
Mean VIF	-----	1.80	2.55	-----	1.80	2.55
Homoscedasticity						
Breusch-Pagan / Cook-Weisberg test	0.586	0.749	0.759	0.586	0.311	0.432
Normality						
Shapiro-Wilk	0.573	0.667	0.663	0.573	0.607	0.855
Skewness/Kurtosis	0.297	0.697	0.714	0.297	0.339	0.547

	Δ Logged infant mortality			Δ Logged old mortality		
Test	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
Multicollinearity						
Mean VIF	-----	1.80	2.55	-----	1.80	2.55
Homoscedasticity						
Breusch-Pagan / Cook-Weisberg test	0.249	0.044	0.240	0.127	0.187	0.771
Normality						
Shapiro-Wilk	0.345	0.326	0.542	0.204	0.873	0.650
Skewness/Kurtosis	0.448	0.301	0.530	0.873	0.901	0.686

	Δ Share on cardiovascular diseases			Δ Share on respiratory diseases			Δ Share on lung cancer		
Test	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
Multicollinearity									
Mean VIF	-----	1.88	2.59	-----	1.88	2.59	-----	1.88	2.59
Homoscedasticity									
Breusch-Pagan / Cook-Weisberg test	0.666	0.195	0.167	0.127	0.997	0.281	0.035	0.839	0.534
Normality									
Shapiro-Wilk	0.192	0.879	0.676	0.204	0.878	0.744	0.004	0.001	0.001
Skewness/Kurtosis	0.267	0.414	0.501	0.873	0.824	0.588	0.006	0.001	0.001

Note: p-values are reported (except meanVIF)
Source: author’s calculations