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Increase in sick leave episodes from short-term fine particulate matter exposure: A case-crossover study in Stockholm, Sweden

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ABSTRACT

Air pollution's short-term effects on a wide range of health outcomes have been studied extensively, primarily focused on vulnerable groups (e.g., children and the elderly). However, the air pollution effects on the adult working population through sick leave have received little attention. This study aims to 1) estimate the associations between particulate matter ≤2.5 μm^3 ($PM_{2.5}$) and sick leave episodes and 2) calculate the attributable number of sick leave days and the consequential productivity loss in the City of Stockholm, Sweden.

Individual level daily sick leave data was obtained from Statistics Sweden for the years 2011–2019. Daily average concentrations of $PM_{2.5}$ were obtained from the main urban background monitoring station in Stockholm. A case-crossover study design was applied to estimate the association between short-term $PM_{2.5}$ and onset of sick leave episodes. Conditional logistic regression was used to estimate the relative increase in odds of onset per 10 μg/m^3 of $PM_{2.5}$, adjusting for temperature, season, and pollen. A human capital method was applied to estimate the $PM_{2.5}$ attributable productivity loss.

In total, 1.5 million (M) individual sick leave occurrences were studied. The measured daily mean $PM_{2.5}$ concentration was 4.2 μg/m^3 (IQR 3.7 μg/m^3). The odds of a sick leave episode was estimated to increase by 8.5% (95% CI: 7.8–9.3) per 10 μg/m^3 average exposure 2–4 days before. Sub-group analysis showed that private sector and individuals 15–24 years old had a lower increase in odds of sick leave episodes in relation to $PM_{2.5}$ exposure. In Stockholm, 4% of the sick leave episodes were attributable to $PM_{2.5}$ exposure, corresponding to €17 M per year in productivity loss.

Our study suggests a positive association between $PM_{2.5}$ and sick leave episodes in a low exposure area.

1. Introduction

Ambient air pollution is a complex mixture of particles that vary spatially and temporally. According to the World Health Organization (WHO), air pollution is the number one environmental health risk and 99% of the world's population was exposed to air pollution levels exceeding the WHO Air Quality Guideline (AQG) values (World Health Organization, 2021).

Particulate matter <2.5 μm ($PM_{2.5}$) exposure is commonly used as exposure measure in epidemiological studies and shown to have stronger effect on adverse health effects compared to other air pollutants, according to projects coordinated by WHO (Heroux et al., 2015). Increased risk of respiratory virus infections and acute cardiovascular events and aggravation of previous chronic conditions (e.g. asthma, chronic obstructive lung disease (COPD)) has been associated with $PM_{2.5}$ exposure (Environmental Protection Agency (EPA), 2019; DeVries et al., 2017). Additionally, air pollution exposure can act as a potential modifier for respiratory system infections in the healthy population, by depressing the immune system. For instance, studies link influenza symptoms to increased air pollution levels (Feng et al., 2016) and the severity level of virus-induced respiratory tract infections (Domingo and Rovira, 2020). Also, positive associations were found between $PM_{2.5}$ and the incidence and fatality rates of SARS-COV-2 in Italy, where results showed that short-term $PM_{2.5}$ induced an over expression of the aryl hydrocarbon receptor in human airways and thereby increased susceptibility to the virus (Borro et al., 2020). All these health outcomes are

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likely to increase the risk of sick leave among the working population in relation to recent day $PM_{2.5}$ exposure.

However, short-term air pollution effects on working adult population in terms of occurrences of sick leave episodes have received little attention in the scientific literature, mainly due to lack of centrally gathered data on sick leave episode occurrences. Health care register data has however been extensively utilized to study both short-term and long-term air pollution health effects among the population (DeVries et al., 2017; Atkinson et al., 2014).

Sick leave episodes can be defined as a suboptimal state of health that is severe enough to prevent people from following their daily activities and can occur frequently, however are not as severe as hospitalization or death, which are rare events. Statistics Sweden has been responsible for gathering sick leave data on an individual level in Sweden. On average, there are 3 million sick leave episodes filed annually in Sweden, out of which 55% lasted one to two days and 90% lasted less than a week (Statistics Sweden, 2019a). An individual does not need a doctor's certificate confirming illness in the first seven days of the sick leave, according to Sweden legislation. This means that most of the sick leave episodes occurring are never diagnosed and registered in health care registers.

The lack of updated research on short-term air pollution exposure and sick leave episodes is evident when the WHO's experts in the method study HRAPIE (2013b) (World Health Organization (WHO), 2013) recommend health impact assessments (HIAs) to use associations between fine particles and self-reported restricted activity days (RADs) and work-loss days (WLDs) based on a study by Ostro and Rothchild (1987) (Ostro, 1987). RADs were defined in a questionnaire as days where individuals have restricted their everyday activities due to sub-optimal health and WLDs were defined as days that the individual was on a sick leave from work (Ostro, 1987). Only one Swedish study has investigated the relationship between particles and RADs (Willers et al., 2013). Both studies found statistically significant risk increases, by 5% and 27%, respectively, per 10 $\mu g/m^3$ increase in particulate matter <10 μm (PM_{10}). However, both these cross-sectional studies relied on self-reported data on the number of RADs. The second health outcome studied by Ostro et al. (1987) were self-reported WLDs within the past two weeks, where three yearly estimates out of five showed an increased risk in relation to average two-week fine particle exposure (Ostro, 1987). A small case-control study from Norway in 1997 used objective sick leave data from a private company with 1500 employees and reported an increase in the number of sick leave episodes by 0.6% per $\mu g/m^3$ PM_{10} (Hansen and Selte, 1997). Unfortunately, cross-sectional studies and case-studies such as these have known limitations in determining causal relationships. In an economic report by Holub et al. (2020), the PM_{10}-attributable labor productivity loss among 1.6 million Spanish workers was assessed based on sick leave episodes filed with the National Institute of Social Security during period 2005–2011 (Holub et al., 2020). They estimated that 7% of the weekly absence rate was attributable to days where PM_{10} levels exceeded the annual EU limit value (Holub et al., 2020). Importantly no up-to-date epidemiological studies exist with objective information on variations in air pollution exposure and sick leave episodes among the adult working population. Therefore, currently health impacts assessments rely on studies with outdated exposure assessments and self-reported information on sick leave episodes, which might lead to an underestimation of short-term $PM_{2.5}$ effects on sick leave episodes.

