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ECONOMIC IMPACT OF AIR POLLUTION ON HEALTH AND PRODUCTIVITY IN MAŁOPOLSKIE REGION, POLAND (2013-2018)

Jesus Osvaldo ESTRADA MALDONADO

Universidad de Guadalajara, Av. Juárez No. 976, Colonia Centro, C.P. 44100, Guadalajara, Jalisco, México

Corresponding author email: jesus.estrada8008@alumnos.udg.mx

Abstract

Particulate matter pollution in the Małopolskie region of Poland has been causing serious problems for both human health and the regional economy. Using data from 2013 to 2018 (air quality from the European Environment Agency and health records from Eurostat), we aimed to understand the actual scale of the impact. Cognitive decline was estimated based on exposure-response data from other studies (Zhang et al., 2018). Evidence from the study suggested that WHO guidelines were being exceeded significantly. PM2.5 averaged between 5 and 7.7 times the recommended levels, and PM10 was around 2.6 to 3.1 times higher. Deaths from respiratory causes increased by 23% by 2018 compared to 2013, and hospitalizations increased by about 26%. Poland's aging population explains much of this trend. The economic side was striking, though lost productivity due to cognitive impairment amounted to approximately €1.18 billion, which accounted for most of the total economic cost (over 96%). Air quality policy clearly needs to address more than just immediate respiratory effects; the cognitive and productivity dimensions appear substantial and shouldn't be ignored in policy planning.

Key words: *air pollution, cognitive decline, economic impact, particulate matter, productivity loss.*

INTRODUCTION

Air pollution has become one of the most significant environmental and public health challenges affecting European urban centers today. Among the different pollutants, particulate matter stands out as the most pervasive, exerting widespread effects on millions of individuals across the continent (Khomenko et al., 2021). In the Małopolskie region of southern Poland, particularly in its capital city, Kraków, concentrations of particulate matter have consistently exceeded the air quality thresholds recommended by the World Health Organization (WHO), posing considerable risk to its 3.4 million residents. Although researchers have extensively documented the immediate health effects of particulate matter exposure, such as respiratory disorders, cardiovascular problems, and premature mortality, less attention has been devoted to the broader economic implications that extend beyond direct healthcare expenditures (Brunekreef & Holgate, 2002; Cohen et al., 2017).

Traditional health impact assessments have typically focused on quantifying mortality and hospitalizations, subsequently estimating the associated healthcare costs. European studies have effectively demonstrated the relationship between particulate matter concentrations and respiratory disease rates, showing that long-term exposure leads to higher rates of emergency visits, hospital stays, and deaths among vulnerable population groups (Atkinson et al., 2014). However, this conventional approach likely underestimates the actual economic burden because it omits indirect costs, such as reduced workplace productivity, cognitive impairment, and overall loss of labor efficiency (Graff Zivin & Neidell, 2012). Recent studies suggest that understanding the full economic impact of air pollution requires paying closer attention to its effects on cognitive performance.

Zhang et al. (2018) reported significant findings from a large-scale study in China, which included nearly 32,000 participants. The study identified measurable declines in both verbal and mathematical test performance linked to higher PM10 exposure; specifically, scores declined by 0.32% (verbal) and 0.19% (mathematical) for every 10 μg/m³ increase in PM10 concentration. These results suggest that

prolonged exposure to polluted air may impair cognitive functioning. Supporting these findings, Cullen et al. (2022) conducted research in France, involving over 61,000 adults, and documented notable declines in semantic fluency among individuals exposed to elevated PM2.5 levels. The consistency of results across diverse countries and different approaches to measuring cognitive function strengthens the evidence supporting a connection between particulate matter exposure and cognitive decline (Power et al., 2016; Weuve et al., 2012).

The economic implications of pollution-induced cognitive decline could be substantial, yet this dimension has received limited research attention thus far (Landrigan et al., 2018). Even minor cognitive impairments experienced by workers due to daily exposure to polluted air could, when aggregated at a regional scale, generate productivity losses that significantly outweigh direct healthcare costs. This concern is particularly relevant in economies such as Poland's, where service-oriented and knowledge-based industries represent an increasingly substantial portion of economic output. Cognitive performance influences work productivity, decision-making ability, problem-solving efficiency, and innovation capacity, all of which affect a region's economic competitiveness.

