HEC Montréal

Disparités socioéconomiques de la mortalité liée à la pollution de l'air au Canada
Socioeconomic disparities of mortality related to air pollution: evidence from Canada

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Résumé

Cette recherche étudie les disparités du risque de mortalité associée à la pollution atmosphérique entre différents groupes socio-économiques à l'échelle nationale canadienne de 2011 à 2016. On utilise le modèle de risque proportionnel de Cox basé sur des données de panel au niveau individuel pour estimer l'impact des ratios de risque de la mortalité en relation avec l'exposition à la pollution de l'air ambiant (NO_2, O_3, SO_2 et $PM_{2.5}$). Ensuite, on explore comment ces ratios varient selon les quantiles de revenu, le niveau d'éducation, la catégorie d'emploi, l'ethnicité et le sexe. Nos principaux résultats montrent une association significative et positive entre les concentrations de pollution de NO_2, O_3, SO_2 et $PM_{2.5}$ et la mortalité non accidentelle. Ensuite, nous observons des disparités en santé en fonction du statut socio-économique, de l'origine ethnique et du sexe. Les individus se situant dans les quantiles de revenu et les niveaux d'éducation plus bas ont des risques plus élevés de mortalité liée au NO_2 et au O_3 mais sont en moyenne moins exposés à ces gaz. Les individus d'origine de l'Amérique latine et de l'Asie présentent des risques plus élevés de mortalité liés au NO_2 et au SO_2, et les Afro-Canadiens sont touchés de façon disproportionnée par le SO_2 par rapport aux Caucasiens. En ce qui concerne l'analyse par sexe, les hommes ont des risques plus élevés de mortalité liée aux polluants NO_2 et SO_2, et les femmes aux $PM_{2.5}$. Cette recherche met en évidence les groupes d'individus plus sensibles à la pollution atmosphérique et contribue à la compréhension des inégalités de santé existantes au Canada.

Mots clés : Disparités socioéconomiques, pollution de l'air, inégalité de santé, mortalité, économie environnementale

Méthodes de recherche: Recherche longitudinale, Économétrie, modèle proportionnel du risque de Cox

Abstract

This research paper studies disparities of mortality risk among different socioeconomic groups associated with air pollution in Canada at the national scale from 2011 to 2016. We use the Cox Proportional Hazard model based on panel data with individual-level data to estimate the impact of the mortality hazard ratios in relation with exposure to ambient air pollution (NO_2, O_3, SO_2 and $PM_{2.5}$) and explore how it varies according to the quantiles of income, the level of educational achievement, the category of labour occupation, ethnicity, and gender. As main results, we find significant and positive association between outdoor NO_2, O_3, SO_2 and $PM_{2.5}$ concentrations and non accidental mortality. Moreover, we observe disparities in health based on socioeconomic status, ethnicity, and gender. Individuals in the lowest quantiles of income as well as those with the lowest levels of education have higher risks of mortality related to NO_2 and O_3, while being less exposed to those gases. Individuals originally from Latin America and Asia, have higher risks of mortality related to NO_2 and SO_2 and Afro-Canadians, are disproportionately impacted by SO_2 compared to Caucasians. Regarding gender analysis, males have a higher risk of mortality related to NO_2 and SO_2 pollutants, and females related to $PM_{2.5}$. This research showcases the groups of individuals with higher sensitivity to air pollution and contributes to the understanding of the existing health inequalities in Canada.

Keywords : Socioeconomic Disparities, Air Pollution, Health Inequalities, Mortality, Environmental Economics

Research methods: Longitudinal research, Econometrics, Cox Proportional Hazard Model

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Liste des abréviations

CanCHEC Canadian Census Health and Environment Cohorts
CANUE Canadian Urban Environmental Health Research Consortium
CAPE Canadian Association of Physicians for the Environment
CICC Canadian Climate Institute
CMDI Canadian Material Deprivation Index
CO Carbon monoxide
HDI Human Development Index
HR Hazard Ratios
ICD International Classification of Diseases
LIM-MI Low-Income Measure of Market Income
SEC Socioeconomic Status
PPB parts per billions
PM Particulate Matter
SO2 Sulphur Dioxide
NO2 Nitrogen Dioxide
O3 Ozone
WHO World Health Organization
µg/m^3 micrograms (one-millionth of a gram) per cubic meter of air

Avant-propos

La question des risques environnementaux est préoccupante pour l'ensemble des êtres vivants, car nous y somment tous exposés d'une manière ou d'une autre. Toutefois, cela n'empêche pas que les répercussions soient distribuées de manière inégale entre les individus et que les inégalités en santé liées à l'environnement continuent à se creuser. Pour un avenir sain, on se doit de comprendre les causes de ces inégalités et d'apporter un support aux individus les plus touchés. Dans cette recherche, on se penche sur des aspects nouveaux en mettant l'accent sur le rapport entre la santé et l'environnement ainsi que le rôle socioéconomique des inégalités environnementales. La notion des inégalités environnementales exprime que certains individus et sous-groupes de la population ne sont ni égaux dans l'exposition aux nuisances environnementales, ni dans leurs capacités de résilience face aux risques environnementaux, qui s'expliquent potentiellement par des facteurs sociaux et économiques. L'objectif de cette recherche est d'explorer les différentes dimensions de sensibilités et de vulnérabilités sur la mortalité face aux risques environnementaux causés par la pollution atmosphérique auprès de la population canadienne afin de mettre en lumière où nous devons miser nos ressources.

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Introduction générale

Traduction litterale de l'introduction en version anglaise, afin de satisfaire aux exigences de la M.Sc. Pour la correction du memoire, se referer a 1.1 Introduction.

En 2021, la revue The Lancet a publié une nouvelle étude sur la santé et la pollution de l'air ambiant, indiquant une menace pour un avenir sain (Romanello et al 2021). Leur rapport indique que malgré l'augmentation des énergies renouvelables, la libération perpétuelle de polluants dans l'air ambiant se poursuit et ce n'est pas sans conséquence. Le rapport The Lancet fournit une évaluation du système énergétique mondial au rythme de l'association de l'exposition mondiale à la pollution de l'air ambiant des particules fines ($PM_2, 5$) et de ses effets sur la santé. En 2019, 4 millions de décès étaient attribuables à l'exposition de ce polluant. Les pays à indice de développement humain (IDH) très élevé, comme le Canada, présentaient un taux de mortalité lié à la pollution atmosphérique plus faible (40 décès pour 100 000 habitants) par rapport aux pays à IDH moyen et élevé. Toutefois, la préoccupation pour les questions d'inégalité demeure, les personnes défavorisées sur le plan socio-économique supportent potentiellement de manière disproportionnée la charge des effets sanitaires de l'exposition à la pollution atmosphérique. De fait, certains groupes de la population peuvent être plus vulnérables aux effets sanitaires liés à la pollution atmosphérique en raison de facteurs de sensibilité tels que l'âge, les problèmes de santé préexistants, la pauvreté, l'accès à un logement approprié, l'emploi, l'éducation, le racisme et les conditions sociales et économiques. Ces facteurs de vulnérabilité sont des variables fondamentales pour mieux comprendre les risques pour la santé et diminuer la sensibilité.

L'énoncé dans le plus récent rapport de l'Institut climatique canadien (CICC) est clair: la pollution de l'air ambiant va non seulement augmenter les coûts du système de santé et l'économie canadienne, mais sera aussi une menace pour la santé publique et un facteur aggravant des inégalités de santé existantes (CICC, 2021). Les résultats du rapport démontrent que l'augmentation des concentrations d'ozone troposphérique (O_3) est associée à environ 14 600 décès prématurés au Canada à chaque année. Le rapport souligne la nécessité d'élaborer des mesures d'adaptation nationales liées à la qualité de l'air afin d'améliorer la situation des groupes défavorisés et de réduire les effets sur la santé induits par les toxines atmosphériques. Pour assurer la protection de la santé de la population, les chercheurs ont souligné l'importance de se préparer non seulement à des risques spécifiques, comme les vagues de chaleur, mais aussi à des facteurs comme la pauvreté, le racisme et la privation économique. En effet, ces facteurs peuvent accroître la vulnérabilité aux effets de la pollution de l'air sur la santé. Néanmoins, les auteurs font état d'un manque de connaissances en ce qui concerne les causes de la vulnérabilité sanitaire et signalent que peu de recherches ou de financements sont actuellement consacrés à la qualité de l'air et à ses conséquences sanitaires.