The aim of this study is firstly, to estimate the association between $PM_{2.5}$ and sick leave episodes among the working population in the City of Stockholm, Sweden. Secondly, we calculate the number of sick leave days and the productivity loss attributable to $PM_{2.5}$.

Since the population of Stockholm live in an area with relatively low exposure the results of this study are important for the derivation of future air quality guidelines.

2. Methods

2.1. Exposure measurement data

Monitoring data for temperature and air pollution was retrieved from the Swedish national air pollution database at the Swedish Meteorological and Hydrological Institute (SMHI). Daily average urban background concentrations of $PM_{2.5}$ in Stockholm were from the main urban background monitoring station in Stockholm (Torkel Knutssongatan), placed on a roof 20 m above the ground. The monitoring station is within the regulatory air pollution control network together with reference instruments to ensure the measurement of air pollution levels according to the EU air quality directive. $PM_{2.5}$ was measured with a gravimetric method and with the instrument TEOM 1400A, Thermo Fisher Scientific, USA. Daily data from this monitoring station has been previously used in Swedish and international epidemiological studies (Olstrup et al., 2019). Daily pollen count data was retrieved from The Palynological Laboratory, Swedish Museum of Natural History, Stockholm. Pollen was divided into five categories (0, 0–10, 10–100, 100–1000, >1000 number of spores in cubic meter of air).

2.2. Outcome

Statistics Sweden has been responsible for collecting statistics on individual level sick leave episodes during the period that the employer stands for the individual wage (days 1–14 of leave) (Statistics Swedena). All employers in the public sector are required to report sick leave data, while a representative sample of 40% of private sector sick leave episodes are included. All private companies with at least 200 employees are included. For companies with fewer than 200 employees a stratified random sample is drawn. There are in total 4100 companies and organizations included, where 1900 are randomly chosen. The data is available at the individual level per day for the period 2011–2019. Cases are defined as the first sick leave day (binary variable) and using all the individuals' sick leave episodes during the study period. The following inclusion criteria were applied: sick leave episodes that occurred on Tuesday-Thursday, during weeks 2–24 and 33–51, and were shorter than 14 days in duration. The weekdays were chosen so that a working day typically would occur both before and after the registration of sick leave, to 1) have a record of the first sick leave day (since the individual reporting a sick day on Monday may have been ill already Saturday or Sunday) and 2) limit the possible difference in incentive for an individual to take a sick leave episode or not (e.g. individuals may work Friday even though they feel ill since they can thereafter rest during the weekend). Weeks 1, 25–32 and 52 with holidays (e.g., Christmas, New Year's Eve) and vacation periods in Sweden were eliminated. Sick leave episodes lasting longer than 14 days were excluded, since less than 10% of annual sick leave episodes last more than 14 days and there might be other reasons for this not related to short-term air pollution exposure, e.g. workplace accidents, traffic accidents, chronic diseases etc. Please, see Fig. 1 for the number of individual sick leave episodes excluded due to selection criteria. For this study, we restricted the analysis to the population living in the City of Stockholm (from here on out referred to as Stockholm), with an average population of 922,263 residents for the period 2011–2019 (Statistics Sweden, 2019b), out of which 463,100 had active employment based on the Statistics Sweden annual Labor Force Survey (Statistics Sweden: Labor Force Survey).

2.3. Statistical methods

A case-crossover design was applied to estimate the short-term air pollution effect on sick leave. In the case-crossover design, individuals act as their own controls and thereby control for individual time-invariant confounders (Lumley and Levy, 2000). For each onset date (cases) we selected two time periods from the week before and after, matched by weekday, to describe usual exposure. This is a preferred

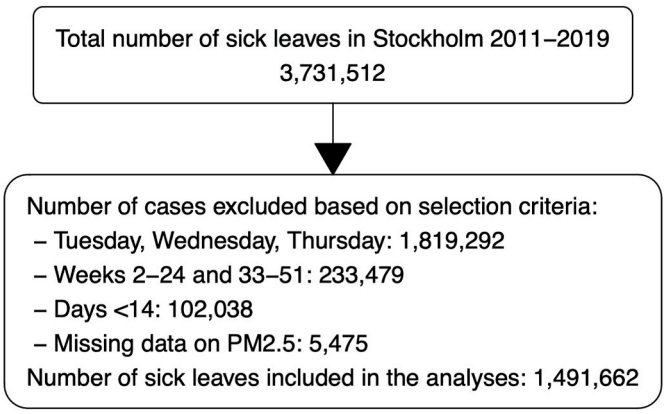

Fig. 1. Total number of cases of sick leave episodes in Stockholm and number of episodes included in the main model after applying the selection criteria.