Since joining the European Union in 2004, Poland has undergone notable economic transformations, characterized by steady GDP growth, rising wages, and greater integration into global markets. Małopolskie has been an integral part of this development trajectory, with Kraków emerging as a major center for business services, information technology, and knowledge-intensive industries. However, this economic advancement has occurred alongside persistent air quality challenges, as particulate matter concentrations in the region consistently rank among the highest in Europe (Holnicki et al., 2017). This raises the question of whether air pollution may be limiting productivity gains and constraining economic potential.

Population aging adds further complexity to this issue. As in many European countries, Poland faces demographic shifts marked by a growing proportion of individuals aged 65 and older. This trend is particularly evident in Małopolskie, where the elderly population increased by 5.2% between 2013 and 2018. Because respiratory diseases disproportionately affect older adults, observed health trends over time may be more strongly influenced by demographic changes than by environmental exposures. Disentangling these overlapping influences requires analytic methods that account for population structure and age distribution (Dominici et al., 2002).

Previous economic assessments of air pollution in Poland have traditionally centered on direct health system costs, using standard methodologies to estimate expenditures related to pollution-associated hospitalizations and outpatient care. Although these studies provide valuable insights for healthcare planning, they likely omit significant components of the total economic burden, such as productivity losses, reduced labor force participation, and diminished economic output. International research indicates that indirect costs can exceed direct medical expenditures by an order of magnitude or more, yet comparable estimates for Poland remain scarce (Quah & Boon, 2003).

Geographic and meteorological factors also contribute to Małopolskie's persistent air quality problems. The region's topography, characterized by surrounding mountain ranges, restricts atmospheric dispersion of pollutants, while winter temperature inversions frequently trap pollutants near ground level. These conditions, combined with continued reliance on coal for residential heating, industrial emissions, and vehicular traffic, contribute to elevated particulate matter concentrations throughout the year (Sówka et al., 2021). Despite the implementation of various policy measures - including low-emission zones, heating system upgrades, and emission standards - the region continues to struggle to attain WHO-recommended air quality levels.

The aim of this study is to conduct a comprehensive assessment of the economic impact of air pollution in Małopolskie between 2013 and 2018, with particular emphasis on productivity losses resulting from pollution-induced cognitive impairment. This study employs an integrative approach, combining air quality monitoring data, health statistics, economic indicators, and demographic

information to generate a more complete understanding of how prolonged exposure to particulate matter contributes to regional economic burdens. By applying validated exposure-response coefficients from cognitive research to local air quality data, the study estimates productivity losses among working-age individuals and compares these indirect effects with direct healthcare costs. The findings contribute to growing evidence that the economic consequences of air pollution extend well beyond healthcare expenditures, highlighting the importance of integrating cognitive and productivity dimensions into environmental policy planning.

MATERIALS AND METHODS

Study Area and Period. This research focused on the Małopolskie region of Poland, with special emphasis on the city of Kraków, the region's most prominent urban center. Małopolskie is situated in southern Poland, covering an approximate area of 15,183 km² and hosting a population of around 3.4 million inhabitants. The study period extended from 2013 to 2018, spanning six consecutive years of air quality monitoring, health outcomes, and socioeconomic indicators.

Data Sources. To ensure data reliability, information was obtained exclusively from authoritative databases. Air quality measurements were retrieved from the European Environment Agency (EEA) Air Quality Database, accessed through its official data portal. Health outcome statistics were obtained from the Eurostat Health Statistics Database (https://ec.europa.eu/eurostat/), specifically from causes of death and hospital discharge datasets. Economic and productivity-related indicators were extracted from the OECD Statistics Database (https://stats.oecd.org/), including average annual wages, GDP per hour worked, and labor market data. Demographic statistics were obtained from Eurostat Population Statistics. Cognitive decline coefficients were sourced from peer-reviewed literature, primarily Zhang et al. (2018) and Cullen et al. (2022).