Comme ce sera décrit dans la revue de la littérature, la majorité des études empiriques sur la santé et l'économie estiment soit la relation entre la santé et la pollution atmosphérique, soit la relation entre la santé et le statut socio-économique (SES). Il existe également une littérature croissante sur la justice environnementale, en particulier aux États-Unis, qui se concentre sur la corrélation entre l'exposition à la pollution atmosphérique et le SSE. Cependant, peu d'études ont examiné l'interaction tripartite entre les résultats sanitaires liés à la pollution atmosphérique et le SSE. Pour n'en citer que quelques-unes, une étude réalisée aux États-Unis par Neidall et al. (2003) a révélé que le monoxyde de carbone (CO) a un effet significatif sur l'asthme chez les enfants âgés de 1 à 18 ans et que l'effet de la pollution est plus important chez les enfants de statut socio-économique inférieur. Ceci indique que la pollution est un mécanisme potentiel par lequel le SSE affecte la santé. Lavaine (2015) a trouvé une relation positive et significative entre les niveaux de NO_2 et le taux de mortalité, ainsi que des disparités de santé liées au revenu entre les départements français. Cependant, Laurent et al. (2007) ont publié une revue de la littérature sur les interactions potentielles entre le statut socio-économique et les effets à court et à long terme de la pollution atmosphérique et de la mortalité et ont établi que les preuves actuelles ne permettent pas de répondre définitivement que les caractéristiques socio-économiques modifient les effets de la pollution atmosphérique sur la mortalité. Cela dit, plus de recherches au Canada sont nécessaire sur l'estimation de la mortalité et sa relation avec la pollution atmosphérique et les facteurs socio-économiques à l'échelle nationale.

D'un point de vue médical, le ministère canadien de l'Environnement et des Ressources naturelles avait formellement évalué et déterminé comme toxiques et affectant la santé les polluants suivants : dioxyde d'azote (NO_2), dioxyde de soufre (SO_2), ozone (O_3) et particules respirables inférieures ou égales à 10 microns ($PM_2, 5$ ou plus). Conséquemment, dans cette recherche, la pollution de l'air ambiant est mesurée par les niveaux de concentration de NO_2, O_3, SO_2, et $PM_{2.5}$. La raison d'être de cette recherche est d'étudier les causes de la variation du ratio de risque de mortalité lié à la pollution atmosphérique. Pour ce faire, on explore l'interaction tripartite entre les ratios de risque de mortalité de la population, les concentrations de pollution de l'air ambiant et le statut socio-économique au niveau des données individuelles à l'aide du modèle de risque proportionnel de Cox comme méthode d'analyse. 5mmL'objectif est de monter un portrait de la distribution actuelle du risque environnemental au sein de la population canadienne. Dans un premier temps, nous observons les impacts des variables socio-économiques sélectionnées sur les ratios de risque de mortalité, sans tenir compte de l'effet de la qualité de l'air. Deuxièmement, nous incluons les données sur la pollution de l'air ambiant (NO_2, O_3, SO_2, $PM_{2.5}$) afin d'observer les effets des polluants sur la mortalité. Troisièmement, nous effectuons des régressions transversales séparées pour chaque groupe socio-économique, afin de capturer l'interaction à trois voies entre le statut socio-économique, la pollution atmosphérique et la mortalité. Cet exercice permet d'observer comment le paramètre d'effet de la mortalité varie en fonction du statut socio-économique à la suite d'une variation de la concentration des polluants atmosphériques.

Les bases de données au niveau individuel provenant des cohortes du recensement canadien sur la santé et l'environnement (CanCHEC), de l'enquête nationale auprès des ménages (ENM) et de la base de données canadienne sur les décès de l'état civil (BCSD) ont été essentielles pour examiner la variation de l'impact de la pollution atmosphérique en fonction des caractéristiques sociales individuelles. Les microdonnées permettent un meilleur contrôle et précision des covariables individuelles et fournissent un échantillon d'observations très large pour étudier les disparités. Par exemple, les ensembles de données comprennent des individus riches vivant dans des zones polluées, ainsi qu'un nombre suffisant d'observations d'individus plus pauvres vivant dans des zones à faible niveau de pollution. Grâce à ces ensembles de données, nous avons également pu observer l'exposition à la concentration moyenne de pollution atmosphérique en fonction des quantiles de revenu **(Figure 1, 2, 3, 4)**.

Comme résultats principaux, nous trouvons une augmentation positive et significative des ratios de risque de mortalité en réponse au NO_2, O_3, SO_2, et $PM_{2.5}$. De plus, nous constatons des disparités de santé liées à la pollution atmosphérique en fonction des niveaux de revenus. Bien que les individus des quantiles de revenus les plus élevés tendent à être exposés à des concentrations moyennes de polluants atmosphériques plus élevées, ils présentent des risques de mortalité associés aux NO_2 et O_3 plus faibles que les autres quantiles de revenus. Nous observons une disparité de 2% à 11% dans les risques de mortalité liés au NO_2 entre le quantile le moins affecté et le plus affecté, et une disparité de 4% à 14% pour le O_3. Cependant, les individus du deuxième quantile présentent les plus faibles ratios de risques de mortalité de 17,3% liés aux polluants SO_2, avec une différence de 15,7% avec le quantile le plus riche.

De plus, l'interaction entre l'éducation et la pollution de l'air démontre des disparités dans les résultats sanitaires liés au NO_2 et au O_3, où les individus sans éducation ou avec seulement un diplôme d'études secondaires ont des risques de mortalité plus élevés par rapport aux individus avec un certificat ou un diplôme universitaire. Cependant, les risques de mortalité liés au SO_2 sont plus élevés pour les personnes ayant un niveau d'éducation supérieur. En ce qui concerne l'analyse de la catégorie d'emploi, les personnes travaillant dans l'agriculture sont affectées de manière disproportionnée par le NO_2 et le O_3 et les travailleurs de l'industrie manufacturière présentent les ratios les plus élevés de risques liés au O_3 et au SO_2. De même, la catégorie de main-d'œuvre qui est moins exposée à la pollution atmosphérique présente des ratios de mortalité liés au NO_2 et au O_3 plus élevés que certains secteurs exposés à la pollution atmosphérique. L'interaction entre les groupes ethniques et la pollution atmosphérique a également révélé des disparités dans les risques de mortalité. Les individus originaires d'Amérique latine et d'Asie semblent supporter un poids plus important de l'impact du NO_2 sur la mortalité par rapport aux Caucasiens. Les Afro-Canadiens, les Latinos et les Asiatiques sont touchés de façon disproportionnée par le SO_2 comparativement aux caucasiens. Les Asiatiques et les caucasiens présentent un risque de mortalité lié au O_3 de 6,3% et 5,4%, respectivement et seul les Caucasiens sont affectés par les $PM_{2.5}$. Dans l'analyse du genre, on constate des disparités dans le risque de mortalité des hommes lié aux polluants NO_2 et SO_2, et un risque de mortalité plus élevé lié aux $PM_{2.5}$ chez les femmes. Enfin, nous n'avons pas trouvé de résultat concluant en matière d'interaction entre la pollution atmosphérique et la mortalité au niveau du SSE par région. En résumé, nous observons l'existence d'une relation entre la mortalité, la pollution atmosphérique et le statut socio-économique. Ces résultats peuvent avoir une implication importante pour les politiques environnementales et sanitaires. Les politiques publiques pourront mieux cibler les interventions visant à réduire la pollution en tenant compte des inégalités et des sous-groupes de la population les plus touchés.

Cette recherche se présente comme suit. Tout d'abord, l'introduction. Ensuite, un aperçu de la littérature sur les résultats en matière de santé et leur association potentielle avec la pollution de l'air et le statut socio-économique, suivi de quelques informations de base sur les inégalités environnementales et conclues par un résumé des études récentes sur le lien tripartite entre la santé, la pollution de l'air et le statut socio-économique. Troisièmement, nous décrivons les ensembles de données et la méthode d'analyse. Quatrièmement, nous présentons les résultats et l'analyse économétrique, et cinquièmement, nous concluons par une discussion.

