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Comparisons of lifetime exposures between differently polluted areas and years of life lost due to all-cause mortality attributable to air pollution

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Abstract

Background Lifetime (or long-term) exposure to air pollution has been linked to an increased risk of premature death. This association might persist even at low air pollutant concentrations level. The objective was to describe and compare lifetime exposures to PM_{10}, $PM_{2.5}$, NO_2, benzene, and benzo(a)pyrene in two differently polluted localities and quantify years of life lost due to all-cause mortality attributable to PM_{10}, $PM_{2.5}$, NO_2.

Methods The study population was selected from two differently polluted localities of the Czech Republic from the period 2000–2017. For determination of lifetime exposures specially developed methodology for historical air pollutants time series concentrations estimation was used. Estimated lifetime exposures, new WHO air quality guideline levels and relative risks were used to quantify years of life lost due to all-cause mortality attributable to air pollutants.

Results Significant differences in lifetime exposures of air pollutants between study areas were found. Average lifetime exposure to PM_{10}, $PM_{2.5}$, NO_2, benzene and B(a)P was 45.6 µg/m^3, 34.9 µg/m^3, 18.1 µg/m^3, 2.1 µg/m^{3}and 2.6 ng/m^3, respectively, in high-polluted area, against 24.9 µg/m^3, 19.4 µg/m^3, 13.3 µg/m^3, 0.8 µg/m^3, 0.4 ng/m^3 in low-polluted area. All-cause mortality and years of life lost due to all-cause mortality (non-external) were higher in high-polluted area. The highest contribution was found for $PM_{2.5}$, when the population attributable fraction was at the 23% level for the high polluted area and at the 14% level for the low polluted area. The highest losses of 35,776 years per 100,000 men or 131 days per 1 man were achieved in the high polluted area and in a case of $PM_{2.5}$ exposure, namely for men in the age category of 80–84 years. Additionally, the results were expressed per number of deaths. The average value for the number of deaths attributable to $PM_{2.5}$ exposure was 4.75 years per1 death man, or 3.51 years per 1 death woman in a high-polluted area.

Conclusions Expression of years of life lost due to all-cause mortality attributable to air pollution per number of deaths can be more appropriate for communication about health risks or in the field of public health protection.

Keywords Lifetime exposure, All-cause mortality, Premature deaths attributable to air pollutant

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Introduction

Air pollution has long been a global problem and represents the most significant environmental risk to human health [1]. Several epidemiological studies have confirmed that long-term exposure to air pollution has been linked to an increased risk of premature death [2–6]. It concerns particularly heart diseases, strokes, chronic obstructive pulmonary disease, and lung cancer. Most consistent positive associations between long-term exposure and mortality are reported for $PM_{2.5}$ [7, 8]. Exposure to $PM_{2.5}$ pollution in 41 European countries in 2018 led, on average, to 890 years of life lost (YLL) per 100,000 population. Still, in several European countries, the values were far above 1000 years of life lost per 100,000 population [9]. These associations have led to the creation of national air quality standards by the US Environmental Protection Agency (US EPA) and the World Health Organization (WHO). Air pollution continues to rise at an alarming rate and affects economies and people's quality of life; it is a public health emergency. Only one person in ten lives in a city that complies with the air quality standards [1].

Moreover, in recent years, an increasing number of studies have suggested that the associations between long-term exposure and an increased risk of mortality might persist even at low concentrations, i.e., concentrations are lower than the current limit values [4, 6, 10–12]. There has been increased evidence of adverse health effects of air pollution since the last update of WHO Global Air Quality Guidelines in 2005. So, In 2021, WHO published a new one based on a systematic review of accumulated evidence, that adjusted air quality guideline levels (AQG) of key air pollutants. In a case of long-term (lifetime) exposure, it is the lowest concentration of an air pollutant above which is assumed to cause an increase in adverse health effects [13]. New long-term AQGs were published for PM_{10}, $PM_{2.5}$, and NO_2 and were adjusted downwards to annual concentrations of 15 μg/m^3, 5 μg/m^3, and 10 μg/m^3, respectively [13].

Within the European Union, certain air pollutants' highest concentrations (or exposures) occur in the Czech Republic. Specifically, these are localities in the Upper Silesian metropolitan area (shared with today's Poland), i.e., the Moravian-Silesian region [14, 15]. At the same time, there are localities in the Czech Republic, in contrast to the above, which can be characterized as environmentally unpolluted, i.e., with low concentrations (under government-set limit values) of air pollutants.

The objective of the study was to describe and compare lifetime exposures (not only concentrations of air pollutants) to PM_{10}, $PM_{2.5}$, NO_2, benzene, and benzo(a)pyrene (B(a)P) in two differently polluted localities of the Czech Republic and quantify years of life lost due to all-cause mortality attributable to selected air pollutants (PM_{10}, $PM_{2.5}$, NO_2).

Using long-term exposures to calculate lifetime losses attributable to air pollutants is a new and, in our opinion, more correct approach to assessing health risks caused by breathing polluted air. A specially developed methodology for estimating historical air pollutants' time series concentrations was used to determine lifetime exposures. And new AQGs were used as reference concentrations for quantifying years of life lost due to all-cause mortality attributable to air pollution.

Materials and methods

Location and study population

The study population was selected from the Czech Republic (CR) from 2000 to 2017. In the northeast part of the CR lies the Moravian-Silesian region (MSR) consisting of six districts: Bruntál (BR), Frýdek-Místek (FM), Karviná (KA), Nový Jičín (NJ), Opava (OP), and Ostrava (OV) (see Fig. 1). The Ostrava, the capital of this region, and its surroundings have long been one of the most air-polluted areas in CR and Central and Western Europe [15]. Although there are a few districts with mountainous nature of landscape, the allowed limits of air pollutants in this region are regularly exceeded due to the concentration of pollution sources and the geographical and meteorological conditions of Upper Silesia, where most of the region belongs [16]. Historically, this region was characterized by heavy industry, especially primary metallurgy, steel and coke production, and the chemical industry [16, 17]. Even though there has been a slowdown in the industry, this region is still one of the most polluted, as mentioned above. Currently, the main sources of pollution in the region are industry and energy, local heating, and road traffic [16, 17]. So, this study considers this region a high-polluted area (from now on referred to as HPA).

On the contrary, The South Bohemia region (SBR), located in the southern part of the CR, is one of the least environmentally polluted areas of CR. This region consists of seven districts: České Budějovice (CB), Český Krumlov (CK), Jindřichův Hradec (JH), Písek (PI), Prachatice (PR), Strakonice (ST), and Tábor (TA) (see Fig. 1). The capital is České Budějovice. This region has a long history in fish farming and forestry and has extensive agricultural areas. Only in the last century has the industry developed with a focus on manufacturing activities [18]. Despite this, the concentrations of air pollutants are below the limit values. So, this region is considered a low-polluted area (from now on referred to as LPA).

Annual limit values set by government of CR for PM_{10}, $PM_{2.5}$, NO_2, benzene and B(a)P are 40 μg/m^3, 20 μg/m^3, 40 μg/m^3, 5 μg/m^3 and 1 ng/m^3, respectively. These limit values are set following EU air quality standards.