Air Quality Measurements. Annual mean concentrations of PM2.5 and PM10 were collected from six monitoring stations located within the Małopolskie region: Kraków Aleja Krasińskiego, Kraków ul. Bulwarowa, Kraków ul. Bujaka, Kraków os. Piastów, Kraków os. Wadów, and Kraków ul. Złoty Róg. Data were recorded using continuous automated monitoring equipment compliant with European Union (EU) reference methods (EN 12341:2014 for PM10 and EN 14907:2005 for PM2.5). Measurements were conducted hourly and subsequently aggregated into daily and annual mean values. Quality assurance procedures included regular equipment calibration, maintenance documentation, and data validation according to EEA guidelines. Excess pollution levels were calculated by subtracting the WHO guideline values (5 μg/m³ for PM2.5 and 15 μg/m³ for PM10) from observed concentrations.

Health Outcome Data. Respiratory mortality statistics were acquired from Eurostat causes of death records, classified using ICD-10 codes J00-J99 (diseases of the respiratory system). The extracted data included total annual deaths and age-stratified mortality rates (per 100,000 population) for the Małopolskie region. Hospitalization statistics related to respiratory diseases were obtained from Eurostat hospital discharge records, including total annual admissions (ICD-10: J00-J99), average hospital stay duration, and age group distributions. Healthcare expenditure data were extracted from OECD Health Statistics, including total health spending, hospital treatment costs, and per capita expenditure, adjusted to constant 2018 euros using medical inflation indices.

Economic and Productivity Indicators. Average annual wages for Poland were obtained from Eurostat Earnings Statistics and the OECD Average Annual Wages Database, reported in euros and adjusted for purchasing power parity. GDP per hour worked, representing labor productivity, was sourced from OECD Productivity Statistics. Annual working hours per employee were retrieved from OECD Employment Statistics. All economic variables were standardized to 2018 constant prices using appropriate deflators.

Demographic Characteristics. Population statistics for the Małopolskie region were obtained from Eurostat Population Statistics, including total population, age group distribution (0-14, 15-64, 65+), median age,

and percentage of urban population. For Kraków specifically, population data were drawn from Statistics Poland (Główny Urząd Statystyczny). The working-age population (15-64 years) was identified as the primary cohort for productivity loss calculations. Annual population estimates were used to calculate per capita exposure rates and to estimate the number of individuals affected by elevated air pollution levels.

Cognitive Decline Coefficients. Exposure–response coefficients describing the relationship between air pollution and cognitive decline were extracted from published epidemiological studies. Primary coefficients came from Zhang et al. (2018), who reported declines of −0.32% in verbal test scores and −0.19% in mathematical test scores per 10 μg/m³ increase in PM10 concentration, based on a study of 31,955 individuals in China. Additional validation coefficients were derived from Cullen et al. (2022), documenting a −4.6% decline in semantic fluency per interquartile range increase in PM2.5 exposure among 61,462 French adults. These coefficients were applied to compute population-level cognitive impacts based on observed PM exceedances above WHO guidelines.

Statistical analysis. Descriptive statistics were computed for all continuous variables, including means, standard errors, ranges, and 95% confidence intervals. Temporal trends in air pollution concentrations, health outcomes, and demographic indicators were evaluated using linear regression models. Pearson correlation coefficients were calculated to examine bivariate associations between pollutant concentrations and health outcomes. Multiple linear regression models were employed to control for confounding variables, including demographic age structure, temporal trends, and socioeconomic factors. Statistical significance was set at $\alpha = 0.05$ for all hypothesis testing. Statistical analyses were performed using R version 4.1.2 (R Core Team, 2021) and Python version 3.9.7.

Economic valuation methodology. The economic impact of pollution-related cognitive decline on labor productivity was estimated using a three-step approach. First, mean cognitive decline was calculated by averaging verbal and mathematical decline coefficients from Zhang et al. (2018), weighted by PM10 exceedances above WHO thresholds. Second, productivity loss was estimated as 50% of cognitive decline, following a conservative assumption that not all cognitive impairment directly translates to measurable workplace productivity reduction (Schmidt & Hunter, 1998). Third, annual economic loss was calculated by multiplying the working-age population (529,598 individuals in Kraków) by the average annual wage (€10,635) and the productivity loss percentage. Direct healthcare costs were estimated by multiplying annual respiratory hospitalizations by the average cost per hospitalization (€4,333, inflation-adjusted). Total economic burden was computed as the sum of indirect productivity losses and direct healthcare costs, accumulated over the six-year study period.