method in air pollution exposure studies to control for time trends in exposure (Navidi, 1998). This approach has in a previous simulation study demonstrated to be the design of choice to minimize the bias that might occur due to short-term autocorrelation in exposure among case and control period (Lumley and Levy, 2000). To identify the exposure time-window of importance, associations were assessed in relation to exposure the day before (lag 1), an average of 2–4 days (lag 2–4) and an average of 5–7 days (lag 5–7) before the sick-leave. A conditional logistic regression was used to estimate the % increase of odds of sick leave onset per 10 μg/m^3 $PM_{2.5}$. The model was further adjusted for temperature, season, and pollen. Temperature was assumed to have non-linear relationship and divided into quintiles and interaction with season (categorized as: December–February, March-Maj, June–August, September–November). Pollen is an allergen that causes allergic symptoms and have been shown to correlate with $PM_{2.5}$ concentrations and to increase allergy symptom prevalence's (e.g. dry cough, rhinitis or eye irritation) among people with asthma and confirmed birch allergy (Carlsen et al., 2022), which in turns might increase the risk for a sick leave episode. We fitted a penalized spline model with 7 degrees of freedom to assess the shape of the $PM_{2.5}$ concentration-response for the unadjusted model. Subgroup analyses were performed, stratifying by gender, age, employment in public or private sector, and duration of sick leave episode (1–2 days, 2–7 days, and 8–14 days). Additionally, interaction analysis was performed to assess if the exposure effect varies by gender, age, employment in public or private sector and duration of sick leave episode.

2.4. Economic valuation

To estimate the monetary value of production loss attributable to $PM_{2.5}$ exposure in Stockholm, we applied the human capital method. The human capital method is commonly applied in labor economics to value productivity losses. In the human capital method, the market value of wages is used to value the time units (days) of sick leave. This means that the days of sick leave are valued equally with the employer's willingness-to-pay for time unit at work (Svensson, 2019; Olofsson and Hjalte, 2020; Drummond et al., 2015). The average gross salary in 2019 in Sweden was SEK 35,300 and the average amount of workdays per month was 21 (Statistics Swedenb). The social security contributions paid by the employer beyond the gross salary per employee consists of two parts in Sweden. Firstly, employers are legally bound to pay a social tax to the state that is 31.41% of the gross salary and consists of insurance fees (e.g., health, parental leave), pension fees, and labor market fees. Secondly, the employer pays additional social security contributions per employee that the labor unions have negotiated every year (e.g., service pensions and agreement insurance fees). This however varies between the so called blue-collar and white-collar working groups, e.g., in 2019 the average social tax for was 37.2% and 51.2%, respectively (Statistics Swedenc). Therefore, based on the proportions of blue-collar (48%) and white-collar workers (52%) in Sweden in 2019 (Larsson, 2020), we calculated the weighted-average monthly salary for the employer's total willingness-to-pay to be SEK 50,500 for an average employee and accordingly that one working day corresponds to ≈ SEK 2, 400. All monetary values are reported in SEK_{2019} and $Euro_{2019}$ values to ease international comparison. One euro corresponded on average to SEK 10.59 in 2019 (European Central Bank (ECB) euro reference exchagne rate: Swedish krona (SEK)). To estimate the average number of sick leaves days attributable to $PM_{2.5}$ exposure, we first calculate the average annual number of sick leave episodes. Secondly, the odds ratio estimated by this study was utilized as a rate ratio, since the study design uses incidence density sampling. We calculate the attributable number of sick leave episodes in relation to annual average $PM_{2.5}$ exposure in Stockholm. Using the annual mean $PM_{2.5}$ is a common method applied in health impact assessments of air pollution also for short-term effects (World Health Organization (WHO), 2013). Additionally, we calculate the number of sick leave episodes in relation to 1 μg/m^3 $PM_{2.5}$ exposure to demonstrate the possible effects of reducing the $PM_{2.5}$ exposure. The number of sick leave episodes were thereafter multiplied with the average number of days spent on sick leave, which was in turns multiplied with the employer's average willingness-to-pay per working day to estimate the monetary burden attributable $PM_{2.5}$ exposure. We also calculate the productivity loss per employee, by dividing the estimated monetary burden of sick leave episodes attributable to $PM_{2.5}$ exposure with the number of employees in Stockholm (463,100) reported by Statistics Sweden (Statistics Sweden: Labor Force Survey).

2.5. Ethical consideration

This study was approved by Swedish Ethical Review Authority (2020–00578).

3. Results

The daily median and mean urban background concentration of $PM_{2.5}$ in Stockholm was 4.2 and 5.1 μg/m^3 respectively. The measured 24-h concentrations of $PM_{2.5}$ varied between −0.77 and 35 with an interquartile range (IQR) of 3.7 μg/m^3, with and 5% and 2% days exceeding 11.35 and 15.33 μg/m^3.

In total, there were 3.7 million sick leave episodes in Stockholm registered during the study period, of which 32% of cases remained in the main model after applying the selection criteria (Fig. 1). Sick leave

Table 1
Descriptive statistics of the sick leave episodes included in the analysis.