Chapitre 1

Socioeconomic disparities of mortality related to air pollution: evidence from Canada

Introduction

In 2021, the Lancet journal reported a new study on health and ambient air pollution indicating a threat to a healthy future (Romanello et al 2021). Regardless of the noticeable increase of renewable energy, the perpetual release of pollutants in the ambient air continues and is not without consequence. The Lancet report provides an evaluation of the global energy system apace with the association of global exposure to ambient $PM_{2.5}$ air pollution and its health impacts. Foremost, in 2019, 4 million deaths were attributable to exposure of $PM_{2.5}$ air pollutants. The very high Human Development Index (HDI) countries, such as Canada, had lower rate of air pollution-related mortality (40 deaths per 100 000 inhabitants) compared to medium and high HDI countries. Despite this, preoccupation with inequality issues persists as the evidence demonstrates that individuals with socioeconomic deprivation[1]. disproportionally bear the burden of health effects from exposure to air pollution. Certain groups of the population can be more vulnerable to health impacts related to air pollution because of sensitivity factors such as age, pre-existing health conditions, poverty, access to appropriate housing, employment, education, racism, and social and economic conditions. These vulnerability factors are fundamental variables to better understand health risks and decrease sensitivity.

In the latest report of the Canadian Climate Institute (CICC), the report statement was clear: ambient air pollution will not only increase costs to Canadian's health system and economy but also become a threat to public health and an aggravating factor to existing health inequalities (CICC, 2021). The report findings show that increased concentrations of ground-level ozone (O_3) are associated with approximately 14,600 premature deaths in Canada every year. The report highlights the need of building national adaptation measures related to air quality to improve the circumstance of disadvantaged groups and reduce health impacts induced by air toxins. To ensure the protection of the population's health, the researchers emphasized the importance not only for specific risks, like heat waves, but also factors like poverty, racism, and economic deprivation. Since, they can increase vulnerability to air-pollution-induced health impacts. However, the authors display a lack of knowledge in terms of causes of health vulnerability and report that only a little research or funding is currently focusing on air quality and its health consequences.

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[1] Socioeconomic deprivation is a multidimensional concept as it refers to the relative disadvantage an individual or a social group experience (including a group defined in geographical terms e.g., a community or a neighborhood) in terms of access and control over economic, material, or social resources and opportunities. (Lamnisos et al. 2019)

As we will learn through the literature overview, most empirical health and economic studies estimate either the relationship between health and air pollution or the relationship between health and socioeconomic status (SES). There is also growing literature on environmental justice, particularly in the United States, which focuses on the correlation between air pollution exposure and SES. However, few studies have investigated the three-way interaction between air pollution-related health outcomes and SES. To name a few, an American study by Neidall et al. (2003) found that carbon monoxide (CO) has a significant effect on asthma for children aged 1-18 and that the effect of pollution is greater for children of lower socioeconomic status, indicating that pollution is one potential mechanism by which SES affects health. Moreover, Lavaine (2015) found a positive and significant relationship between NO_2 levels and the mortality rate, so as disparities in health related to income among French departments. However, Laurent et al. (2007) published a literature review of potential interactions between socioeconomic status and the short-and long-term effects of air pollution and mortality and established that current evidence does not provide a definitive answer that socioeconomic characteristics modify the effects of air pollution on mortality.To the best of my knowledge, more research in Canada is needed on the estimation of mortality and its relationship to air pollution and socioeconomic factors on a national scale.

From a medical perspective, the Canadian Ministry of the Environment and Natural Resources had formally assessed and determined to be toxic and affecting health the following pollutants: nitrogen dioxide (NO_2), sulphur dioxide (SO_2), Ozone (O_3) and breathable particulate matter equal to 2.5 microns ($PM_{2.5}$). Consequently, in this research, ambient air pollution is measured by levels of concentration of NO_2, O_3, SO_2, and $PM_{2.5}$. The rationale of this research is to investigate the causes of variation in the mortality hazard ratio related to air pollution. A hazard ratio is a metric used to compare the likelihood of an event (such as death) occurring in one group versus another group over time, reflecting the relative risk of the event in each group. To achieve this, we explore the three-way interaction between population mortality hazard ratios, ambient air pollution concentrations, and socioeconomic status at the individual-level data using the Cox Proportional Hazard model as method of analysis. The objective is to provide a portrait of the current distribution of environmental risk among the Canadian population. At first, we observe the impacts of the selected socioeconomic variables on the hazard ratios of mortality, without accounting for the effect of air quality. Second, we include the ambient air pollution (NO_2, O_3, SO_2, $PM_{2.5}$) data to observe the effect of pollutants on mortality. Third, we perform separate cross-sectional regressions for each socioeconomic groups, to capture the three-way interaction between socioeconomic status and air pollution and mortality. This exercise showcases how the effect parameter of mortality varies according to SES following a variation in the concentration of air pollutants.

The individual-level databases from the Canadian Census Health and Environment Cohorts (CanCHEC), the National Household Survey (NHS) and the Canadian Vital Statistics Death Database (CVSD) were essential to examine the variation of the impact of atmospheric pollution according to individual social characteristics. Micro-data allows better control and precision of individual covariates and provides an extensively large sample of observations to study disparities. For example, the data sets include rich individuals living in polluted areas, as well as enough observations of poorer individuals living in areas with low levels of pollution. Using these data sets, we could also observe the exposure to average concentration of air pollution according to quantiles of income **(Figures 1, 2, 3, 4)**[2]

As primary findings, we observe a positive and significant increase in hazard ratios of mortality in response to NO_2, O_3, SO_2, and $PM_{2.5}$. Moreover, we find health disparities related to air pollution according to levels of income. Despite that, individuals in the highest quantiles of income tend to be exposed to higher average concentration of air pollutants, they have lower hazards of mortality associated with NO_2 and O_3 compared to other quantiles of income. We observe a disparity of 2% to 11% in hazards of mortality related to NO_2 between the least affected to the most affected quantile, and a disparity of 4% to 14% for O_3. However, individuals in the second quantile have the lowest ratios of hazards of mortality of 17.3% related to SO_2 pollutants, with a difference of 15.7% with the richest quantile.

Furthermore, the interaction between education and air pollution demonstrates disparities in health outcomes related to NO_2 and O_3, where individuals with no education or with only a high school diploma experience higher hazards of mortality compared to individuals with a certificate or a university diploma. However, the mortality hazards related to SO_2, are higher for individuals with higher levels of educational achievement. In terms of labour occupation analysis, individuals working in agriculture are disproportionately affected by NO_2 and O_3 and workers in manufacturing have the highest ratios of hazards related to O_3 and SO_2. Also, the category of labour which is less exposed to air pollution have higher ratios of mortality related to NO_2 and O_3 than some sectors exposed to air pollution. The interaction between ethnic groups and air pollution also revealed disparities in mortality hazards.

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[2] The average concentration of pollutants is at the scale of postal codes.

Individuals originally from Latin America and Asia seem to bear a higher burden of the impact of NO_2 on mortality compared to Caucasians. Afro-Canadians, Latinos, and Asians are disproportionately impacted by SO_2 compared to the white Canadian population. Asians and Caucasian's have a risk of mortality related to O_3 of 6.3% and 5.4%, respectively. At last, only Caucasians' health is impacted by $PM_{2.5}$. Regarding gender, we found disparities in the risk of mortality of males related to NO_2 and SO_2 pollutants, and a higher risk of mortality related to particulate matter ($PM_{2.5}$) for females. Finally, we found no conclusive result in terms of area-level SES interaction with air pollution and mortality. In sum, we observe the existence of a relationship between mortality, air pollution and socioeconomic status. These results can have an important implication for environmental and health policies. It could allow public policies to better target the interventions aiming at reducing pollution by accounting for the most affected subgroups of the population and inequalities.

The research paper is laid out as follows. At first, the introduction. Second, a literature overview on health outcomes and their potential association with air pollution and socioeconomic status, followed by some background information on environmental inequalities and concludes with recent studies on the three-way link between health, air pollution and SES. Third, we describe the data sets and the method of analysis. Fourth, we present the econometric results and analysis, and fifth, we conclude with a discussion.