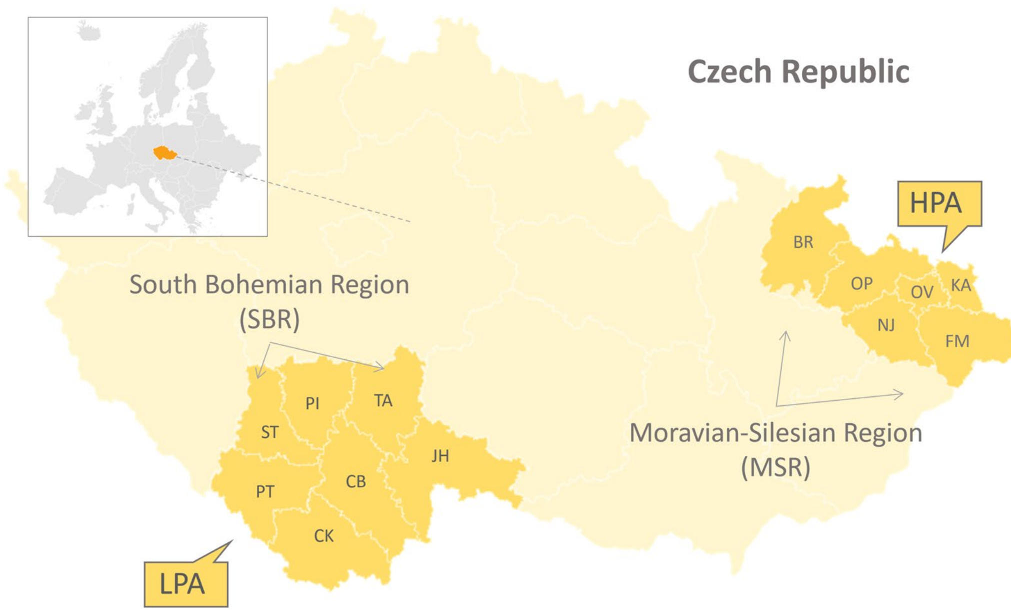

Fig. 1 Location of high and low polluted areas (HPA and LPA) with their districts

Input data

Historical time series of air pollutant concentrations

Originally developed method for historical time series analysis of air pollutant concentrations for a whole evaluated period at the level of districts was used [17]. Annual concentrations of PM_{10}, $PM_{2.5}$, NO_2, benzene, and benzo(a)pyrene from valid national databases were used. The following air quality databases and air pollution characteristics were used:

a) The average annual concentrations from air quality monitoring stations for the period 1997–2019 (in the case of the Ostrava city district since 1972) from a nationally verified air quality database [19]. The air quality monitoring station network meets the quality system requirements of the international standard EN ISO/IEC 17025:2017.
b) Modeled spatial five-year average annual concentrations of air pollutants in a regular network of squares with 1 km step for the interval 2007–2011 [20]. Database processing according to the Air Protection Act 201/2012 Coll., 11, Paragraphs 5 and 6.
c) Emission balance of PM and NO_x for the years 1980–1997 from data processed by the Czech Hydrometeorological Institute. In the case of Ostrava city district, data were available even for 1960 and 1972 [21].
d) Data about dust downfall for the years 1960–1972 in the Ostrava city district from Air Pollution Commission in Ostrava in 1972 [21].
e) Historical data about iron, steel, and coke production volume in the main industrial plants of Ostrava city district [22–25].

The basic procedures of historical time series analysis of air pollutants are summarized in four main steps:

1) Creation time series of annual air pollutants concentrations for the period 1997–2019 according to available air quality data (see Fig. 2, Step 1)
a) Processing of available air quality monitoring data for individual districts and assessed air pollutants for the period 1997–2019
b) Creation of a spatial regular network (squares with 1 km step) of annual air pollutants concentrations for HPA and LPA for the period 1997–2019 by a combination of monitored and modeled data from air quality databases (Input data: air pollutants concentrations).
c) Replacing data where air quality monitoring data were unavailable for 1997–2019 by a linear trend determined by the closest known values.
d) Correction of annual average concentrations of territorial units for residential zones.
2) Estimation of annual average concentrations of air pollutants from 1980 to 1997 (Fig. 2, Step 2).
a) Estimation of annual average concentrations of air pollutants for 1980, 1985, 1990, and 1995 based on emission balance data for individual evaluated dis-

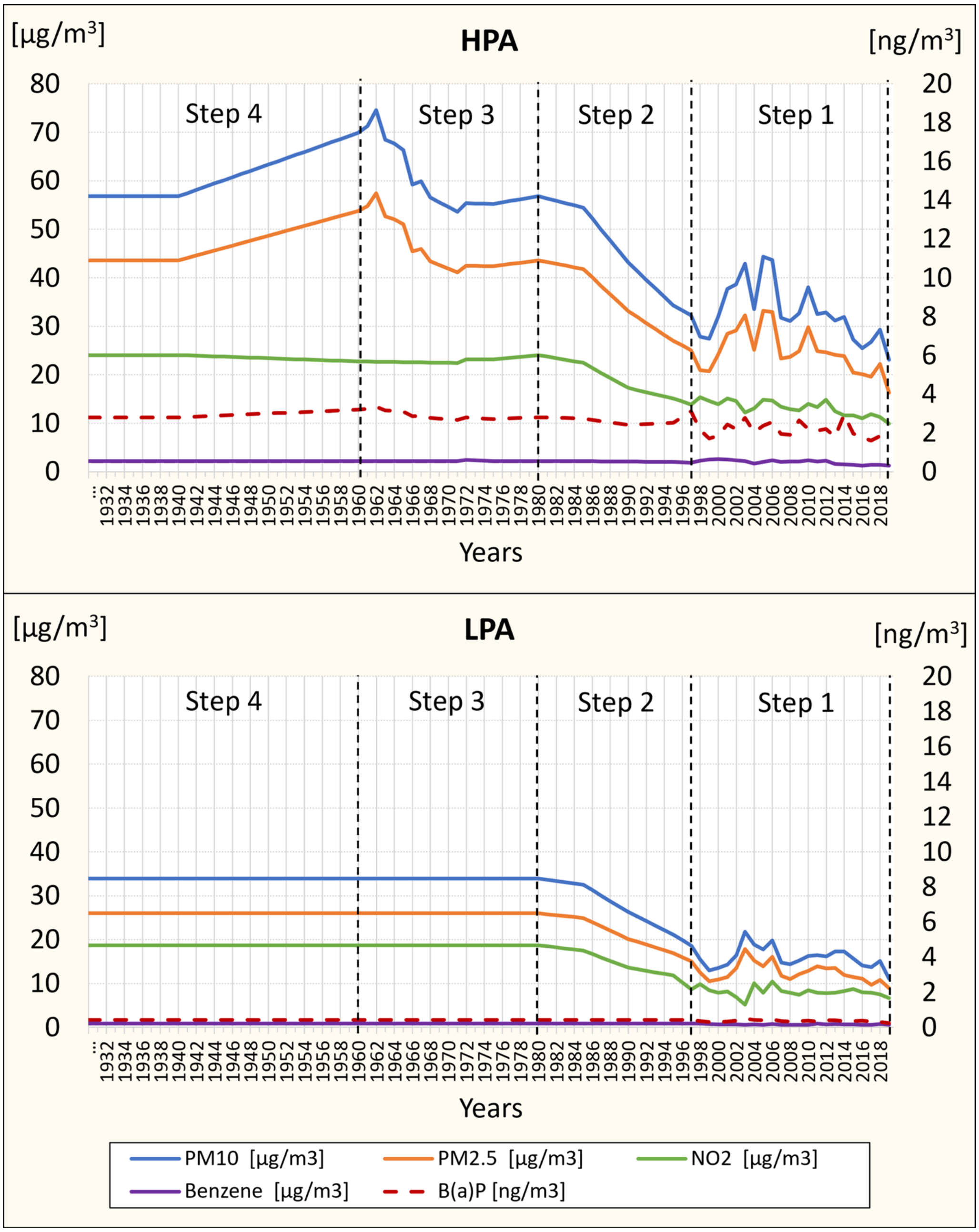

Fig. 2 Time series of mean annual ambient concentrations of air pollutants in the high and low polluted areas (HPA and LPA) in the period 1930–2019

tricts and its subsequent correlation with air quality monitoring data from Ostrava city district

b) Approximation for all years from 1997 to 1980 using linear trend based on the closest known values.

3) Back extrapolation from 1960 to 1980 (Fig. 2, Step 3).

a) In the case of the Ostrava city district, where the data from air quality monitoring stations have been available since 1972, the period between 1980 and 1972 was estimated based on the steps mentioned above. Between 1972 and 1960, the extrapolation was made based on regression and correlation analysis of air quality monitoring data, emission balance, and dust downfall. A similar extrapolation was also done for Karvina district, the second most polluted district of HPA.

b) For other districts, where the exact data from air quality monitoring stations or emission balance data were unavailable, a constant trend was used to back extrapolate into deeper history. Local coal-fired heating was the primary source of air pollution here, from the end of the nineteenth century until more significant gasification, which gradually occurred from the 1980s onwards.

4) Back extrapolation before the year 1960, where are no exact data about air quality or emission balance (Fig. 2, Step 4).

a) Based on documented data on the increasing volume of production, especially of iron, steel and coke since the beginning of the Second World War and on the establishment of large industrial plants in the 1950s in the Ostrava district (see Input data), the extrapolation was carried out using a linear trend between 1960 and 1940. The level of pollution is extremely difficult to estimate for these years. Still, it can be assumed that it may have reached approximately the level of 1980, when the volume of production was significantly higher, but the first measures to reduce the amount of emissions were already in place. For the period before 1940, i.e., the period between the world wars, which partially affects only the population from the oldest age category 85+, the trend was kept constant at the level of 1940.

b) For other districts, a constant trend was used as in Step 3.