Stratification	Total	Proportion (%)
Sex		
Females	960,540	64%
Males	531,122	36%
Age		
15–24	150,941	10%
25–34	487,636	33%
35–44	332,137	22%
45–54	280,833	19%
55–64	220,376	15%
65–74	19,660	1%
Sector		
Private	823,999	55%
Public	651,536	44%
Sick-leave duration (days)		
1–2	800,005	54%
3–7	604,154	41%
8–14	87,481	6%
Total number of sick leave episodes included in the analysis	1,491,662	

episodes were almost twice as common among women compared to men (Table 1). The largest proportion (33%) of sick leave episodes were among 25-34-year old's and thereafter, a decreasing trend of sick leave episodes was observed with increasing age. The great majority of sick leave episodes lasted up to a week, of which 54% where 1–2 days in duration and additional 41% lasted up to a week.

The odds of sick leave episodes was estimated to increase by 7% (95% CI: 7–8%) per 10 μg/m^3 higher $PM_{2.5}$ exposure for lag 2–4 (Table 2). The concentration-response function fitted with a smooth function did however show similar odds of sick leave episodes on days with $PM_{2.5}$ between approximately 4 and 7 μg/m^3, suggesting increases in odds only on days with lower or higher $PM_{2.5}$ concentrations (Fig. 2). Adjusting for pollen, temperature and its interaction with season, the odds for a sick leave episode was estimated to increase by 8.5% (95% 7.8–9.3%) per 10 μg/m^3 higher $PM_{2.5}$ exposure (Table 2). No dose-response relationship was found in relation to $PM_{2.5}$ exposure for lag 1 and lag 5–7.

A slightly higher odds of sick leave episodes were estimated for men compared to women, 8% and 7% per 10 μg/m3 respectively, in the unadjusted model. After adjusting for potential confounders, the odds for a sick leave episode were 9 and 8% for men and women respectively, but this difference was not statistically significant (Table 2). Public sector employees had higher increased odds of sick leave episodes compared to private sector, 9% and 6% per 10 μg/m^3 in the unadjusted model, respectively. Also, after adjustment, this difference between sectors remained and was statistically significant. The odds of sick leave episodes in relation to $PM_{2.5}$ exposure also differed between different age groups, where in both the unadjusted and adjusted model lower odds were seen in the youngest age group. Considering the duration of sick leave episodes, a lower increase in odds was estimated in relation to sick leave episodes lasting more than seven days; 4 and 5% increase per 10 μg/m^3 higher $PM_{2.5}$ exposure in the unadjusted and adjusted model, respectively.

Table 2
Odds ratios for onset of a sick leave episode per 10 μg/m^3 increase in average $PM_{2.5}$ 2–4 days prior to the outcome for unadjusted and adjusted models, with interaction effects in the adjusted model.

	Unadjusted[a]	Adjusted[b]	Interaction[b]
	OR 95% CI	OR 95% CI	OR 95% CI
All	1.074 (1.069–1.081)	1.085 (1.078–1.093)	
Men	1.078 (1.068–1.089)	1.089 (1.074–1.092)	1
Women	1.072 (1.064–1.080)	1.083 (1.074–1.092)	0.99 (0.98–1.00)
Privat sector	1.064 (1.055–1.072)	1.073 (1.064–1.083)	1
Public sector	1.088 (1.078–1.097)	1.10 (1.089–1.11)	1.02 (1.011–1.038)
Age			
15-24	1.047 (1.027–1.067)	1.048 (1.026–1.07)	1
25-34	1.075 (1.064–1.086)	1.091 (1.079–1.104)	1.041 (1.017–1.066)
35-44	1.086 (1.073–1.100)	1.10 (1.085–1.12)	1.049 (1.024–1.076)
45-54	1.077 (1.063–1.092)	1.083 (1.067–1.10)	1.034 (1.008–1.061)
55-64	1.068 (1.052–1.084)	1.074 (1.056–1.093)	1.025 (1.00–1.053)
65-74	1.092 (1.037–1.149)	1.119 (1.055–1.186)	1.067 (1.003–1.135)
Duration (days)			
1-2	1.074 (1.066–1.083)	1.083 (1.073–1.093)	1
3-7	1.079 (1.069–1.089)	1.092 (1.081–1.103)	1.008 (0.99–1.02)
8-14	1.04 (1.016–1.065)	1.053 (1.025–1.081)	0.97 (0.945–1.00)

[a] Unadjusted – OR per 10 μg/m^3 increase in average $PM_{2.5}$ 2–4 days prior to the outcome.

[b] Adjusted – OR per 10 μg/m^3 increase in average $PM_{2.5}$ 2–4 days prior to the outcome adjusted for pollen, temperature, and season.

3.1. Economic valuation

On average, there were 466,439 sick leave episodes registered annually in Stockholm with an average duration of 4.0 days. Utilizing the estimate of 8.5% increased odds (as rate ratio) per 10 μg/m^3 for lag 2–4 exposure and no threshold, we calculate that 17,998 sick leave episodes were attributable to the annual average $PM_{2.5}$ exposure in Stockholm. This corresponds to a monetary value of SEK 183 million (M) (€17 M) in production losses annually. Per employee the average monetary loss corresponds to SEK 396 (€37) for the mean $PM_{2.5}$ concentration in Stockholm. If the annual average $PM_{2.5}$ exposure were to be lowered by 1 μg/m^3 in Stockholm, we estimate the number of incident cases of sick leave episodes avoided to be 3790 (15,159 sick leave days), corresponding to SEK 36M (€ 3M).