1.2 Literature overview

1.2.1 ***Health and air pollution***.

In different parts of the world, numerous studies have been conducted on the impact of air pollution on a variety of health outcomes. Various research studied the effect of urban ambient air pollution on adults' health in the United States. Ito et al (2005) observed a short-term association between exposure to ozone and daily mortality in seven cities in the United States. The authors found that all-age non accidental mortality increases by 0.39% per ppb increase in 1-hour daily maximum ozone. Huang et al (2005) have similar findings as they observed that an increase of 10ppb in summer ozone level is associated with a 1.25% increase in cardio-respiratory mortality across 19 cities in the United States. Children's health is not less vulnerable to air pollution exposure as Morello Frosch et al. (2002) have found associated health risks with ambient air toxic exposure on children while they are in school. Moreover, children of colour, such as Latinos and African Americans, bear the highest burden. The effect of air pollution is also particularly harmful to infant health. Currie and Neidall's (2005) findings demonstrate that reducing carbon monoxide in the ambient air can save thousands of infant lives. Some research was also conducted in the Canadian context, Burnett et al (1998) observed the effect of the urban ambient air pollution mix on daily mortality in 11 cities in Canada over 10 years and found a strong positive effect of nitrogen dioxide and ozone on daily mortality rates. They found that nitrogen had the largest effect with a 4.1% increased risk of mortality, followed by ozone at 1.8%. At last, two recent studies from Canada found associations between $PM_{2.5}$ and non accidental mortality. First, Pappin et al. (2019) published their analysis on a large population-based cohort with up to 25 years of follow-up and estimated a positive hazard ratio (HR) of mortality of 1.041, 1,084 and 1.053 per 10 micrograms per cubic meter of air (ug/m3) change in $PM_{2.5}$ for the 1991, 1996, 2001 and 2006 cohort, respectively[3] . Second, Brauer et al. (2022) used census records of more than 7 million Canadians between 1981 and 2016 and found a positive association between very low levels of $PM_{2.5}$ and non accidental mortality consistently throughout all cohorts[4].

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[3] They estimated hazard ratio of 1.041 for the 1991 and 1996 cohorts

[4] $PM_{2.5}$ was associated with non accidental mortality at concentrations as low as 5 µm

1.2.2 *Health and Socioeconomic status*

Event though, air pollution can be harmful to human health, a certain level of socioeconomic status seems to mitigate those effects. Namely, the well-known study "The human capital model of the demand for health" (Grossman, 1999) has shown that more educated individuals have better health behaviour which results in better health outcomes in the long run. Further, the effect of income has been extensively studied in the context of health outcomes. A vast literature has established a strong positive relationship between income and health status and a negative relation between income and mortality. Lindahl et al (2005) study the effects of income on health and mortality, using only a variation of an exogenous factor that is part of the income: the monetary lottery prizes of individuals. The authors were in line with the literature, as they find that higher income causally generates good health. However, evidence for an association between income and health may be affected by bias. Gunasekara et al (2011) reviewed panel studies exploring the income and self-related health relationship and found only a small positive association between the two. Those results would be explained by the lack of control for possible biases from confounding effects and health selection, known as the reverse pathway from health to income. Additionally, using only one indicator of SES, such as income, may not be sufficient to capture the broader construct of SES and its impact on human health. Hajat et al (2015) raise the issue in their extensive review of socioeconomic disparities and air pollution by suggesting using more than one indicator of SES when it comes to health studies

1.2.3 *Environmental inequality perspective*

1.2.3.1 Air pollution exposure and socioeconomic status

Another important sphere of literature to this research is the one on air pollution exposure and socioeconomic status. A substantial number of studies in the United States looked into temporal exposure to air pollution and individual's difference in socioeconomic status. Rososfky et al (2017) and Brochu et al (2011) found exposure inequality in ambient air pollution in urban areas, whereas, in Europe, Viel et al (2011) analyzed if there was an association between proximity to hazardous facilities and socioeconomic characteristics. As a result, after controlling for the deprivation index, the authors found that noxious facilities are disproportionately located in larger foreign-born communities. A similar finding exists in the United States, as Mohai et al (2009) observed that African Americans and individuals with a lower educational level and lower income levels were more likely to live within a mile of polluting facilities, creating racial ethnic and socioeconomic disparities in environmental hazard exposure risk. Many other studies from the United States have studied ethnic issues and marginalized populations and their exposure to air toxins. Namely, Grineski et al (2007) found chronic environmental hazards disproportionately affecting groups with lower neighbourhood socioeconomic status, with higher proportions of Latino immigrants, and higher proportions of renters. Other findings by Morello-Frosch et al (2006) demonstrated clear social-class and ethnic-based environmental injustices in the distribution of air pollution. Even if the literature on the matter is not well established in Canada, Giang et al (2020) found unique patterns of disparities in three major cities in Canada. They observed that marginalized groups, such as indigenous residents, immigrant residents and low-income residents were disproportionately exposed to air pollution. Finkelstein et al (2003) investigated the relationship between neighbourhood-level income, air pollution exposure and mortality in a small sample of the population in Ontario and found that mean pollutants levels tended to be higher in lower-income neighbourhoods and both income and pollutant levels were associated with mortality differences. Additionally, people in the most favourable settings (high income and low exposure to air pollutants) had a lower risk of death from non accidental causes compared to those with all other income–particulate combinations. In the same line, Premji et al. (2007) were able to demonstrate that pollution measures were positively associated with the unemployment rate, the proportion of workers in the secondary sector, and the proportion of individuals with less than a high school education in Montreal, Canada.

1.2.3.2 Variation in health outcomes related to air pollution based on different socioeconomic groups

More specifically, there is increasing research on environmental inequality and its possible negative health outcomes. More developed and larger studies of socioeconomic disparities and health outcomes related to air pollution were conducted elsewhere. Mostly, stratification techniques were used to map health inequalities related to pollution. Lavaine (2015), analyzed atmospheric pollution, poverty indicators and mortality rates using national-level panel data of French departments. However, besides finding a positive and significant relationship between Nitrogen Dioxide (NO_2) levels and the mortality rate, the relationship to poverty indicators and SES was not conclusive. The impact of air pollution on health and its distribution within SES groups was also extensively studied in China. Wong et al (2008) observed a higher rate of respiratory mortality associated with NO_2 and SO_2 in areas with middle or high social deprivation index (SDI). From low to high SDI, the point estimate increased from 0.76 to 1.44% for NO_2 and from 0.90 to 2.27% for SO_2. Whereas author Zhang et al. (2022) used education as an SES indicator and were able to demonstrate that as per capita educational level increases, the impact of increased air pollution on public health damage diminished gradually.

In Canada, several researchers have looked at various health outcomes related to air pollution, and few studies have investigated the three-way interaction between air pollution-related mortality and socioeconomic status. For example, Lin et al. (2004) investigated individual-level data on children's asthma hospitalization related to gaseous air pollutants in British Columbia, Canada and found disparities in the health outcomes based on SES groups and gender. Authors found no associations between carbon monoxide and ozone with asthma hospitalization, however, a 4-day average exposure to nitrogen dioxide for males showed significant positive effects on asthma hospitalization in the low SES group, with relative risk estimates of 1.14. Similarly, a 6-day average exposure to sulphur dioxide for females was found to be significantly and positively associated with asthma hospitalization in the low SES group with relative risks of 1.19. Burra et al. (2009) conducted research with children aged 1-17 individual-level data from Ontario, Canada and observed that the risk ratios for ambulatory physician visits for males were significantly greater in the low socioeconomic group compared to those in the high socioeconomic group in several of the models of SO_2 and $PM_{2.5}$. The mean daily asthma visit rate was 5.96/10 000 in the lowest quantile of income and 2.17/10 000 in the highest quantile of income and an interquartile range increase in SO_2 was associated with a visit rate of 6.09/10 000 in quantile 1 and 2.21/10 000 in quantile 5. Moreover, in Canada, we witness some heterogeneity in results in the relationship between socioeconomic status and mortality related to air pollution. Christidis et al. (2019) found that outdoor $PM_{2.5}$ concentrations were associated with non-accidental mortality, however, when adjusting for individual-level behavioural covariates, the relationship was not affected. Moreover, Laurent et al. (2007) produced a literature review on the effect of SES on the relationship between atmospheric pollution and mortality and found mixed results. He observed that no effect modification was found in studies using socioeconomic characteristics at the city or county-wide area level. However, studies using finer geographic resolutions found mixed results, and five of six studies using individually measured socioeconomic characteristics found that pollution affected disadvantaged individuals more. Hence, these findings showcase the importance of using individual-level data when it comes to SES characteristics and health outcomes. After all, Laurent et al (2007) established that current evidence does not provide a definitive answer that socioeconomic characteristics modify the effects of air pollution on mortality. Nevertheless, existing results, do tend to show notable effects among individuals with lower SES, exposing the need to pursue the investigation of this topic. Moreover, the Canadian literature on the three-way link between air pollution, mortality and SES is not well established. Existing studies primarily assesses the effects of air pollution on mortality by controlling for SES and demographic factors (Christidis et al. (2019); Pappin et al. (2019)) and studies that do perform an interaction analysis between air pollution, mortality and SES, only analyze a subgroup of the population in a given region (Lin et al. 2014; Burra et al. 2009).