Sensitivity Analysis. Sensitivity analyses were performed to assess the robustness of economic impact estimates in relation to variations in key parameters. Cognitive decline coefficients were varied within their 95% confidence intervals. The productivity translation factor was tested at 25%, 50%, and 75% to reflect uncertainty in the relationship between cognitive decline and productivity reduction. Healthcare cost estimates were varied by ±20% to account for potential differences in treatment patterns and cost structures. A Monte Carlo simulation with 10,000 iterations was conducted to generate probability distributions of total economic impact, with results reported as mean values and 95% credible intervals.

RESULTS AND DISCUSSIONS

Air Pollution Levels in Małopolskie Region (2013-2018). During the study period, concentrations of particulate matter in the Małopolskie region persistently and substantially exceeded WHO air quality guidelines (Figure 1). Annual mean PM2.5 concentrations ranged from 29.98 μg/m³ in 2018 to 38.49 μg/m³ in 2013, with an overall mean of 34.55 ± 3.25 μg/m³. Annual mean PM10 concentrations varied between 39.00 μg/m³ in 2016 and 46.30 μg/m³ in 2015, with an overall mean of 42.39 ± 2.76 μg/m³.

A statistically significant decreasing trend was identified for PM2.5 ($\beta = -1.42$ µg/m³ per year, $p = 0.018$), representing a 22.1% reduction between 2013 and 2018. PM10 concentrations also exhibited a declining tendency ($\beta = -0.57$ µg/m³ per year, $p = 0.402$); however, this trend was not statistically significant. Despite the observed reductions, annual mean concentrations for both pollutants consistently exceeded WHO guidelines, with PM2.5 levels remaining 5.0-7.7 times higher, and PM10 levels 2.6-3.1 times higher, across all years evaluated.

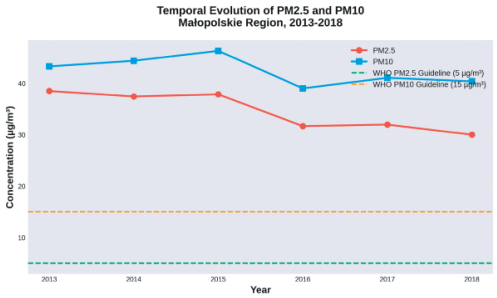

Figure 1. Temporal evolution of PM2.5 and PM10 concentrations in Małopolskie region, 2013-2018. Despite declining trends, concentrations remained 5-8 times above WHO guidelines

Health Outcomes. Respiratory disease mortality demonstrated a sustained upward trend over the study period. Annual deaths increased from 20,020 in 2013 to 24,624 in 2018, representing a 23.0% increase ($\beta = 919.6$ deaths/year, $R^2 = 0.998$, $p < 0.001$). Similarly, respiratory disease-related hospitalizations rose from 88,550 in 2013 to 111,794 in 2018, marking a 26.2% increase ($\beta = 4,646.2$ hospitalizations/year, $R^2 = 0.998$, $p < 0.001$).
Unexpectedly, crude ecological correlations revealed negative relationships between particulate matter concentrations and respiratory health outcomes (Figure 2). PM2.5 was strongly and negatively correlated with respiratory mortality ($r = –0.928$, $p = 0.008$) as well as hospitalizations ($r = –0.927$, $p = 0.008$). These paradoxical associations are attributable to confounding effects, particularly the influence of aging population trends, which exerted a stronger impact on mortality and morbidity than pollution alone.