4. Discussion

This is the first assessment using population register data on sick leave episodes and measurements of $PM_{2.5}$. The odds of sick leave episodes increased by 8.5% per 10 μg/m^3 higher $PM_{2.5}$ concentration for lag 2–4. Utilizing the estimated risk increase, 4% of annual sick leave episodes in Stockholm were attributable to $PM_{2.5}$ exposure, which was estimated to corresponded to €17M in productivity loss.

Currently the health and economic assessments of air pollution are guided by recommendations from the WHO HRAPIE project. Based on the results by Ostro et al. (1987) (Ostro, 1987), the HRAPIE project recommends implementing a meta-estimate of 4.6% (95% CI: 3.9–5.3%) increased WLDs per 10 μg/m^3 increase in annual average $PM_{2.5}$. There was however considerable heterogeneity between calendar years in this meta-analysis. The observed heterogeneity could be due to the exposure data being based on airport visibility measurements and that the outcome was based on questionnaires about previous WLDs in the last 14-days, and only included a sample of a population. In this study the exposure was retrieved from a measurement station, which can detect low levels and has been shown to have good reliability according to the quality assessment conducted by the Stockholm's Environmental Administration (Hurkmans et al., 2022). The $PM_{2.5}$ concentration was reported to be negative a few days, which could happen with TEOM instruments at very low levels if particles at the filter loses volatile substances. Additionally, in this study, population-based register data was available for individual sick leave episodes for nine consecutive years.

Utilizing the risk increase from this study with WHO HRAPIE recommendation to calculate the $PM_{2.5}$ attributable sick leave days in Stockholm City, shows that the health economic assessments possibly underestimate the $PM_{2.5}$ attributable productivity loss by a factor of two. This has important implications for example within the Swedish Transport Agency (STA) assessment of total socioeconomic costs attributable to air pollution which are used as basis of decision making in transport policy (Forsberg et al., 2022). STA currently applies the WHO recommendations and estimates that the proportion of WLDs corresponds to 1% of the total monetary value attributable to $PM_{2.5}$ exposure including both premature mortality and morbidity outcomes. This would increase to 2% when applying the odds ratio estimated by this study.

The WHO has highlighted key questions for the revision of EU Air Quality to consider the strength of evidence for setting a limit value for shorter time periods in addition to a threshold averaged over a year (World Health Organization, 2021 Europe: Key questions for guidance of EU policies: the REVIHAAP and HRAPIE projectes). The revised WHO AQG found sufficient evidence to set a daily limit value for $PM_{2.5}$

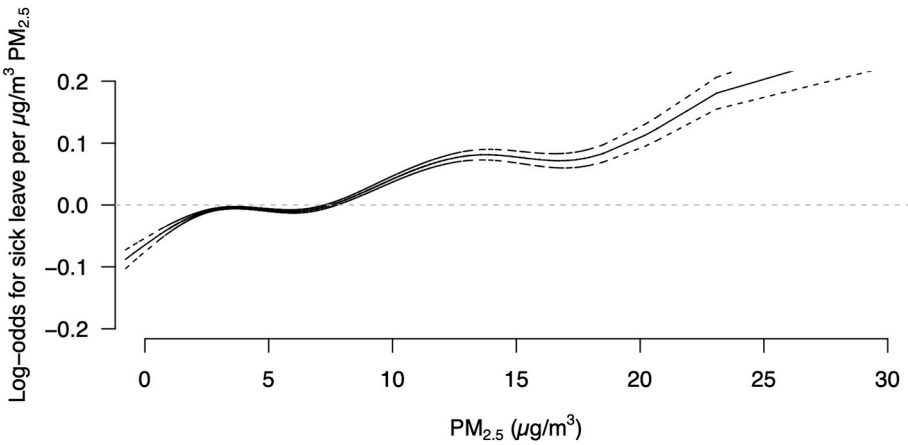

Fig. 2. The estimated concentration-response relation between $PM_{2.5}$ and log-odds of sick leave episodes in Stockholm, using a penalized spline with 7 degrees of freedom. The dashed lines represent the 95% CI.

exposure to 15 μg/m^3 with the specification that daily exceedance of this limit value should not occur more than 3–4 times per year (World Health Organization, 2021). Although the average annual levels at this monitoring station were below the WHO AQG annual limit value, the 24-h $PM_{2.5}$ measurements exceeded the short-term limit value of 15 μg/m^3 on average ten times annually during this study period. If all days that exceeded 10 μg/m^3 would be equal with 10 μg/m^3, then a 6% decrease in sick leave episodes could be achieved. The Swedish Environmental Protection Agency (EPA) quantified the population exposure to $PM_{2.5}$ with dispersion modelling and concluded that 82% of the population was exposed to higher annual average $PM_{2.5}$ concentrations than the 5 μg/m^3 limit recommended by WHO AQG (Gustafsson et al., 2022). This study provides supportive evidence that daily limit values of $PM_{2.5}$ exposure are motivated from an urban population health perspective.

Public sector employees had higher odds of sick leave in relation to $PM_{2.5}$ exposure, compared to those in the private sector. Previous studies on sick leave (>14 days) with diagnosis data from Social Security register in Sweden found increased risk for SA due to common mental disorders among public sector employees (Björkenstam et al., 2022). Björkenstam et al., 2022 also observed higher morbidity among public sector employees (Björkenstam et al., 2022). Moreover, a higher rate of sick leave episodes have been observed among health and social welfare workers (Aagestad et al., 2016), who are largely employed by the public sector in Sweden. Private sector employees have been found to have lower risk for sick leave compared to the general population (Farrants and Alexanderson, 2021). Possible explanations for increased morbidity and sick leave have previously been discussed to be differences in the work characteristics and distribution of socioeconomic status between the sectors (e.g., education level and income). Due to the higher prevalence of morbidity among public sector employees, these employees may constitute a group sensitive to air pollution exposure. However, we have not compared the differences in exposure between socioeconomic groups. A previous study in Stockholm by Olsson et al. (2020) demonstrated that families with higher income and education level were exposed to a higher concentration of exhaust particles, compared with individuals with lower income and education (Olsson et al., 2020).