Estimated annual average concentrations of air pollutants from 1980 to 2019 (Steps 1 and 2) and their statistical comparison between HPA and LPA are shown in Fig. 3. More detailed numerical data and partial comparison between individual districts of the assessed areas are presented in Additional file 1.

Also, the air quality guideline levels for PM_{10}, $PM_{2.5}$, and NO_2, recently published by WHO [13], were used for further calculations as a reference concentrations. Based on an extensive meta-analysis, these concentrations were revised and adjusted downwards to annual concentration for PM_{10}, $PM_{2.5}$, and NO_2 to 15 μg/m^3, 5 μg/m^3, and 10 μg/m^3, respectively [13]. In the case of long-term exposure, these concentrations represent the lowest exposure level above, which is assumed that there is an increase in adverse health effects.

Population numbers and mortality rate

The data from publicly available information sources (The Institute of Health Information and Statistics of the Czech Republic) about the number population (N_{pop}) and number of all-cause mortality (mortality rate, MR) by age groups from years 2000 to 2017 on the level of the region was used (see Table 1). This MR represents all non-external causes of death, it means only disease-related causes of death without external causes such as injuries, homicides, suicides, and traffic accidents (for now on referred to as all-cause mortality). Trends of the mean age-standardized mortality rates of all-cause-mortality are shown in Fig. 4.

Also, the theoretically ideal median life span published by the World Health Organization [26] was used to for further calculations.

Data processed

The methodology of this study was based on two follow-up procedures. First, the lifetime exposures of air pollutants were estimated. For this purpose, it was necessary to define the historical time series concentrations of air pollutants in studied localities as precisely as possible (see data input above). Secondly, years of life lost due to all-cause mortality attributable to air pollution were quantified.

Quantification of lifetime exposure to air pollutants [PM_{10}, $PM_{2.5}$, NO_2, benzene, B(a)P]

Life time exposure was expressing by the lifetime average exposure concentration (LC_{xpqr}) of individual air pollutant x for age group p in locality q (area or district) and year r by following equation:

$$LC_{xpqr} = \frac{\sum_{r-p}^{r} IC_{xqr}}{p} \quad (1)$$

where:

IC_{xqr}—average concentration of air pollutant x in district q and year r [μg/m^3 or ng/m^3 for B(a)P];

p-age group

Quantification of years of life lost due to all-cause mortality attributable to PM_{10}, $PM_{2.5}$. NO_2

Quantification of years of life lost due to mortality from all causes attributable to air pollution was calculated for PM_{10}, $PM_{2.5}$, NO_2. New AQGs and values of relative risks of all-cause mortality were published for these pollutants. Partial calculations of the following parameters were performed for final quantification:

1) The population attributable fractions (PAF)
2) The absolute and relative years of life lost (YLL) due to all-cause mortality
3) The absolute and relative years of life lost due to all-cause mortality attributable to PM_{10}, $PM_{2.5}$, NO_2, the so-called burden of all-cause mortality attributable to air pollution (from now on BAAP—burden attributable to air pollution)

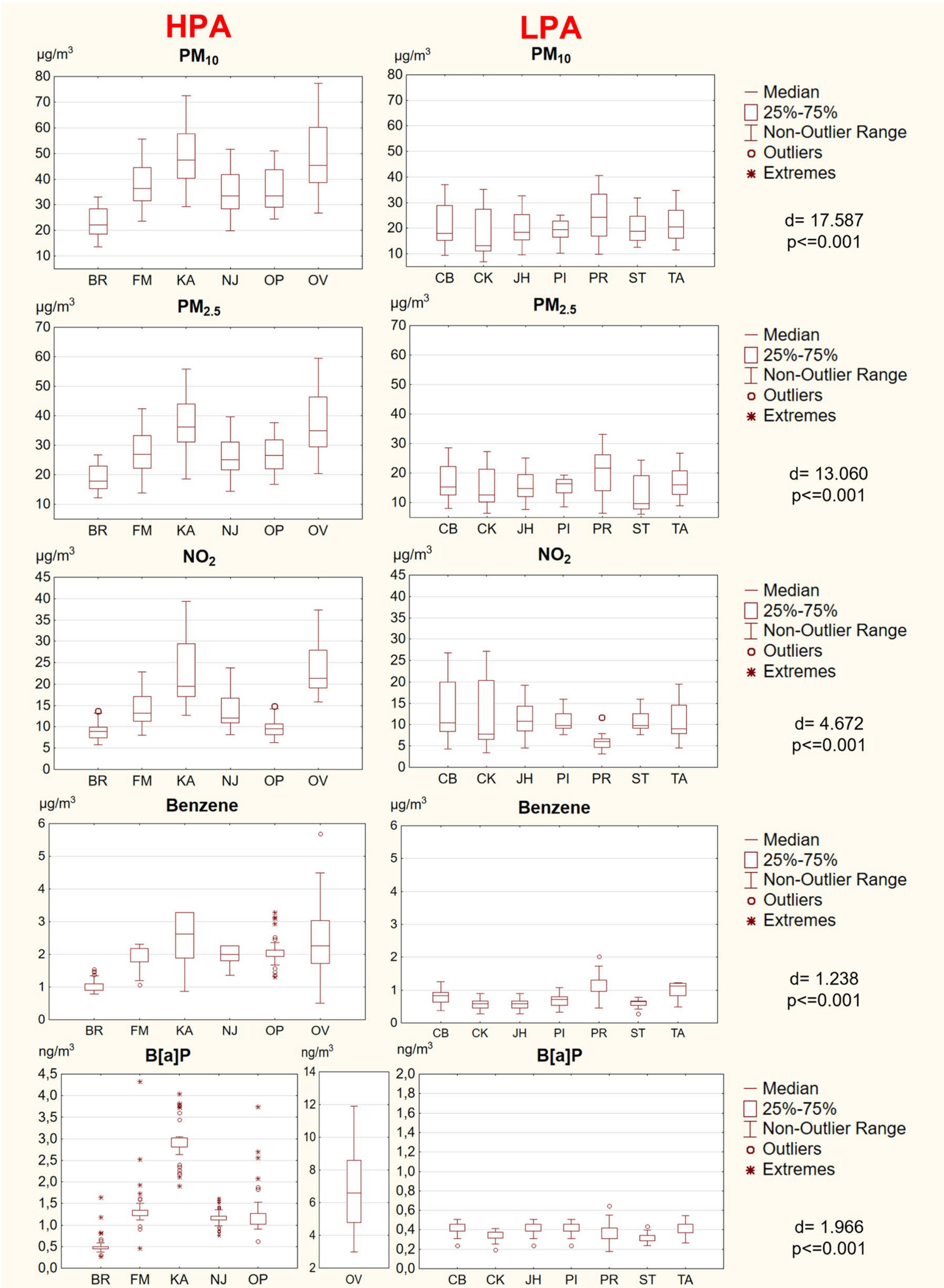

Fig. 3 Estimated annual average concentrations of air pollutants for 1980–2019 of HPA and LPA. *(d- Hodges–Lehmann estimates of the median of differences, p-value of the Wilcoxon Signed Rank Test for Paired Data)*

Table 1 The number of population and mortality rate from all causes

Locality	Men				Women			
	N_{pop}	MR_C	MR_S	SD	N_{pop}	MR_C	MR_S	SD
HPA	613,964	1021	1651	160	639,999	958	1073	109
LPA	310,587	969	1554	259	320,826	951	1006	119
[a]Difference			93				56	
[b]*p-value*			< 0.001				< 0.001	

N_{pop}—annual arithmetic mean of men/women from years 2000–2017 in monitored regions, MR_C—the mean of crude mortality rates per 100,000 men/women from years 2000–2017. MR_S—the mean of age-standardized mortality rates per 100,000 men/women from years 2000–2017, standardization using the 2019 Czech population