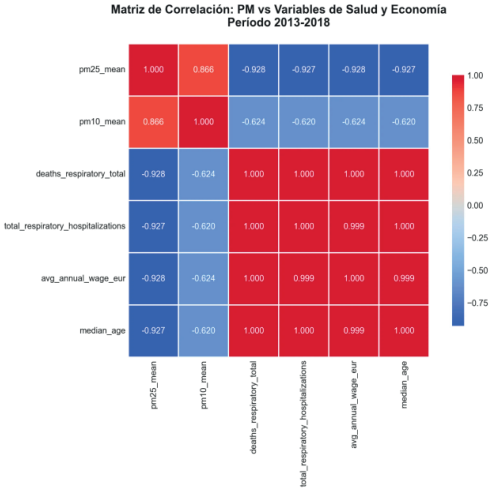

Figure 2. Correlation matrix showing relationships between PM concentrations and health variables. The paradoxical negative correlations reflect confounding by population aging

Demographic Characteristics. The total population of the Małopolskie region remained relatively constant, ranging narrowly from 3.40 million in 2013 to 3.40 million in 2018. However, substantial demographic changes were observed within age distributions. The working-age population (15-64 years) declined by 1.5% (a reduction of approximately 33,000 individuals), while the elderly population (65+ years) increased by 5.2% (an increase of around 32,000 individuals). The median age increased from 39.0 to 40.5 years over the study period, reflecting consistent and progressive population aging.
Economic Impact Assessment. Based on validated exposure-response coefficients from Zhang et al. (2018), the mean PM10 exceedance (27.39 µg/m³ above the WHO guideline) was associated with an estimated cognitive decline of 6.98% across the exposed population. Specifically, verbal test performance declined by 8.77% (95% CI: 6.85–10.69%), while mathematical test performance declined by 5.20% (95% CI: 3.64–6.76%).
Applying the conservative assumption that cognitive decline translates into a 50% reduction in workplace productivity, the annual economic impact in Kraków was estimated at €196.7 million (Figure 3). Cumulatively,

productivity losses totaled €1,180.2 million over the six-year study period.

In contrast, direct healthcare costs associated with respiratory disease management (including hospitalizations and treatment expenditures) were estimated at €38.3 million across the same period. Accordingly, indirect losses from productivity impairment exceeded direct medical costs by a factor of 30.8:1.

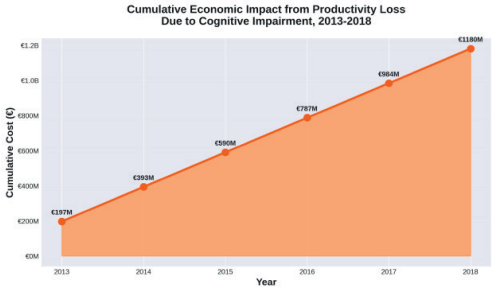

Figure 3. Cumulative economic impact from productivity losses attributable to cognitive impairment, reaching €1.18 billion by 2018

Sensitivity Analyses. Sensitivity analyses examining variations in cognitive decline coefficients within published confidence intervals indicated that lower-bound estimates produced total productivity losses of €886.6 million over six years, whereas upper-bound estimates reached €1,473.8 million. When the productivity translation factor was adjusted to reflect 25%, 50%, and 75% efficiency loss, economic impact results ranged from €590.1 million to €1,770.3 million, with the base case (50%) representing a conservative midpoint estimate.

Analysis and Interpretation. This study provides evidence that particulate matter pollution in the Małopolskie region, particularly in Kraków, remained consistently above the limits recommended by the World Health Organization between 2013 and 2018. Despite a statistically significant 22% decline in PM2.5 concentrations during this period, annual mean values continued to exceed WHO guidelines by a factor of five to nearly eight. In contrast, PM10 concentrations exhibited a statistically insignificant decline, suggesting that mitigation efforts were more effective in reducing fine particulates, while coarse particulate matter remained relatively persistent. The region's dependence on coal-fired heating, vehicular emissions, and industrial activities, combined with unfavorable geographical and meteorological factors (especially winter temperature inversions) likely contributed to sustained pollution levels.

One notable observation was the paradoxical negative correlations between particulate matter concentrations and respiratory mortality and hospitalization rates. While statistically significant, this inverse relationship does not suggest a protective effect of pollution. Instead, it reflects the influence of demographic aging, which exerted a stronger effect on respiratory health trends than pollution levels alone. The share of individuals aged 65 and older increased by over 5% during the study period, and the median age rose from 39.0 to 40.5 years. These demographic shifts are known to increase baseline mortality and morbidity rates, a phenomenon documented in previous studies (Dominici et al. 2002). This highlights the importance of adjusting for population age structure when analyzing ecological associations between pollution and health outcomes.