A short-term air pollution effect on sick leave episodes probably includes an effect among already vulnerable individuals. In a systematic review, a meta-estimate of 2.5% increase in COPD emergency department (ED) visits and HAs per 10 μg/m^3 increase in $PM_{2.5}$ exposure was reported (DeVries et al., 2017). A stronger relationship was estimated with multi-day average $PM_{2.5}$ exposure compared to single day exposure (DeVries et al., 2017). A few days' delay in effect could be explained by a delay in the lung function itself but could also be postponed by self-medication. One report estimated a 4.4% and 1.9% increased risk of ED visits in relation to 10 μg/m^3 PM_{10} exposure for asthma and other respiratory diseases, respectively, among the adult population in Sweden (Tornevi and Forsberg, 2019). Besides the air pollution effects on respiratory morbidity, an increase in psychiatric ED visits of 3.6% per 10 μg/m^3 PM_{10} exposure the same day has been estimated in Sweden (Oudin et al., 2018). In a report by Holub et al. (2020), a stronger association between PM_{10} exposure and sick leave episodes was found with psychiatric causes such as dementia and depression (Holub et al., 2020). The effect of air pollution on WLDs was also higher in the study by Ostro et al. (1987) among individuals with chronic diseases (Ostro, 1987). Unfortunately, we did not have data on individual health status and therefore were not able to stratify according to the presence of chronic disease or cause specific sick leave.

Previous studies on short-term effects of $PM_{2.5}$ exposure on viral respiratory disease showed effects on influenza (Feng et al., 2016) and SARS-COVID-19 (Domingo and Rovira, 2020). The typical duration of mild influenza symptoms is 3–7 days, although a persistent cough can last up to two weeks (Centers for Disease Control and Prevention NCfIaRDN: Clinical Signs and Symptoms of Influenza). Even though we did not have the diagnoses of the sick leave episodes, the stratified analysis on duration showed higher increased odds of sick leave episodes lasting 1–7 days. Therefore, it is theoretically plausible to assume that some of the sick leave episodes lasting 1–7 days could be due to influenza or another respiratory virus. This provides some supportive evidence that $PM_{2.5}$ can potentially act as a modifier for viruses causing respiratory disease. However, more research is needed on the air pollution effect for different sick leave causes.

4.1. Strengths

The strength of this study are the large registry dataset on individual sick leave episodes over a long period of time. Almost 1.5 million sick leave episodes were analysed, resulting in high statistical power. Applying a case-crossover study design excludes confounding by individual level risk factors, such as lifestyle or geographical differences. Adjustment was made for confounding by temperature and pollen that may covary with $PM_{2.5}$ daily measurements. Therefore, this study results suggest that $PM_{2.5}$ has an independent effect on the adult working population through increased sick leave episodes.

4.2. Limitation

Firstly, the exposure data was based on one fixed-site monitoring station, introducing a risk of misclassification of exposure at the individual level (outdoor vs indoor, variation in individual mobility levels, etc.) leading to an underestimation of the air pollution associated risk (Weisskopf and Webster, 2017). A modelling study by Evangelopoulos

et al. (2021) quantified the possible short-term exposure measurement error effect on mortality estimates and concluded that the measurement error contributes to underestimating the true health effects (Evangelopoulos et al., 2021). However, if control days systematically had lower $PM_{2.5}$ exposure compared to the previous day of first day of sick leave, this would cause a positive bias. This could for instance occur in relation to summer and winter holiday's that affect both $PM_{2.5}$ concentration levels and sick leave episodes. The study was, however, designed to exclude these time periods of the year.

Secondly, the exposure effect on sick leave episodes was assessed for a time-period of up to 7 days. There might be a longer built-up time of the cumulative air pollution effect on sick leave episodes. However, no association was seen with exposure beyond four days. This is also the first study on sick leave episodes that investigates the importance of exposure in different time-windows.

Thirdly, even though we had detailed individual data on sick leave episodes, we did not have information on the cause or diagnoses for a sick leave episode. In Sweden, there is a high level of trust between employees and employers in general. The employee has extensive personal responsibility and based on the legal system; the employee can take a sick leave for up to seven consecutive days without a doctor's certificate. However, after seven days, a primary care physician certificate with a diagnosis is needed. Diagnoses set at the primary care level are, however, never shared with the sick leave register holder Statistics Sweden.

Fourthly. The calculation of attributable cases was based on the OR for sick leave episodes for only a selection of weekdays. This selection of weekday was necessary to 1) only analyse the first day of sick leave (i.e. exclude Saturday-Monday) and 2) not including Friday that otherwise may have caused a bias by for instance economic incentives (by to a greater extent not reporting ill). Applying this OR to all sick leave episodes thereby assumes that sick leave episodes starting on Friday-Monday do not differ from those starting Tuesday-Thursday.