[a] Difference between HPA and LPA

[b] *p*-value of Wilcoxon Signed Rank Test for Paired Data

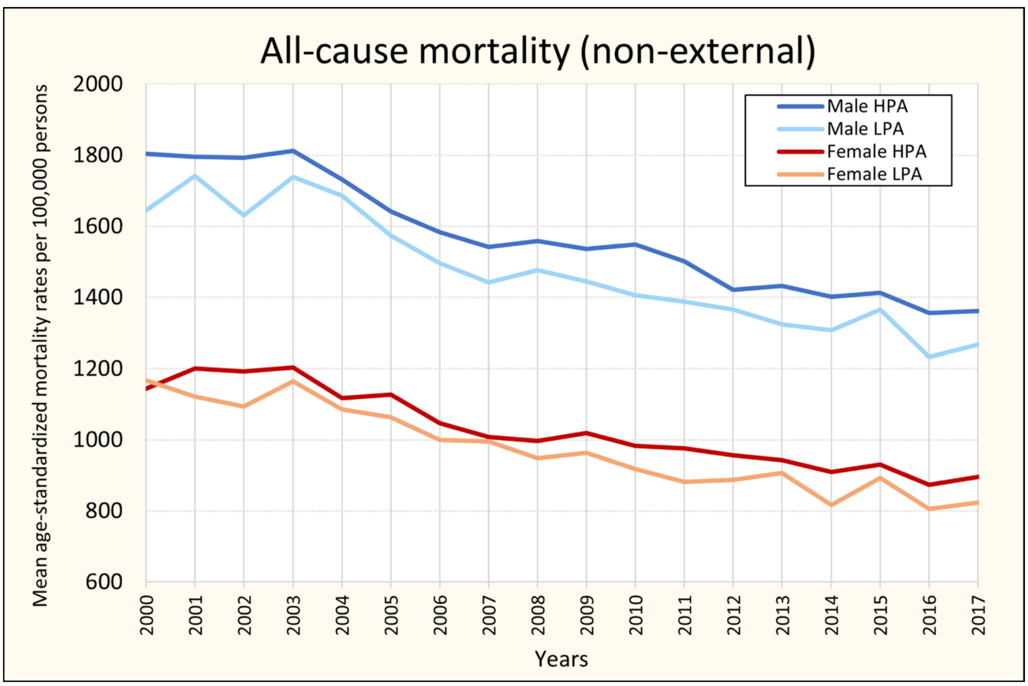

Fig. 4 Time series of the average age-standardized mortality rates of all-cause mortality (non-external) in the high and low polluted areas (HPA and LPA) by sex per 100,000 men/women

Calculation of population attributable fractions (PAF) for PM_{10}, $PM_{2.5}$, NO_2

In this case, population attributable fraction (PAF) represents the proportion of all-cause mortality attributable to lifetime exposure to an air pollutant. So, PAF depends on the level of air pollution and the relative risk (RR) of premature death from all causes. The RR can be expressed using the defined enhancement of the risk RR_{x10} corresponding to an increase in the exposure concentration of 10 μg/m^3 [16].

$$RR_{xpqr}\left(LC_{xpqr}\right) = \frac{(RR_{x10} - 1) \cdot \left(LC_{xpqr} - RC_o\right)}{10} + 1 \quad (2)$$

where:

RR_{xpqr}—the relative risk of all-cause mortality in age category *p*, for locality *q*, in year *r*, for exposure of air pollutant *x*.

RR_{x10}—the relative risk of all-cause mortality for a population exposed to a lifetime concentration of air pollutant x increased by 10 μg/m^3 against a non-exposed population. In case of PM_{10}, $PM_{2.5}$, and NO_2 were used values of relative risk 1.04, 1.08 [11], and 1.02 [27], respectively.

RC_0—reference concentration, an estimate of the lowest concentration above, which is assumed that there is an increase in adverse health effects. In this case, for

$PM_{2.5}$, PM_{10}, NO_2 reference concentrations 15 μg/m^3, 5 μg/m^3, 10 μg/m^3 were used, respectively [26].

LC_{xpqr}—lifetime average concentration of air pollutant *x* for age group *p* in district *q* and year *r* (see Eq. 1).

Then, PAF can be expressed using the relationship according to [28]:

$$\mathrm{PAF}_{xpqr} = \frac{\mathrm{PE}\left(\mathrm{RR}_{xpqr} - 1\right)}{1 + \mathrm{PE}\left(\mathrm{RR}_{xpqr} - 1\right)} \quad (3)$$

where:

PAF_{xpqr}—the proportion of all-cause in age category *p*, for locality *q* in year *r*, attributable to lifetime exposure to an air pollutant *x*.

RR_{xpqr}—the relative risk of all-cause mortality in age category *p*, for locality *q*, in year *r*, for exposure of air pollutant *x* (see Eq. 2).

PE—the proportion of the population exposed to a given level of air pollutant *x*, in location *q* in year *r* to the total relevant population. Using annual average concentrations of air pollutant *x* (IC_{xqr}), see Eq. 1) in all studied localities, $PE_{qr} = 1$, as this assumes that the entire population of all ages *p* is equally exposed in a particular locality *q* for a specific year r.

Calculation of absolute and relative years of life lost (YLL)

YLL was calculated using data of the number of deaths from all causes (non-external) and life expectancy according to relationship:

$$\mathrm{YLL(abs)}_{pqr} = \mathrm{NM}_{pqr} \cdot \mathrm{LF}_{p} \quad (4)$$

where:

$YLL(abs)_{pqr}$—years of life lost due to mortality from all causes expressed in years, for age group *p*, locality *q* and year *r*.

NM_{pqr}—number of deaths from all causes in age categories *p (*from first category 0–4 to last categories 80–84, 85+) in locality *q* in year *r* (period 2000–2017).

LF_p (lost function)—difference between the estimated life expectancy without risk factors (SEYLL—standard expected years life lost) and the time lost of an individual's life in years for each age category *p* (actual life expectancy of a person). Values of LF published by WHO [26] were used.

The relative value of YLL can be expressed as follows:

$$\mathrm{YLL(rel)}_{pqr} = \frac{\mathrm{YLL(abs)}_{pqr}}{\mathrm{NP}_{pqr}} \quad (5)$$

where:

$YLL(rel)_{pqr}$—years of life lost in years due to all-cause mortality of all causes for age group *p*, locality *q* and year *r*.

NP_{pqr}—number of population in age category *p*, locality *q* and year *r*.

By summing the values of $YLL(abs)_{pqr}$ for all age groups *p* the YLL_{qr} can be calculated for the entire population of each locality *q* and year *r*. Then, from the values of $YLL(abs)_{qr}$ can be calculated the average value $YLL(abs)_q$ for the entire period 2000–2017 for each locality *q* according to relationships:

$$\mathrm{YLL(abs)}_{qr} = \sum_{p} \mathrm{YLL(abs)}_{pqr} \quad (6)$$

$$\mathrm{YLL(abs)}_{q} = \frac{\sum_{r} \mathrm{YLL(abs)}_{qr}}{r} \quad (7)$$

The relative values of total years of life lost can then be obtained by dividing with the respective population:

$$\mathrm{YLL(rel)}_{q} = \frac{\mathrm{YLL(abs)}_{q} \cdot N}{\mathrm{NP}_{q}} \quad (8)$$

where:

$YLL(rel)_q$ is the total years of life lost in locality q due to mortality of all causes per N inhabitants.

N—the population in which the results are expressed, $N = 1$ (per capita) or $N = 100{,}000$ (persons, i.e., men or women).

NP_q—the total population in locality q.

Calculation of population attributable fractions (PAF) of the *burden of all-cause mortality attributable to* PM_{10}, $PM_{2.5}$, NO_2.

A burden of disease attributable to air pollution BAAP can be estimated by YLL and PAF according to the relationship:

$$\mathrm{BAAP(abs)}_{xpqr} = \mathrm{PAF}_{xpqr} \cdot \mathrm{YLL(abs)}_{pqr} \quad (9)$$

where:

$BAAP(abs)_{xpqr}$—years of life lost (YLL) due to all-cause mortality in age category *p* for area *q* in year *r*, attributable to lifetime exposures to air pollutant x (PM_{10}, $PM_{2.5}$, NO_2).

See above for PAF_{xpqr} and $YLL(abs)_{pqr}$.

The relative value of the attributable burden $BAAP(rel)_{xpqr}$ can then be calculated by dividing $BAAP(abs)_{xpqr}$ with NP_{pqr} number of population in age category p, locality q and year r.