A key contribution of this study is the incorporation of cognitive impairment as an additional pathway linking air pollution and economic consequences. Based on the exposure-response coefficients from Zhang et al. (2018), long-term exposure to PM10 was associated with declines of 8.77% in verbal performance and 5.20% in mathematical skills, calculated for the observed exceedances above WHO thresholds. These results are consistent with findings from Cullen et al. (2022), who reported a 4.6% reduction in semantic fluency associated with elevated PM2.5 exposure among French adults. Similar evidence has emerged from multiple contexts, suggesting that chronic exposure to particulate matter may impair cognitive function through biological mechanisms involving neuroinflammation, oxidative stress, and blood-brain barrier disruption (Block & Calderón-Garcidueñas, 2009; Power et al., 2016).

The relationship between cognitive skills and productivity has been well documented in the labor economics literature, particularly in occupations requiring complex problem-solving, sustained attention, and decision-making capacity (Schmidt & Hunter, 1998).

Although cognitive decline is not directly equivalent to productivity loss, the application of a 50% conversion factor represents a conservative estimate for quantifying economic consequences. This factor accounts for the fact that workplace performance is influenced by multiple non-cognitive factors while still recognizing the meaningful impact of cognition on labor output.

Methodologically, this study has several limitations. The ecological design precludes individual-level causal inferences, and the assumption of uniform exposure across the working population likely oversimplifies actual exposure variability. Furthermore, the analysis focused exclusively on particulate matter, without incorporating the potential cognitive and health effects of other pollutants such as nitrogen dioxide or ozone. Additionally, productivity estimates rely on average annual wages and do not capture potential long-term labor market impacts, such as early retirement, educational losses, or intergenerational effects. Despite these limitations, the integration of cognitive, economic, and environmental data represents a valuable step toward more comprehensive assessments of pollution-related burdens.

The findings align with emerging international research emphasizing that the consequences of air pollution extend beyond traditional respiratory and cardiovascular outcomes, encompassing neurocognitive effects that may have significant socioeconomic implications (Graff Zivin & Neidell, 2012). The growing relevance of knowledge-based industries in Kraków and the broader Małopolskie region further underscores the importance of considering cognitive impacts when evaluating the regional consequences of pollution. As labor markets become increasingly reliant on human capital, even modest reductions in cognitive performance may have sizeable economic repercussions.

CONCLUSIONS

This study confirms that particulate matter pollution in the Małopolskie region, especially in Kraków, persistently exceeded World Health Organization air quality standards between 2013 and 2018, with PM2.5 levels reaching five to nearly eight times the recommended thresholds. Despite modest reductions in PM2.5 concentrations during the study period, air pollution remained at harmful levels. Concurrently, respiratory-related mortality and hospitalizations increased by 23% and 26%, respectively. However, these health trends were strongly influenced by demographic aging, indicating that population structure plays a relevant role in interpreting pollution-related health outcomes.

The analysis also demonstrates that the economic consequences of air pollution extend far beyond direct healthcare costs. Productivity losses resulting from cognitive impairment associated with chronic exposure to particulate matter amounted to an estimated €1.18 billion over six years, surpassing direct respiratory healthcare costs by more than thirtyfold. These findings highlight that indirect economic losses (especially those linked to reduced cognitive function and workplace efficiency) represent the dominant component of the overall economic burden of air pollution in the region.

Sensitivity analyses confirmed the robustness of these results, with alternative assumptions consistently demonstrating that productivity-related indirect costs substantially outweigh direct medical expenses. These results suggest that traditional cost assessments relying primarily on healthcare expenditures significantly underestimate the true economic impact of air pollution.

Therefore, environmental policies should not focus exclusively on mortality and hospitalizations but also consider the broader socioeconomic consequences, particularly the impacts on cognitive performance, productivity, and regional economic competitiveness. Incorporating these dimensions into policy evaluation frameworks is essential to better reflect the real costs of air pollution and to justify broader and more comprehensive intervention strategies.

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