Fiftly, we used a human capital approach to value the productivity losses of sick leave, which takes the societal perspective and is a recommended method in health economics (Olofsson and Hjalte, 2020; Drummond et al., 2015; Zhang et al., 2011). Although, since half of the sick leave episodes analysed were 1–2 days in duration and the first day of sick leave is not compensated by the employer an overestimation of productivity losses from the employer perspective would occur. The employer might not lose the productivity totally, due to a rearrangement of tasks between employees at work or utilization of additional staff. This extra personnel is associated with higher costs for the employer and therefore a friction cost approach to account for extra costs is recommended. Applying this method usually results in lower estimates of productivity losses from the employer perspective. However, when applying a societal perspective, it is recommended by Drummond et al. (2015) to also account for losses related to ill-health outside work, such as unpaid work and leisure activities missed (Drummond et al., 2015). Regulation of air pollution levels lies under state jurisdiction and minimizing the adverse effects of air pollutants has significant impacts on welfare for both the employers and employees, which justifies the choice of the societal perspective. Therefore, it is more likely that this study underestimates the monetary value of air-pollution-attributable productivity losses since missed leisure activities and unpaid work have not been included.

5. Conclusion

This is the first study to show an association between short-term $PM_{2.5}$ and sick leave episodes in a low exposure area using objective register data. The effect estimate of this study suggests that current health impacts and economic assessments underestimate the short-term air pollution effects on adult working population.

Declarations

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CRediT authorship contribution statement

Hedi Katre Kriit: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing - original draft, Writing - review & editing. **Bertil Forsberg:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing. **Johan Nilsson Sommar:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

References

Aagestad, C., Tyssen, R., Sterud, T., 2016. Do work-related factors contribute to differences in doctor-certified sick leave? A prospective study comparing women in health and social occupations with women in the general working population. BMC Publ. Health 16 (1), 235.

Atkinson, R.W., Kang, S., Anderson, H.R., Mills, I.C., Walton, H.A., 2014. Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: a systematic review and meta-analysis. Thorax 69 (7), 660–665.

Björkenstam, E., Helgesson, M., Gustafsson, K., et al., 2022. Sickness absence due to common mental disorders in young employees in Sweden: are there differences in occupational class and employment sector? Soc Psychiatry Psychiatr Epidemiol 57, 1097–1106.

Borro, M., Di Girolamo, P., Gentile, G., De Luca, O., Preissner, R., Marcolongo, A., Ferracuti, S., Simmaco, M., 2020. Evidence-based considerations exploring relations between SARS-CoV-2 pandemic and air pollution: involvement of PM2.5-mediated up-regulation of the viral receptor ACE-2. Int. J. Environ. Res. Publ. Health 17 (15).

Carlsen, H.K., Haga, S.L., Olsson, D., Behndig, A.F., Modig, L., Meister, K., Forsberg, B., Olin, A.C., 2022. Birch pollen, air pollution and their interactive effects on airway symptoms and peak expiratory flow in allergic asthma during pollen season - a panel study in Northern and Southern Sweden. Environ. Health 21 (1), 63.

Centers for Disease Control and Prevention NCfIaRDN: Clinical Signs and Symptoms of Influenza [https://www.cdc.gov/flu/professionals/acip/clinical.htm#anchor_1552063059446].

DeVries, R., Kriebel, D., Sama, S., 2017. Outdoor air pollution and COPD-related emergency department visits, hospital admissions, and mortality: a meta-analysis. COPD 14 (1), 113–121.

Domingo, J.L., Rovira, J., 2020. Effects of air pollutants on the transmission and severity of respiratory viral infections. Environ. Res. 187, 109650.

Drummond, M.F., 2015. In: Drummond, Michael F., Sculpher, Mark J., Claxton, Karl, Stoddart, Greg, Torrance, George W. (Eds.), Methods for the Economic Evaluation of Health Care Programmes, fourth ed. Oxford University Press, Oxford: Oxford.

Environmental Protection Agency (EPA), 2019. In: US: Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2019). U.S. Environmental Protection Agency, Washington, DC. EPA/600/R-19/188.

European Central Bank (ECB) euro reference exchagne rate: Swedish krona (SEK) [https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-sek.en.html].

Evangelopoulos, D., Katsouyanni, K., Schwartz, J., Walton, H., 2021. Quantifying the short-term effects of air pollution on health in the presence of exposure measurement error: a simulation study of multi-pollutant model results. Environ. Health 20 (1), 94, 94.

Farrants, K., Alexanderson, K., 2021. Sickness absence among privately employed white-collar workers: a total population study in Sweden. Scand. J. Publ. Health 49 (2), 159–167.