As in the case of YLL(abs), by summing the values of $BAAP(abs)_{pqr}$ for all age groups *p* the $BAAP_{qr}$ can be calculated for the entire population of each locality *q* and year *r*. Then, from the values of $BAAP(abs)_{qr}$ can be calculated the average value $BAAP(abs)_q$ for the entire period 2000–2017 for each locality *q* (analogue to Eqs. 6 and 7). And also the relative values of years of $BAAP(rel)_q$ can then be obtained by dividing with the respective population NP_q (analogue to Eq. 8). $BAAP(rel)_q$ results were expressed in years per 100,000 persons or days per 1 person.

Statistical analysis

All estimated parameters are presented as average values (Avg). Variability was expressed by the standard deviation (SD) calculated using the directional data of these parameters on the time axis of the study period. Also the maximum values (Max) and identification of the locality and the year of occurrence were presented.

For the comparison of the results between HPA and LPA localities, a standardization of mortality data was performed, and the current population of the Czech Republic was chosen as a standard. Hodges–Lehmann estimate of the median of differences between HPA and LPA have been used to calculate differences between areas and Wilcoxon Signed Rank Test for Paired Data was used for the statistical significance of these differences, because some input data were found to have a distribution partially different from the normal distribution. Statistica 13.4 (TIBCO Software Inc, Palo Alto, USA) and KyPlot 6.0. (KyensLab Inc, Japan) were used for statistical analysis.

Results

The results of average lifetime exposures (LC_{pqr}) to individual air pollutants of the whole population of HPA and LPA and their districts in 2000–2017 is shown in Table 2. Figure 5 also shows results of lifetime exposures, but by age category (from category 30–34 to 85+). These expositions are based on historical time series of mean concentrations of air pollutants. So, in the case of age category 85+in year 2000 exposures are based on historical concentrations since the beginning of the twentieth century.

Table 3 shows proportion of all-cause mortality attributable (PAF) to lifetime exposure to air pollutants PM_{10}, $PM_{2.5}$, and NO_2 (same for men and women) and years of life lost (YLL) due to all-cause mortality per 100,000 men/women.

Results of the burden of all-cause mortality attributable to air pollutants PM_{10}, $PM_{2.5}$, and NO_2 for the whole

Table 2 Average lifetime exposures to air pollutants in locality HPA and LPA and their districts in 2000–2017

Lifetime average exposure concentration															
Locality/district	PM_{10}			$PM_{2.5}$			NO_2			Benzene			B(a)P		
	LC_{pqr} [μg/m³]			LC_{pqr} [μg/m³]			LC_{pqr} [μg/m³]			LC_{pqr} [μg/m³]			LC_{pqr} [ng/m³]		
	Avg[a]	SD[b]	Max[c]	Avg[a]	SD[b]	Max[c]	Avg[a]	SD[b]	Max[c]	Avg[a]	SD[b]	Max[c]	Avg[a]	SD[b]	Max[c]
HPA	45.6	2.4	55.8	34.9	1.9	42.8	18.1	1.0	22.3	2.1	0.1	2.6	2.6	0.1	2.8
OV	61.2	4.1	79.4	47.0	3.2	61.2	27.2	1.7	33.9	2.6	0.1	5.0	8.1	0.6	9.9
OP	41.2	1.9	49.6	30.7	1.4	37.3	10.3	0.1	14.0	2.1	0.0	3.1	1.2	0.1	3.2
NJ	40.2	1.9	48.5	30.5	1.4	37.3	17.2	1.2	22.3	2.1	0.0	2.2	1.1	0.0	1.5
KA	60.4	3.3	76.8	46.4	2.6	59.3	27.4	2.1	35.8	2.9	0.2	3.3	3.1	0.1	3.7
BR	26.7	1.3	32.2	21.7	1.1	26.0	9.5	0.1	13.0	1.0	0.0	1.5	0.5	0.0	1.0
FM	43.8	2.2	52.5	32.9	1.9	40.1	17.1	1.2	21.6	2.1	0.1	2.3	1.3	0.1	3.1
LPA	24.9	1.7	31.9	19.4	1.3	24.5	13.3	1.0	17.5	0.8	0.0	0.9	0.4	0.0	0.5
TA	25.8	1.7	32.7	20.0	1.3	25.2	6.0	0.2	9.4	1.2	0.1	1.9	0.4	0.0	0.6
ST	23.8	1.3	29.9	16.5	1.4	22.8	13.7	1.2	18.3	1.1	0.0	1.2	0.4	0.0	0.5
PR	29.6	2.5	38.3	23.7	2.0	30.8	12.3	0.6	15.1	0.6	0.0	0.7	0.3	0.0	0.4
PI	21.2	0.7	24.3	16.9	0.5	18.8	12.3	0.6	15.1	0.7	0.0	0.9	0.4	0.0	0.5
JH	24.1	1.5	30.6	18.7	1.1	23.6	13.8	1.1	18.1	0.6	0.0	0.7	0.4	0.0	0.5
CK	23.6	2.3	32.8	19.1	1.6	25.5	17.1	2.1	25.2	0.6	0.0	0.7	0.4	0.0	0.4
CB	26.4	2.0	34.8	20.8	1.4	26.8	17.7	1.9	25.0	0.8	0.0	1.0	0.4	0.0	0.5
Difference[d]	20.8			15.5			4.8			1.3			2.2		
p-value[e]	< 0.001			< 0.001			< 0.001			< 0.001			< 0.001		

[a] Average life-time exposure to air pollutant in population of HPA and LPA and their districts

[b] Standard deviation of LC_{pqr} expressing the variability in the time axis

[c] Maximum life-time exposure to air pollutant in population of HPA and LPA and their districts

[d] Hodges–Lehmann Estimates of median of differences between HPA and LPA

[e] *p*-value of Wilcoxon Signed Rank Test for Paired Data

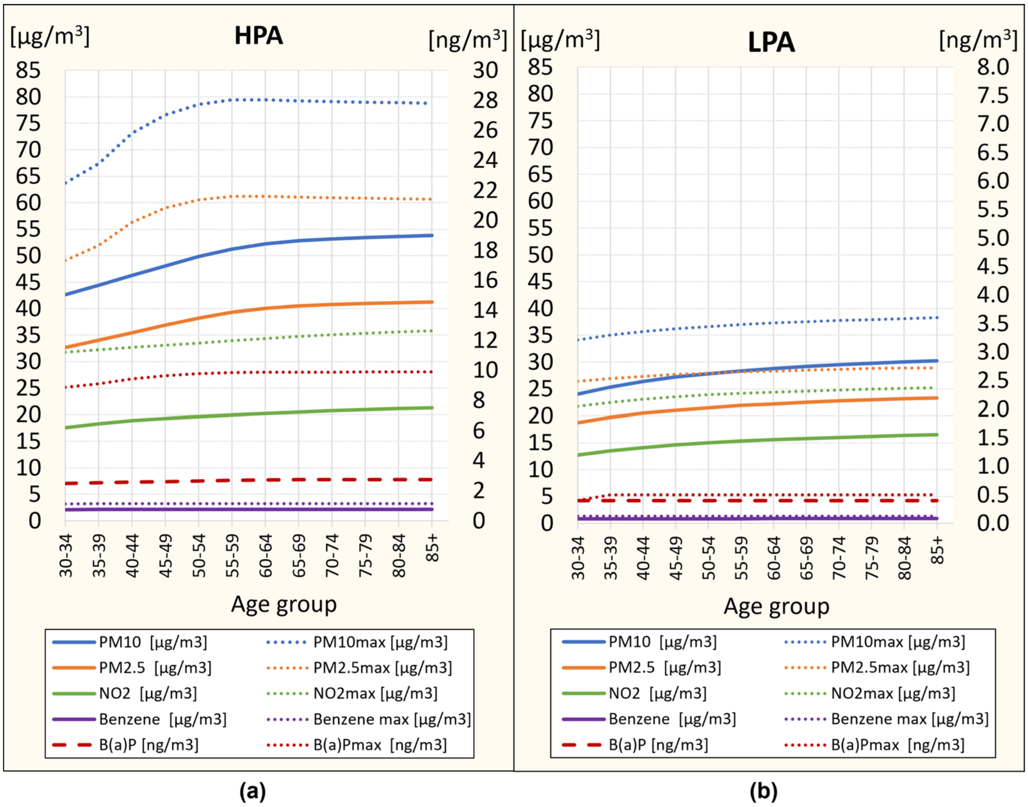

Fig. 5 Average lifetime exposures to air pollutants in the period 2000–2017 by age categories: **a** population of HPA, **b** population of LPA