From that perspective, we witness a knowledge gap in Canadian studies regarding health inequalities and the distribution of environmental hazard risk. This research paper has the potential to make several contributions to the existing literature. At present, no study has investigated how the effect of air pollution on mortality vary according to socioeconomic groups at a national scale in Canada. We would extend the current literature, by attempting to provide nationwide results, covering all 10 provinces and three territories among Canadian adults using the most recent Canadian Census Health and Environment Cohorts (CanCHEC) cohort census panel data from 2011 to 2016. We will also analyze the effect of a multiple pollutant model on non accidental mortality based on four air pollutants concentrate (NO_2, O_3, SO_2, $PM_{2.5}$) compared to previous Canadian studies using no more than two. Moreover, to observe the effect of air pollution on mortality according to SES, we will perform separate cross-sectional regressions for multiple individual socioeconomic status indicators (income, education level, category of labour and occupation) and gender. At last, this research has the potential to contribute to the preoccupying issue of environmental racism in Canada (Canadian Association of Physicians for the Environment [CAPE], 2022) as we explore whether health disparities exist among individuals from different ethnic groups.

1.3 Presentation of the data sets

1.3.1*Environmental data*

1.3.1.1 The adverse health effects of each selected pollutant explained

From a medical perspective, the Canadian Ministry of the Environment and Natural Resources had formally assessed and determined to be toxic under the Canadian Environmental Protection Act, 1999 (CEPA 1999) many pollutants that contribute, or may contribute, to air quality issues. Within the air-related toxic listed that can affect health, we can find nitrogen dioxide (NO_2), sulphur dioxide (SO_2), Ozone (O_3) and breathable particulate matter less than or equal to 10 microns ($PM_{2.5}$ or higher) (ECCC, 2013). As result, these pollutants are considered in this research paper. First, sulphur dioxide (SO_2) formation comes from the sulphur that is found in raw materials such as coal, oil and metal-containing ores during the combustion and refining processes. SO_2 can be harmful to human health and the environment after its dissolves in water vapour in the air to form acids, which then enter in contact with other gases and particles in the air to form particles named sulphates. Among adverse effects, SO_2 can affect the respiratory systems and the functions of the lungs (ECCC, 2013). World Health Organization [CMHC], (2021) stated that hospital admissions for cardiac disease and mortality increase on days with higher SO_2 levels. Secondly, particulate matter (PM) is solid or liquid form airborne particles that are emitted at the emissions source in particle form, such as the smokestack of an electrical power plant. Secondary PM is formed from chemical and physical reactions involving various gases, such as sulphur oxides and nitrogen oxides reacting to create sulphate, nitrate, and ammonium PM (ECCC, 2013). A significant body of research has established a strong link between fine particulate matter ($PM_{2.5}$) and exacerbated cardiac and respiratory diseases, as well as premature mortality. $PM_{2.5}$, which refers to particles less than 10 micrometers in diameter, has been recognized as the particle size with the greatest impact on human health (Kim et al. 2015). This paper focuses on $PM_{2.5}$ as a result. Third, nitrogen dioxide (NO_2) mainly originated from burning fuel. NO_2 forms from emissions from vehicles, power plants and off-road equipment. It is a powerful oxidizing gas that gets in the breathing air and at a high concentration can irritate airways in the human respiratory system. Over longer exposure, NO_2 may alongside contribute to the development of respiratory infections and asthma (United States Environmental Protection Agency [U.S. EPA], 2022). Lastly, ozone (O_3) is a secondary pollutant that forms from nitrogen oxides (NOx) from vehicles and industrial emissions and volatile organic compounds (VOCs) pollutants emitted by vehicles, solvents and industry reaction with sunlight and stagnant air. It stays above the earth's surface and can be a highly irritating gas known to have significant effects on human health following exposure, especially at high levels from periods of sunny weather (WHO, 2021). Excessive ozone in the air has been linked to premature mortality and can cause breathing problems, reduce lung function, cause lung disease, etc. (WHO, 2021). Possibly, other pollutants are also likely to be associated with differences in mortality. Unfortunately, data were not available in the database Canadian Urban Environmental Health Research Consortium (CANUE) used in this paper.

1.3.1.2 Description of the Air Pollution Concentrations Data

The outdoor air pollution concentrations data were provided by the Canadian Urban Environmental Health Research Consortium (CANUE). The following air pollutants are included in the analysis: $PM_{2.5}$, NO_2, SO_2 and O_3. The first air pollutant is the annual mean concentration in ug/m^3 of ground-level fine particulate matter ($PM_{2.5}$) surfaces at a 0.01x 0.01-degree gridded resolution for all postal codes in Canada each year from 2011 to 2016. The $PM_{2.5}$ concentrations were estimated by combining Aerosol Optical Depth (AOD) retrievals from the NADA MODIS, MISR and SeaWiFS instruments with the GEOS-Chem chemical transport model, and subsequently calibrated to regional ground-based observations of both total and compositional mass using Geographically Weighted Regression (GWR). The second pollutant is the annual average parts per billion (ppb) of nitrogen dioxide (NO_2) concentration based on a national land-use regression model developed from the national air pollution surveillance (NAPS) monitoring stations for 24 census Divisions for the period of 2011-2016. Third, is the annual average ground-level sulphur dioxide (SO_2) concentrations which have been estimated from the Ozone Monitoring Instrument (OMI) satellite data using SO_2 profiles from the Global Environmental Multi-scale – Modelling Air quality and Chemistry (GEM-MACH) model over North America between 2011-2015. The annual gridded data were aggregated to 3-year running averages and were assigned values to all annual mean concentrations of SO_2 to the ensemble of Canadian postal codes. Last, the annual ground-level ppb ozone (O_3) concentration, for all postal codes in Canada from 2011 to 2015 was estimated with GEM-MACH (Global Environmental Multi-Scale Modelling Air Quality and Chemistry) developed by Environment and Climate Change Canada. Throughout the estimations, the real concentrations of pollutants are used.

1.3.2 *Socioeconomic and health data*

Data on death, demographics and socioeconomic and ethnocultural characteristics were provided by the Canadian Census Health and Environment Cohorts (CanCHEC) of 2011 to 2016. These data sets cover the ten canadian provinces and three territories at the level of individual respondents. The 2011 CanCHEC has been described in detail elsewhere (Tjepkema et al. 2019). Briefly, this large cohort study is a population-based probabilistically linked dataset. The CanCHECs combine long-form census respondents or National Household Survey (NHS) respondents with administrative health data, such as mortality, cancer incidence records, hospitalizations records, emergency ambulatory care, and annual mailing address postal codes (Statistics Canada, 2021). The full cohort is a nationally representative sample following approximately 6.5 million Canadian adults between 2011 and 2016. The National Household Survey of 2011 is used for socio-economic, ethnocultural and demographic characteristics information. The NHS voluntary survey is received by one in three Canadian households and includes data on labour, income, education, housing, relationships, language, and ethnic origin (Statistics Canada, 2021). To account for the mortality, the Canadian Vital Statistics Death Database (CVSD) was used and linked to the CanCHEC data sets. The CVSD is an administrative survey which follows subjects for mortality and collects annual information on demographics and causes of death on a national scale. The cause of death information is coded using *the International Classification of Diseases (ICD)* (Statistics Canada, 2021). Finally, the linkage of CanCHEC and CANUE was approved by Statistic Canada, after which the two data sets were linked using annual postal codes. In the context of health studies, including control variables from an individual's social context is paramount as socioeconomic factors will form people's health. The likelihood that an individual experiences poor health during his lifetime are largely determined by his income, access to quality housing, being educated and having a job, to name a few. (Romanello et al. 2021).