Feng, C., Li, J., Sun, W., Zhang, Y., Wang, Q., 2016. Impact of ambient fine particulate matter (PM2.5) exposure on the risk of influenza-like-illness: a time-series analysis in Beijing, China. Environ. Health 15, 17.
Forsberg, B., Löwenhem, B., Sommar, J.N., Kriit, H., Strömgren, M., Johansson, C., 2022. Bättre metoder att beskriva hälsovinster av minskad exponering för luftföroreningar från vägtrafik. In: Trafikverkets Publikationer. Borlänge: Trafikverket, p. 45.
Gustafsson, M., Linden, J., Forsberg, B., Åström, S., 2022. Quantification of population expousre to NO2, PM10 and PM2.5 and estimated health impacts 2019. In: IVL Swedish Environmental Research Institute.
Hansen, A.C., Selte, H.K., 1997. Air pollution and sick-leaves - is there a connection? A case study using air pollution data from Oslo. In: Statistics Norway. Research Department.
Heroux, M.E., Anderson, H.R., Atkinson, R., Brunekreef, B., Cohen, A., Forastiere, F., Hurley, F., Katsouyanni, K., Krewski, D., Krzyzanowski, M., et al., 2015. Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe project. Int. J. Publ. Health 60 (5), 619–627.
Holub, F., Hospido, L., Wagner, J.U., 2020. Urban Air Pollution and Sick Leaves: Evidence from Social Security Data.
Hurkmans, J., Säll, B., Brudolf, M., Elmgren, M., 2022. Kvalitetssärkingsprogram för mätningar och modellberäkningar av luftföroreningar in. In: Stockholms Luft- Och Bulleranalys Stockholms Luft- Och Bulleranalys.
Larsson, M., 2020. Lönerapport. Löner och löneutveckling år 1913-2019 efter klass och kön. In: Landsorganisationen I Sverige.
Lumley, T., Levy, D., 2000. Bias in the case - crossover design: implications for studies of air pollution. Environmetrics 11 (6), 689–704.
Navidi, W., 1998. Bidirectional case-crossover designs for exposures with time trends. Biometrics 54 (2), 596–605.
Olofsson, S., Hjalte, F., 2020. Produktionsboortfall - en metodologisk genomgång och beräkningar In, vol. 4. Institutet för Hälso- och Sjukvårdsekonomi (IHE), p. 4.
Olsson, D., Johansson, C., Forsberg, B., 2020. Associations between vehicle exhaust particles and ozone at home address and birth weight. Int. J. Environ. Res. Publ. Health 17 (11).
Olstrup, H., Johansson, C., Forsberg, B., Tornevi, A., Ekebom, A., Meister, K., 2019. A multi-pollutant air quality health index (AQHI) based on short-term respiratory effects in Stockholm, Sweden. Int. J. Environ. Res. Publ. Health 16 (1).
Ostro, B.D., 1987. Air pollution and morbidity revisited: a specification test. J. Environ. Econ. Manag. 14 (1), 87–98.
Oudin, A., Åström, D.O., Asplund, P., Steingrimsson, S., Szabo, Z., Carlsen, H.K., 2018. The association between daily concentrations of air pollution and visits to a psychiatric emergency unit: a case-crossover study. Environ. Health 17 (1), 4.
Statistics Sweden, 2019a. Oförändrad Antal Sjukdagar Andra Kvartal. https://www.scb.se/hitta-statistik/statistik-efter-amne/arbetsmarknad/sjukloner/konjunkturstatistik-over-sjukloner-ksju/pong/statistiknyhet/konjunkturstatistik-over-sjukloner-2a-kvartalet-2019/.
Statistics Sweden, 2019b. Folkmängd efter region, ålder, kön och år. In: Statistics Sweden. SCB). https://www.scb.se/hitta-statistik/statistik-efter-amne/befolkning/befolkningens-sammansattning/befolkningsstatistik/.
Statistics Sweden: Labor Force Survey: [https://www.scb.se/hitta-statistik/statistik-efter-amne/arbetsmarknad/arbetskraftsundersokningar/arbetskraftsundersokningarna-aku/].
Statistics Sweden. Konjunkturstatistik över sjuklöner (KSju). https://www.scb.se/hitta-statistik/statistik-efter-amne/arbetsmarknad/sjukloner/konjunkturstatistik-over-sjukloner-ksju/.
Statistics Sweden: Genomsnittlig månadslön, kronor efter sektor, Yrke (SSYK 2012), kön, utbildningsnivå och år [http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__AM__AM0110__AM0110A/LonYrkeUtbildning4A/].
Statistics Sweden: **Sociala avgifter över tid** [https://www.ekonomifakta.se/Fakta/Skatter/Skatt-pa-arbete/Sociala-avgifter-over-tid/].
Svensson, M., 2019. Hälsoekonomisk Utvärdering: Metod Och Tillämpningar. Studentlitteratur AB, Lund.
Tornevi, A., Forsberg, B., 2019. Luftföroreningars effekt på akutbesök för andningsorganen och uttag av astmamedicin. In: *Folkhälsa Och Klinisk Medicin I Umeå Rapporterar*. Umeå: Umeå Universitet, Institutionen För Folkhälsa Och Klinisk Medicin. Avdelningen för hållbar hälsa, p. 34.
Weisskopf, M.G., Webster, T.F., 2017. Trade-offs of personal versus more proxy exposure measures in environmental epidemiology. Epidemiology 28 (5), 635–643.
Willers, S.M., Eriksson, C., Gidhagen, L., Nilsson, M.E., Pershagen, G., Bellander, T., 2013. Fine and coarse particulate air pollution in relation to respiratory health in Sweden. Eur. Respir. J. 42 (4), 924–934.
World Health Organization, 2021. WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. World Health Organization, Geneva.
World Health Organization: Europe: Key questions for guidance of EU policies: the REVIHAAP and HRAPIE projectes [https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/health-aspects-of-air-pollution-and-review-of-eu-policies-the-revihaap-and-hrapie-projects/key-questions-for-guidance-of-eu-policies].
World Health Organization (WHO), 2013. Health Risks of Air Pollution in Europe – HRAPIE Project: Recommendations for Concentration–Response Functions for Cost–Benefit Analysis of Particulate Matter, Ozone and Nitrogen Dioxide. World Health Organization, Geneva.
Zhang, W., Bansback, N., Anis, A.H., 2011. Measuring and valuing productivity loss due to poor health: a critical review. Soc. Sci. Med. 72 (2), 185–192, 1982.