Table 3 Proportion of all-cause mortality attributable to life time exposure to air pollutant and years of life lost due to all-cause mortality per 100,000 men/women

Loca-tion	Population attributable fractions [%]						Total relative years of life lost per 100,000 men/women of locality									
	PM_{10}		$PM_{2.5}$		NO_2		Male					Female				
	PAF_q		PAF_q		PAF_q		$YLL(rel)_q$					$YLL(rel)_q$				
	Avg[a]	Max[b]	Avg[a]	Max[b]	Avg[a]	Max[b]	Avg[c]	SD[d]	Max[e]	Diff.[f]	*p*-value[g]	Avg[c]	SD[d]	Max[e]	Diff.[f]	*p*-value[g]
HPA	11	14	20	23	2	2	24,432	696	156,409	3354	< 0.001	16,920	453	140,200	1330	< 0.001
LPA	4	6	11	14	1	1	21,376	654	165,545			15,771	734	142,619		

[a] Average population attributable fraction (PAF_q) in percent for specific air pollutant in locality HPA and LPA same for male and female

[b] Maximum PAF in percent for specific air pollutant in locality HPA and LPA over the observed period

[c] Average of years of life lost [$YLL(rel)_q$] due all-cause mortality per 100,000 population

[d] Standard deviation of $YLL(rel)_q$ expressing the variability in the time axis. [e]Maximum $YLL(rel)_q$ of the whole observation period

[f] Hodges–Lehmann Estimates of median of differences between HPA and LPA

[g] *p*-value of Wilcoxon Signed Rank Test for Paired Data

population of HPA and LPA expressed as years of life lost per 100,000 men/women are shown in Table 4.

Figures 6 and 7 also show the burden of all-cause mortality attributable to these air pollutant, but by age groups (from category 30–34 to 85+) and expressed in lost years per 100,000 men/women, and moreover, in lost days per 1 man/woman. Figure 6 is for males and Fig. 7 is for females.

Table 5 shows the total relative years of life lost $YLL(rel)_q$ and burden of all-cause mortality attributable to air pollution $BAAP(rel)_q$ expressed in lost years per 1 death man/death woman of locality HPA and LPA.

Table 4 Burden of all-cause mortality attributable to air pollution in lost years per 100,000 men/women of localities HPA and LPA

Loca-lity	Years of life lost due to all-cause mortality attributable to air pollutant in locality per 100,000 men/women of locality														
	PM_{10}					$PM_{2.5}$					NO_2				
	$BAAP(rel)_q$					$BAAP(rel)_q$					$BAAP(rel)_q$				
	Avg[a]	SD[b]	Max[c]	Diff.[d]	*p*-value[e]	Avg[a]	SD[b]	Max[c]	Diff.[d]	*p*-value[e]	Avg[a]	SD[b]	Max[c]	Diff.[d]	*p*-value[e]
Male															
HPA	2771	249	21,488	1869.7	< 0.001	4854	351	35,776	2553.5	< 0.001	420	58	3573	255.5	< 0.001
LPA	911	153	10,165			2326	231	21,968			171	47	2330		
Female															
HPA	1919	170	19,420	1257	< 0.001	3362	239	32,266	1663.5	< 0.001	291	40	3272	170	< 0.001
LPA	672	124	8757			1717	199	18,935			126	37	2007		

[a] Average years of life lost due to all-cause mortality attributable to air pollutant [$AAP(rel)_q$] per 100,000 men/women

[b] Standard deviation of $BAAP(rel)_q$ reflecting variability on the time axis

[c] Maximum $BAAP(rel)_q$ of all ages over the observed period

[d] Hodges–Lehmann Estimates of median of differences between the HPA and LPA

[e] *p*-value of Wilcoxon Signed Rank Test for Paired Data

Discussion

As the first, this study presents the results of the originally developed method of historical air pollutants concentrations estimation [17] applied to quantify lifetime exposures. This method enables to estimating the most reliable historical time series of air pollutants concentrations based on commonly available air quality monitoring data. The resulting historical time series of annual concentrations of pollutants, which served as input data (Figs. 2, 3), shows a statistically significant difference between evaluated localities of HPA and LPA. This difference between those two localities allows long-term (lifetime) study of the adverse health effects of air pollution.

In both localities, HPA and LPA, there is an obvious decreasing trend in annual air pollutants concentrations during the years. In recent years air pollutant concentrations have been under limit values, but it was not like that in the past. Especially in the HPA, they were significantly exceeded in the past. This is reflected in estimated lifetime exposures, which are, on average, up to almost twice as large for selected air pollutants in HPA than LPA (Table 2). Average lifetime exposure to PM_{10}, $PM_{2.5}$, NO_2, benzene and B(a)P was 45.6 μg/m^3, 34.9 μg/m^3, 18.1 μg/m^3, 2.1 μg/m^{3}and 2.6 ng/m^3, respectively, in HPA, against 24.9 μg/m^3, 19.4 μg/m^3, 13.3 μg/m^3, 0.8 μg/m^3, 0.4 ng/m^3 in LPA.

Several methods exist for assessing lifetime (long term) exposure to air pollution [29–32]. Their use should always appear where the relationship between polluted air and chronic diseases is considered. However, due to their difficult estimation, their use is often replaced by average concentrations over the past few years, or complex mathematical models are used (e.g., based on regression modeling—see LUR [29]), which requires a large amount of data. In the case of historical concentrations, there is generally a problem with the availability of this data, not to mention its completeness over time. The complexity of the method we used is somewhere between the examples discussed above. It deals with insufficient, missing, or different available input data and provides much more accurate information on historical concentrations than a simple average of concentrations over the past few years.

For example, in a recent study by Li et al. [27], they used a computer-aided probabilistic model system (based on models of life course trajectory, time activity, and atmospheric models) to calculate the exposure to $PM_{2.5}$ and NO_2 over the whole lifetime. For the European person who was 70 years old in 2015, the average lifelong exposure to outdoor $PM_{2.5}$ and NO_2 resulted in 11.68 μg/m^3, and 9.53 μg/m^3, respectively. In our study, the results of the average lifetime (life-long) exposure of persons in the age category 70–74 in 2015 for $PM_{2.5}$ and NO_2 were 39.1 and 19.7 μg/m^3 in HPA and 21.6 and 15, 1 μg/m^3 in LPA. Although these data do not include the contribution of indoor air as in the study of Li et al. [27] mentioned above, the concentrations are higher, indicating a polluted area. Data on concentration levels in the indoor environment of buildings depend on the state of the outdoor air and according to some data [33, 34] are variable, i.e., they can take on lower or higher values depending on the presence of internal sources of pollution.

Long-term exposure to air pollutants, especially to PMs and NO_2, is associated with reduced life expectancy, particularly as a consequence of heart diseases, strokes, chronic obstructive pulmonary diseases, and lung cancers. This has been confirmed by a growing number of