1.4 Method of Analysis

1.4.1 *Econometric model*

Several studies analyzing individual-level data from cohort used the Cox Proportional Hazard model to analyze the risk hazard ratios of mortality related to air pollution. Christidis et al. (2019) estimated a low concentration of fine particle air pollution and mortality and stratified the model by immigration status, sex, age, and behavioural covariates while controlling for several SES and demographic characteristics. A similar study was conducted by Pappin et al. (2019), where the same variables were stratified using three CanCHEC cohorts (1991- 2001). Finally, Finkelstein et al. (2002) followed the same logic, but used a neighbourhood-level geographical unit, in Ontario. On the other hand, studies elsewhere performed a similar analysis using a variety of econometric methods, such as the Ordinary Least Square linear regression model and fixed effects (Hill et al.2018; Neidall et al. 2003; Zhang et al.2021). On the other hand, to account for spatial autocorrelation Lavaine (2015) used the Driscoll-Kraay Standard Error model alongside Fixed-Effects. Finally, Wong et al (2008) used logistic regression to count for their binary dependent variable. In terms of this paper, we study a very large population sample of the CanCHEC 2011 cohort, and we aim to observe outcomes on a binary dependent variable counting an extensive number of zeros. Considering those parameters and the literature, the Cox proportional Hazard Model (Cox 1972) is the most appropriate model for this analysis.

We run the Cox proportional hazard model to estimate the air pollutants exposure with the non-accidental causes of death. This method simultaneously investigates the effect of several risk factors on survival. In other words, it allows to examine how specified factors influence the rate of a particular event happening. In this case, the event is determined by the year of death for non accidental causes, at a particular point in time between 2011 and 2016. The association is made between the survival time of individuals and the other predictor variable by calculating a hazard ratio (HR). The hazard ratio is a measure that compares the likelihood of an event occurring in one group versus another group over time. It is calculated as the ratio of two hazard rates, which are measures of the frequency of the event occurring in each group. The hazard rate is calculated as the number of events divided by the number of person-time units in a group. The hazard ratio is typically expressed as a unitless number, and its interpretation is based on whether it is greater than, less than, or equal to 1. The latter will report the risk of mortality associated with exposure to the selected air pollutants ($PM_{2.5}$, NO_2, SO_2 and O_3). If the hazard ratio is greater than 1, the event is more likely to occur in this group compared to the other groups, while a hazard ratio less than 1 indicates that the event is less likely to occur in this group compared to the other groups. A hazard ratio of 1 means that the risk of the event is the same in all groups. Subsequently, we run cox proportional hazard regressions by groups of social and economic characteristics to analyze the variations in the hazards of mortality related to air pollution according to SES. The Cox model is expressed by the hazard function denoted by h(t), which in this setting relates to the risk of dying at time t. The model is estimated as follows:

$$h^k(t) = h_0(t) * exp(\beta_{1g}P_i + \beta_{2g}SES_i + \beta_{3g}DEM_i + \beta_{4g}Z_i)$$

Where h(t) is the hazard function determined by the set of i covariates, t refers to survival time, i to individuals, and k to the kind of mortality (non-incidental mortality). h0(t) represents the baseline hazard, which is the inherent risk of an event (such as death) occurring at a given point in time, in the absence of any other factors. By computing the exponential of the regression coefficients β_{1g} to β_{4g}, we can calculate the HR. The main coefficient of interest is β_{1g}, where g stands for each group of regression based on individual socioeconomic factors selected from the National Household Survey. We use individual micro-level data as unit of analysis to improve the reliability and accuracy of the study as suggested by Bowen et al. (2002); Hajat et al. (2015); Laurent et al. (2007) and Maantay et al. (2002). We perform separate cross-sectional regressions, where the beta of each "g" group showcases the effects of a variation in air pollutant concentrations on the mortality hazard ratio according to the following SES group: quantiles of income, educational achievement, category of labour occupation, ethnicity group, and gender, while controlling for numerous individual-level confounding characteristics and temperature. Our last model examines area-level SES with community-level variables based on the Canadian Material Deprivation Index (CMDI). We could not use individual fixed-effects model to account for unobserved confounding factors to avoid potential omitted variable bias due to the very large sample of the study.

P_{it} accounts for the following air pollution concentrations: NO_2, SO_2, O_3 and $PM_{2.5}$. SSE_{it} accounts for the socioeconomic control variables, including total employment income, a dummy variable for unemployment, educational achievement level, and immigration status (whether the individual has immigrated to Canada or not). Further, we have a dummy variable for whether the individual lives in subsidized housing or not and the individual's category of labour occupation. We also account for the unavailable information on behavioural covariates, by including two proxies for individual's health status. First one being if individuals have difficulty with activities of daily living and the second being if individual's have reduction in the amount or kind of activity at work or at school. We also include the low-income measure of market income (LIM-MI) poverty index. DEM_{it} accounts for the demographic control variable, including age structure across individuals and sexe. Finally, Z_{it} are the meteorological variables at the postal code level to control for average pollution levels. It accounts for the annual highest and lowest temperature (Celsius), the annual number of cool, heat and rain events and annual smoke exposure ($PM_{2.5}$). The model thus captures the effect of very cold, hot, and rainy years so as extreme temperatures.

To reduce bias in estimates, we exclude several variables. For the dependent variable of mortality, we only account for the non accidental mortality. The objective is to identify the effect of air pollution on mortality, consequently external causes of mortality as classified by the $International Classification of Diseases$ (CIM10) were excluded from the analysis. These include accidents (road and water accidents), intentional self-harm, homicides, legal interventions and operations of war and complications of medical and surgical care. If all causes of mortality were kept in the analysis, a possible bias would have been introduced. For example, in major traffic zones, levels of NO_2 are usually higher and so as in road accidents, therefore we would not be able to extract the only effect of pollution on mortality. Further, we exclude individuals of 24 years old and younger at the beginning of the 2011 cohort, to control for possible bias of having a group of individuals, such as a young student with low income, that would appear as individuals in a lower SES but whose status would vary in a couple of years to higher education and income values. However, we did perform regression for both scenarios, and the results estimates were similar. We also account for individuals older than 85 years old. The elderly may experience larger health effects since they are more vulnerable to air pollution, thus areas with a larger count of elderly people may have higher mortality rates (Cakmak et al. 2007). Moreover, we exclude immigrants living in Canada for less than 10 years at cohort commencement due to the healthy immigrant effect (Ng, 2011) and lack of knowledge of their historical air pollution exposure . Finally, we exclude individuals who changed their home addresses between 2011 and 2016, as the exposure to air pollution can change depending on the new home's location. As far as this research goes, we could not include important risk factors for mortality such as behavioural covariates namely smoking habits, Body Mass Index (BMI), diet habits or control for the access to healthcare system due to their unavailability in the data sets.

The number of observations, the mean and the standard deviation of the selected variables are presented in **Table 1** for the overall sample. The top panel of the summary statistics presents the non-accidental mortality incidence rate per 100,000 individuals, followed by female and male mortality incidence rates respectively. The second panel presents the air pollution data and the third panel the socioeconomic variables: total income, the achievement level of education, unemployment status, difficulty with activities of daily living, reduction in the amount or kind of activity at work or at school, structural type of dwelling, subsidized housing, visible minority, low-income status based on LIM-MI, immigration status and ethnicity. The last panels describe demographic variables. Some variables were excluded from the descriptive statistics for length purposes.