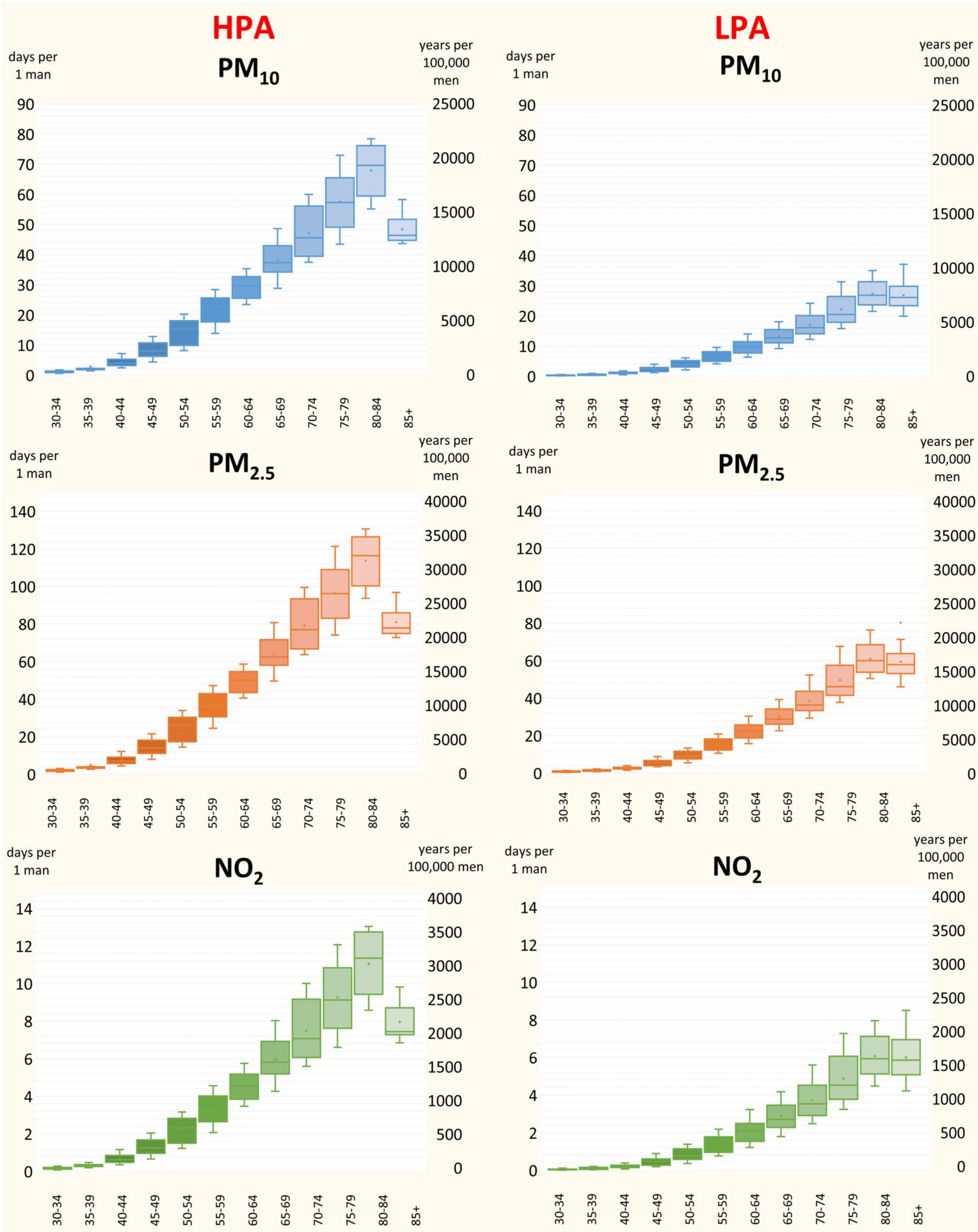

Fig. 6 Male—the burden of all-cause mortality attributable to air pollution in localities HPA and LPA by age group (in years per 100,000 men and in days per 1 men)

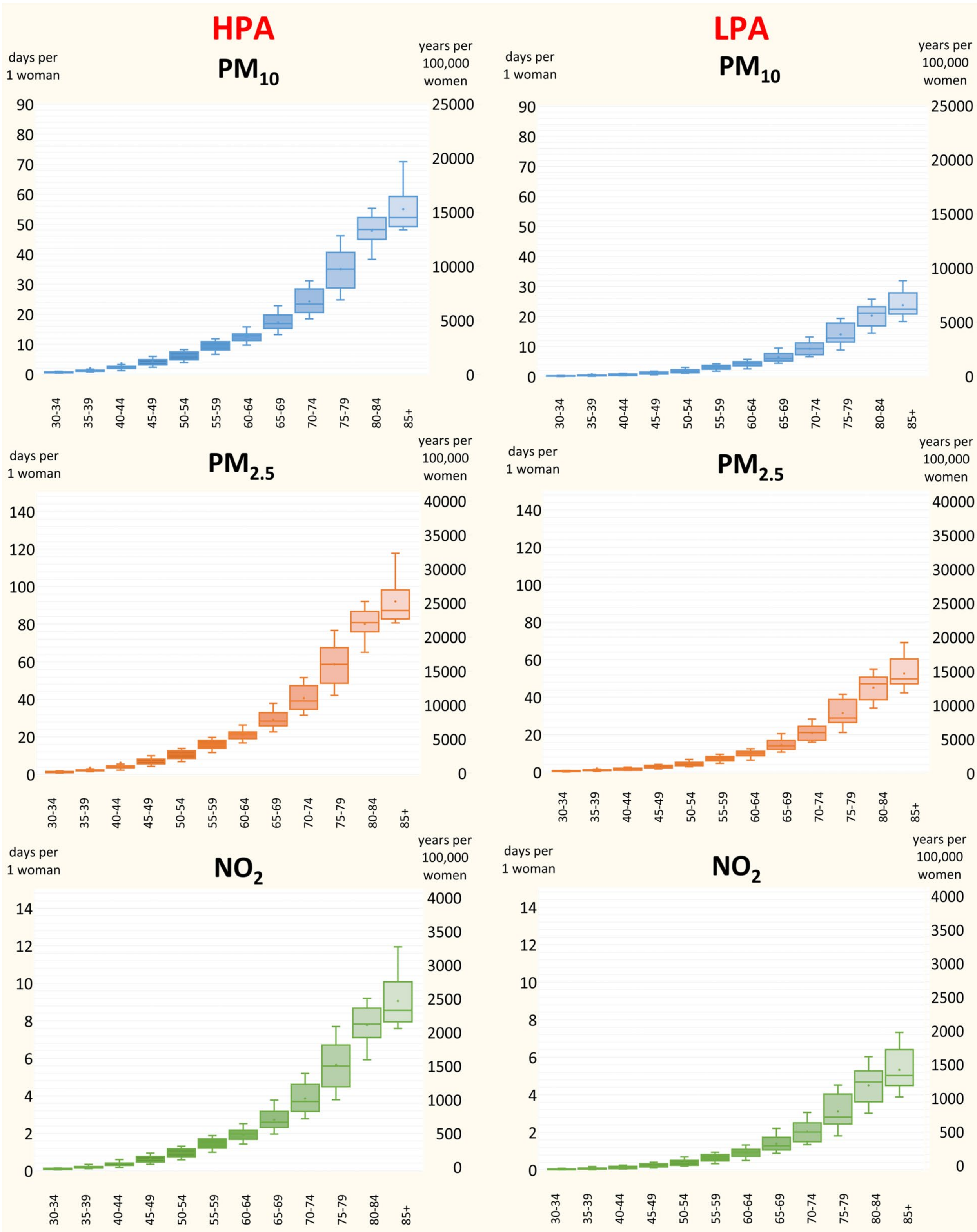

Fig. 7 Female-the burden of all-cause mortality attributable to air pollution in localities HPA and LPA by age (in years per 100,000 women and in days per 1 women)

Table 5 Total relative years of life lost due to all-cause mortality and burden of all-cause mortality attributable to air pollution in lost years per 1 death man/death woman of locality HPA and LPA

Loca-lity	Total relative years of life lost due to all-cause mortality in years per 1 death man/death woman				Years of life lost due to all-cause mortality attributable to air pollutant in years per 1 death man/death woman											
	$YLL(rel)_q$				PM_{10}				$PM_{2.5}$				NO_2			
					$BAAP(rel)_q$				$BAAP(rel)_q$				$BAAP(rel)_q$			
	Avg[a]	SD[b]	Diff.[c]	*p*-value[d]	Avg[e]	SD[f]	Diff.[c]	*p*-value[d]	Avg[e]	SD[f]	Diff.[c]	*p*-value[d]	Avg[e]	SD[f]	Diff.[c]	*p*-value[d]
Male																
HPA	23.9	1.2	1.850	< 0.001	2.71	0.31	1.768	< 0.001	4.75	0.46	2.341	< 0.001	0.41	0.07	0.241	< 0.001
LPA	22.1	1.0			0.94	0.18			2.40	0.30			0.18	0.05		
Female																
HPA	17.7	1.0	1.058	< 0.001	2.00	0.24	1.296	< 0.001	3.51	0.37	1.697	< 0.001	0.30	0.05	0.175	< 0.001
LPA	16.6	0.7			0.71	0.13			1.81	0.21			0.13	0.04		

[a] Average of years of life lost [$YLL(rel)_q$] due all-cause mortality per 1 death man/death woman

[b] Standard deviation of $YLL(rel)_q$ expressing the variability in the time axis

[c] Hodges–Lehmann Estimates of median of differences between the HPA and LPA

[d] *p*-value of Wilcoxon Signed Rank Test for Paired Data

[e] Average years of life lost due to all-cause mortality attributable to air pollutant [$BAAP(rel)_q$] per 1 death man/death woman

[f] Standard deviation of $BAAP(rel)_q$ reflecting variability on the time axis

epidemiological studies [2–8]. All these consequences are included in the parameter of all-cause mortality (non-external without injuries) attributable to air pollution. For its calculation, the population attributable fractions (PAF) and years of life lost (YLL) due to all-cause mortality need to be quantified.