Table 1

Descriptives statistics

Variable	**Observations**	**Mean**	**S. D**
Pollutant Variables			
NO_2 (ppb)	14,494,155	7.815	.090
O_3 (ppb)	12,212,185	34.532	4.944
SO_2 (ppb)	10,879,785	.338	4.486
$PM_{2.5}$ (ug/m3)	12,199,835	7.072	.235
Total deaths (2011-2016)	121,620		
Population incidence rate per 100,000	835		
Female Incidence rate per 100,000	706		
Male incidence rate per 100,000	976		
Socioeconomic variables			
Total Income (CAD)	NA		
if individual is unemployed (%)	36.1		
Education level (%)			
No certificate, diploma, or degree	15.6		
High school diploma or equivalency certificate	22.3		
Registered apprenticeship	33.1		
University certificate or diploma below bachelor	4.8		
level	30		
University diploma			
Subsidized Housing (subsidy) (%)	84		
Not applicable	13.7		
No, not a subsidized dwelling	2.3		
Yes, a subsidized dwelling			
Reduction amount of activity at work or at school	90.2		
(%)	3.4		
No	6.4		
Yes, often			
Yes, sometime			
Difficulty with activities of daily living (%)			
No	83		
Yes, often	6.2		
Yes, sometimes	10.8		
Visible minority (%)			
not visible minority	84		
Afro-Canadian	1.3		
Latino	0.6		
Asian	8		
Arab	0.5		
Aboriginal self-reporting	5.2		
Visible minority, n.i.e	0.1		
Multiple visible minorities	0.3		
Structural Type of Dwelling (%)			
Individual has a house	79.5		
Individual has an apartment	19.2		
Individual lives in mobile house	1.3		
Non-immigrants(%)	80.7		
Immigrants(%)	18.9		
Non-permanent residents (%)	0.4		
Labour Industry Sectors (NAICS 2007) controls	**X**		
Marital Status Legal (%) controls	**X**		
No-low-income person (at or above LIM-MI)(%)	84.4		
Low-income person (below LIM-MI) (%)	19.6		
Demographic variables			
Age *(continues variables controls)*	**X**		
Female (%)	52.4		
Male (%)	47.6		
Population age >85 years old (%)	1.2		
Temperature control variables	**X**		

1.5 Results and Analysis

1.5.1 *Impact of air pollution on non accidental mortality*

1.5.1.1 The standard model of mortality

The first model of the research examines the mortality outcome without considering the air pollutants concentrations. The objective is to observe whether the selected variables, besides the air quality, have an impact on the hazard ratios of mortality. In **Table 2**, we observe that most of the determinants' hazards of non accidental mortality are significant (see Appendix A). Following, the hazard ratio of income on non-accidental mortality is less than 1, indicating a lower relative risk of death with increasing income. To put it in more concrete terms, we observe that for every 1,000$ CAD increase in annual income, there is a 0.05% decrease in the relative risk of death from non-accidental causes during the specified time period of 2011 to 2016. At this stage, we are in line with the literature saying that income is a significant determinant of good health. Having a certain level of educational achievement compared to not being educated is also negatively linked to mortality as we may have expected, at a 1% level of significance. Specifically, as individuals increase their level of education, we observe a descending risk of mortality. Individuals who are unemployed, in situations of a reduced amount of kind of activity at work or at school and are living in subsidized dwellings have higher hazards of mortality. Hazard ratios estimates suggest that if we increase these determinants by one unit, there is an increased risk of mortality by 29.3%, 34.2% and 40.9%, respectively. For the ethnicity analysis, excluding aboriginal self-reporting individuals, all ethnicity in the study, i.e., Afro-Canadian, Latino-Canadian, Asians, Arabic, ethnic visible minorities (n.i.e.,) and multiple ethnic visible minorities, have a lower risk of mortality compared to Caucasians. We also observe that individuals who immigrated have a 16.1% lower risk of death than those who did not. Finally, as expected, individuals in the low-income group based on the LIM-MI have a higher risk of mortality of 12.5% compared to the reference group.

1.5.1.2 Simple pollutant model and non accidental mortality

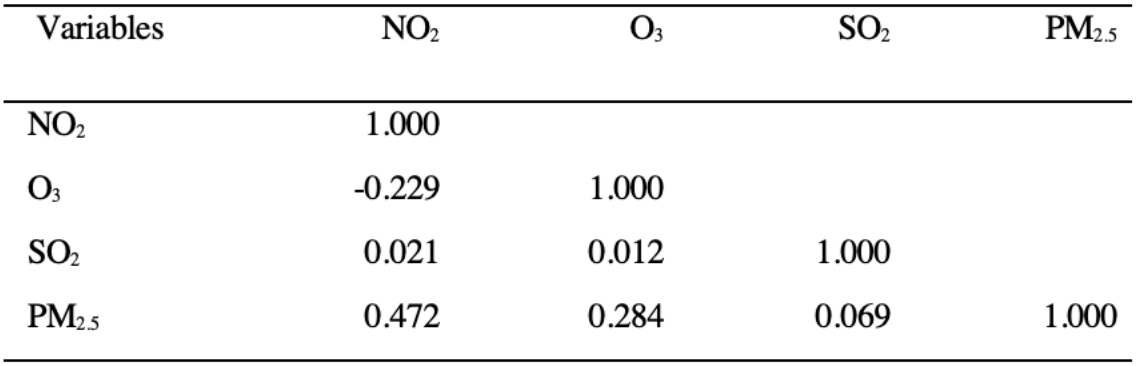
The second model of the paper integrates the selected air pollutants NO_2, O_3, SO_2 and $PM_{2.5}$ individually to study the relationship between single pollutants and mortality hazard ratios. In **Table 3**, we observe that all four pollutants estimates increases significantly the risk of mortality, at a 1% level of significance (see Appendix A). An increase of one unit of ppb changes the level of concentration of NO_2 from the mean by 2.11%, O_3 by 1,67% and SO_2 by 41.7%. Whereas estimate suggest that for every one ug/m^3 increase in $PM_{2.5}$, the concentration level increase by 3.27% from the mean. In terms of risk of mortality, an increase of one unit in the concentration for each pollutant is associated with an increased hazard ratio of 0.7%, 5.3%, 27% and 3.6%, respectively. The substantial increase of 27% in the hazards of mortality related to SO_2 can be explained by the fact that one unit increase of ppb in the concentration of SO_2 means a deviation from the mean of 41.7%. Moreover, the effects of the SES controls are similar.

1.5.1.3 Multiple pollutant model and non accidental mortality

In the third model, we analyze a multiple pollutant regression by accounting for the four pollutants altogether. This way, it allows coefficients to be examined at the same time, so as to not overestimate the impact of one pollutant. (Lavaine., 2015). In **Table 5**, we observe that all pollutants increases the risk of non accidental mortality, at a 1% significance level. Precisely, as the concentration of pollution increases by one unit, the hazards ratios of mortality increase by 1.9% for NO_2, by 6.2% for the O_3, by 20.3% for SO_2 and by 1.5% for $PM_{2.5}$. When accounted jointly, we witness that the impact of NO_2 on mortality hazards has increased, whereas the impact of the rest of the pollutants has diminished compared to the simple pollutant model. The differences in results of the multiple pollutant model may be attributable to collinearity between pollutants or to the spatial nature of the pollution. In fact, in **Table 4**, we can observe that NO_2 is positively correlated to $PM_{2.5}$ with a correlation coefficient of 0.472 and is negatively correlated to O_3 with a coefficient of -0.229. Following, O_3 is positively correlated to $PM_{2.5}$ with a coefficient of 0.284 and SO_2 has very weak correlation coefficient for all pollutants.

Table 4

Correlation coefficients of air pollutants



Variables	NO_2	O_3	SO_2	$PM_{2.5}$
NO_2	1.000			
O_3	-0.229	1.000		
SO_2	0.021	0.012	1.000	
$PM_{2.5}$	0.472	0.284	0.069	1.000

Moreover, Crouse et al. (2015) and Pappin et al (2019) previously demonstrated that the hazard ratio of $PM_{2.5}$ can partly be explained by NO_2 and O_3 due to the correlation of their gaseous components. Nonetheless, contrary to Lavaine. (2015), we found an impact for the particulate matter on adult mortality, when analyzing a multiple pollutant model with individual-level data. Our results are in line with the Canadian study made by Brauer et al. (2022) who found a positive association between $PM_{2.5}$ and non accidental mortality. Overall, these results suggest that there is a short-term relationship between air pollution levels and non accidental mortality in Canada. For the fourth model, we run a diagnostic test to verify if the assumption of proportional hazard made by the Cox model is respected. As a result, the assumption that the effect of a given covariate do not change over time is violated. However, in large samples and data sets, such as the one used in this study, the results of the diagnostics are usually insignificant and create no differences in the interpretation of the results (Sestelo, 2017). Further, the proportional hazard assumption is a strong one to make for any covariate because of the complexity of biological and physiological responses and associations.