YLL depends on the number of deaths from all causes and life expectancy. So, for YLL calculation was used mortality rates at each age and value of the lost function (LF_p) published by WHO [26]. The value of LF_p is the estimated average life expectancy of the population without exposure to concrete risk factors. All-cause mortality as well as YLL due to all-cause mortality (non-external), were higher in both men and women in the high-polluted area in our study (see Tables 1 and 3). The contribution of air pollution to these values was estimated using the population-attributive risk PAF (see Table 3).

PAF is the same for men and women and depends on air pollution exposure and the relative risk (RR) of premature death from all causes. RR is expressed using the risk (RR_{x10}), corresponding to an increase in the air pollutant concentration of 10 μg/m^3, and the reference concentration (RC_0). This study, calculated relative risk based on the linear relation of the concentration and risk of increased mortality published by [16]. Values of RR_{x10} 1.04, 1.08, and 1.02 from the systematic reviews and meta-analyses [11, 27] also published in new WHO Air quality guidelines [13] were used for PM_{10}, $PM_{2.5}$, and NO_2, respectively. New long-term AQGs published by WHO were used as RC_0. The highest PAF values in this study were achieved when exposure to air pollution was expressed in terms of the particulate respirable fraction $PM_{2.5}$ (PAF in HPA and LPA areas was up to 23% and 14%, respectively). In the case of the assessment of the effect of air pollution with NO_2 on premature deaths, PAF was only up to 1 to 2%. These data also correspond to years (or days) of life lost due to all-cause mortality attributable to air pollution (burden attributable to air pollution—BAAP), see Table 4. The value of average years of life lost due to all-cause mortality attributable to $PM_{2.5}$ was 4854 years per 100,000 men from HPA against 2326 years per 100,000 men from LPA, and 3362 years per 100,000 women from HPA against 1717 years per 100,000 women from LPA, respectively. While in the case of NO_2, the highest average value was 420 years per 100,000 men from HPA. These are average values from the entire study period 2000–2017. For example, according to European Environment Agency report [35], the value of years of life lost attributable to $PM_{2.5}$ for the whole Czech Republic in 2016 was 957 years per 100,000 inhabitants. From the 41 European countries, the average value was 900 years per 100,000 inhabitants, and the highest value of 2100 years per 100,000 inhabitants was estimated in Kosovo.

Figures 6, 7, and Table 5 provide probably the best interpretation of the data found in this study. From Figs. 6 and 7, which present the burden attributable to air pollution in individual age categories, it can be easily determined that the highest losses of years (or days) were achieved, of course, in the high polluted area, namely for men in the age category of 80–84 years and exposure to $PM_{2.5}$. In this case, the losses amounted to 34,624 years per 100,000 men or 126 days per 1 man. While for women, the highest losses were achieved in the age category over 84 and amounted to 26,740 years per 100,000 women or 98 days per 1 woman for $PM_{2.5}$ exposure. Few studies express the results in terms of losses in days per one man or woman and, in addition, for different age categories. The closest to that expression is a recent study by Li et al. [32], mentioned above in a case of lifetime exposures, where authors transformed results into days of life lost. They state that a European citizen exposed to $PM_{2.5}$ and NO_2, who was 70 years old in 2015 is associated with a reduction of life expectancy of 14.65 (95% CI 1.82–52.29) days per year of exposure from age 30 onwards.

Very interesting interpretations, or applicability, of results, can be obtained by comparing the data in Tables 4 and 5. The values of years (or days) of life lost due to all-cause mortality attributable to air pollution (BAAP), expressed per population, are substantially different from those expressed per number of deaths. For example, in the high polluted area, the average values given per population amount to 0.04854 years per 1 man, or 0.03362 years per 1 woman, while the average values given for the number of deaths are 4.75 years per 1 death man or 3.51 years per 1 death woman. In our opinion, data on lifetime losses due to premature deaths, whether total or only attributable to air pollution, are appropriate to report according to their intended use. Expression per number of inhabitants is probably more appropriate to use in environmental epidemiology as a measure of comparison of areas, regions, or states. On the contrary, expression per number of deaths is more appropriate for communication about health risks or in the field of public health protection.

Conclusions

This study compares lifetime exposure to air pollution between two different polluted areas. It quantifies the burden attributable to exposure to selected air pollutants by expressing years (or days) of life lost due to all-cause mortality attributable to these air pollutants. Lifetime exposures were estimated using the originally developed method of historical air pollutants concentrations estimation, which deals with insufficient, missing, or different available input data and provides much more accurate information on historical concentrations than a simple average of concentrations over the past few years. This method thus enables the calculation of exposure for individual age groups using the estimated historical concentrations from the beginning of the twentieth century (for individuals older than 85 years in 2000) in the case of this study. Long-term or lifetime exposure to air pollutants is associated with a reduction in life expectancy, so the most accurate estimation of long-term exposure is essential for quantifying the adverse health effects of air pollution. There are complex mathematical models, of course, but they require a large amount of data, which in the case of historical estimation reaching deep into the past is not usually available.

Significant differences in lifetime exposures of air pollutants between study areas were found. All-cause mortality and YLL due to all-cause mortality (non-external) were higher in high polluted area. The contribution of air pollution to these values was estimated using the population attributive risk PAF, calculated from lifetime exposures and data from published epidemiological studies. The highest contribution was found for $PM_{2.5}$, when the attributable fraction was at the 23% level for the high polluted area and at the 14% level for the low polluted area, respectively. In the case of the assessment of the effect of air pollution with NO_2 on premature deaths, the attributable fraction was at the 2% level, respectively, at the 1% level. These data also correspond to years (or days) of life lost due to all-cause mortality attributable to air pollution. Of course, the highest losses of years (or days) were achieved, in the high polluted area and the case of $PM_{2.5}$ exposure, namely for men in the age category of 80–84 years (34,624 years per 100,000 men or 126 days per 1 man). Additionally, the results of years of life lost due to all-cause mortality attributable to air pollution were expressed per number of deaths, which in our opinion, is more appropriate for communication about health risks, or in the field of public health protection. The average values for the number of deaths attributable to $PM_{2.5}$ exposure was 4.75 years per 1 death man, or 3.51 years per 1 death woman in high polluted area.

Abbreviations

AQG	Air quality guideline level
Avg	Average
BAAP	Burden of all-cause mortality attributable to air pollution (burden attributable to air pollution) expressed by life lost due to all-cause mortality attributable to air pollutant
BR	Bruntál district
CB	České Budějovice district
CK	Český Krumlov district
CR	Czech Republic
Diff.	Difference
FM	Frýdek-Místek distric
HPA	High-polluted area
IC	Average concentration of air pollutant
JH	Jindřichův Hradec district
KA	Karviná distric
LC	Lifetime average exposure concentration
LF	Lost function
LPA	Low-polluted area
Max	Maximum

Min	Minimum
MR_C	The mean of crude mortality rates
MR_S	Mean of age-standardized mortality rates
MSR	Moravian-Silesian region
NJ	Nový Jičín district
NM	Number of deaths from all causes
NP	Number of population
N_{pop}	Annual arithmetic mean of men/women number
OP	Opava district
OV	Ostrava city district
PAF	Population attributable fractions
PE	Proportion of the population exposed to a given level of air pollutant
PI	Písek district
PR	Prachatice district
RR	Relative risk
SBR	South Bohemia region
SD	Standard deviation
ST	Strakonice district
TA	Tábor district
YLL	Years of life lost

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-023-00778-5.

Additional file 1: Comparison of estimated annual average concentrations of air pollutants for the period 1980–2019 between districts of HPA and LPA.

Author contributions

OM and VJ conceptualization of the work. OM original draft preparation. VJ and OM methodology. VJ validation. OM, VJ, TJ, and JM data analysis and interpretation. OM visualization. VJ, JM, GS, LO, EK, and JT review and editing. JT supervision. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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