Table 5

Multiple pollutant model and non accidental mortality

Variable	Model (1) (HR)
NO_2	1.019***
	(0.00193)
O_3	1.062***
	(0.00216)
SO_2	1.203***
	(0.0335)
$P.M_{2.5}$	1.015***
	(0.00552)
Total Income	0.9992***
	(1.30e-07)
Unemployment	1.309***
	(0.0323)
High school diploma	0.875***
	(0.0152)
Registered apprenticeship certificate	0.815***
	(0.0168)
College, CEGEP, or other non-university certificate	0.721***
	(0.0151)
University certificate below bachelor level	0.731***
	(0.0246)
University diploma	0.608***
	(0.0141)
Socioeconomic controls	**X**
Demographic controls	**X**
Temperature controls	**X**
Observations	7,598,949

seEform in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Before jumping into the analysis of the interaction between air pollution related mortality according to socioeconomic status, we want to analyze the correlation between individual's air pollution exposure and their quantiles of income. Since we consider the disparities in health outcomes, the spatial distribution of air pollution among individuals may be another reason why mortality hazards can differ. If individuals are living in areas with lower levels of air pollution it may influence positively their health relatively to individuals living in areas with high levels of pollution. In the following figures, we aim to observe whether richer individuals are also living in areas with better air quality and thus are less exposed to air pollution.

In **Figures 1 to 4**, we observe how the concentration of pollutants are distributed among percentiles of income. In **Figure 1**, we observe a curved relationship between concentration of NO_2 and quantiles of income. Individuals in the first quantiles of income seem to be more exposed to NO_2, compared to quantiles 30 to 60. However, a positive relationship is observed between NO_2 and upper quantiles of income, with extremely higher values for the 95th percentile. In **Figure 2**, we observe potentially a positive relationship between O_3 and quantiles of income, with some outliers in the lowest and highest percentiles. In **Figure 3**, we perceive a weak positive correlation between concentration of SO_2 and income, as the clusters of the data points are more spread out than previous graphs. Finally, in **Figure 4**, we see a non-linear relationship between $PM_{2.5}$ and income. The data is highly spread out for the first to 20th percentiles, further from the 20th to 80th percentiles we see an increase in the mean concentration of $PM_{2.5}$ following an increase in income. At last, with exception of outliers, individuals in the 80th percentiles and higher experience a drop in the exposure to the pollutant.

Fig. 1

Correlation between quantiles of income and NO_2

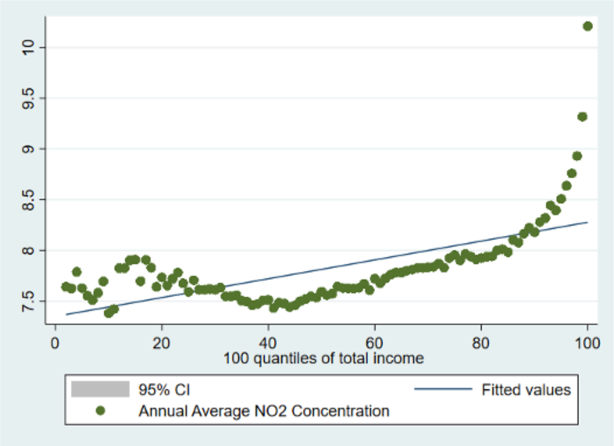


Fig. 2

Correlation between quantiles of income and O_3

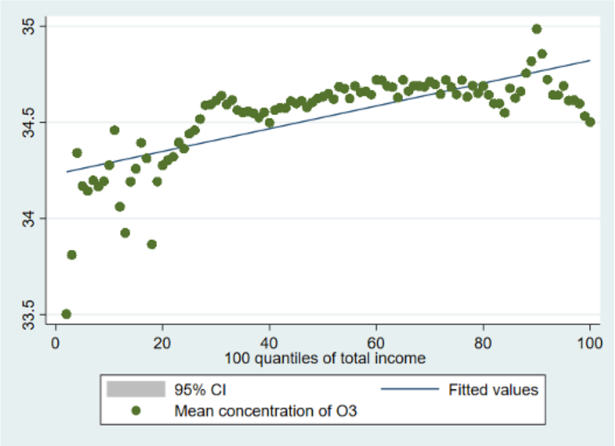


Fig. 3

Correlation between quantiles of income and SO_2

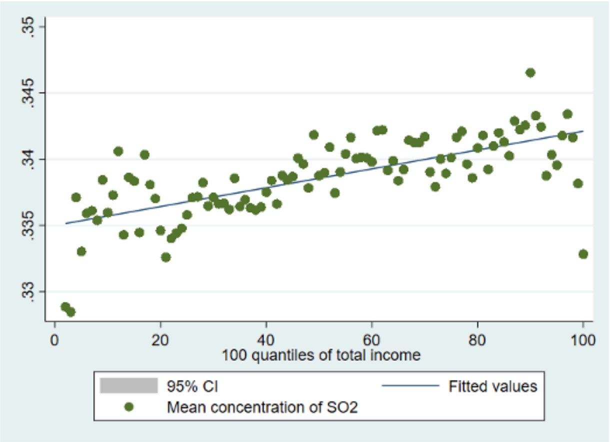
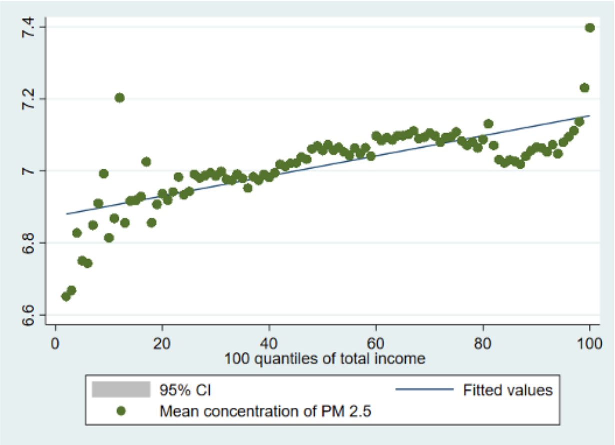


Fig. 4

Correlation between quantiles of income and $PM_{2.5}$



In these figures we can observe the distribution of exposure to pollution based on income, nonetheless, they do not allow to observe the variability of the health outcome related to air pollution with respect to social categories. In the following section, we will estimate analyses regression by groups of social and economic characteristics in relation to air pollution and mortality, as referred by the g index in the regression equation.

1.5.2 Interaction between air pollution-related mortality and individual-level socioeconomic status

We test the hypothesis that the effect of exposure to air pollution on health could vary with socioeconomic status. For instance, individuals with lower incomes or less educational achievements may be disproportionately affected by exposure to air pollution due to vulnerability factors, such as economic and social conditions. For example, poorer individuals may not have the basic capabilities to protect themselves from environmental hazards (Larrère. 2007) or have less available solutions to counteract air pollution impacts on health. Or individuals with higher education may have more information on favourable avoidance behaviour to undertake to reduce the negative effects on health related to air pollution, such as the benefits of responding to measures meant to reduce adverse effects of pollution, like “smog alerts” (Neidall et al. 2004). This suggests that SES is one potential mechanism for the well-known relationship between air pollution and health. Many authors agree that using only one indicator of SES, income for instance, may not be sufficient to capture the broader construct of SES. The usual trio which conceptualizes the social standing or class of an individual includes income, education, and occupation. With that in mind, this research includes a broader framework of SES, by integrating a combination of quantiles of income, levels of educational achievements and categories of labour occupation.

1.5.2.1 Interaction between air pollution-related mortality and quantiles of income

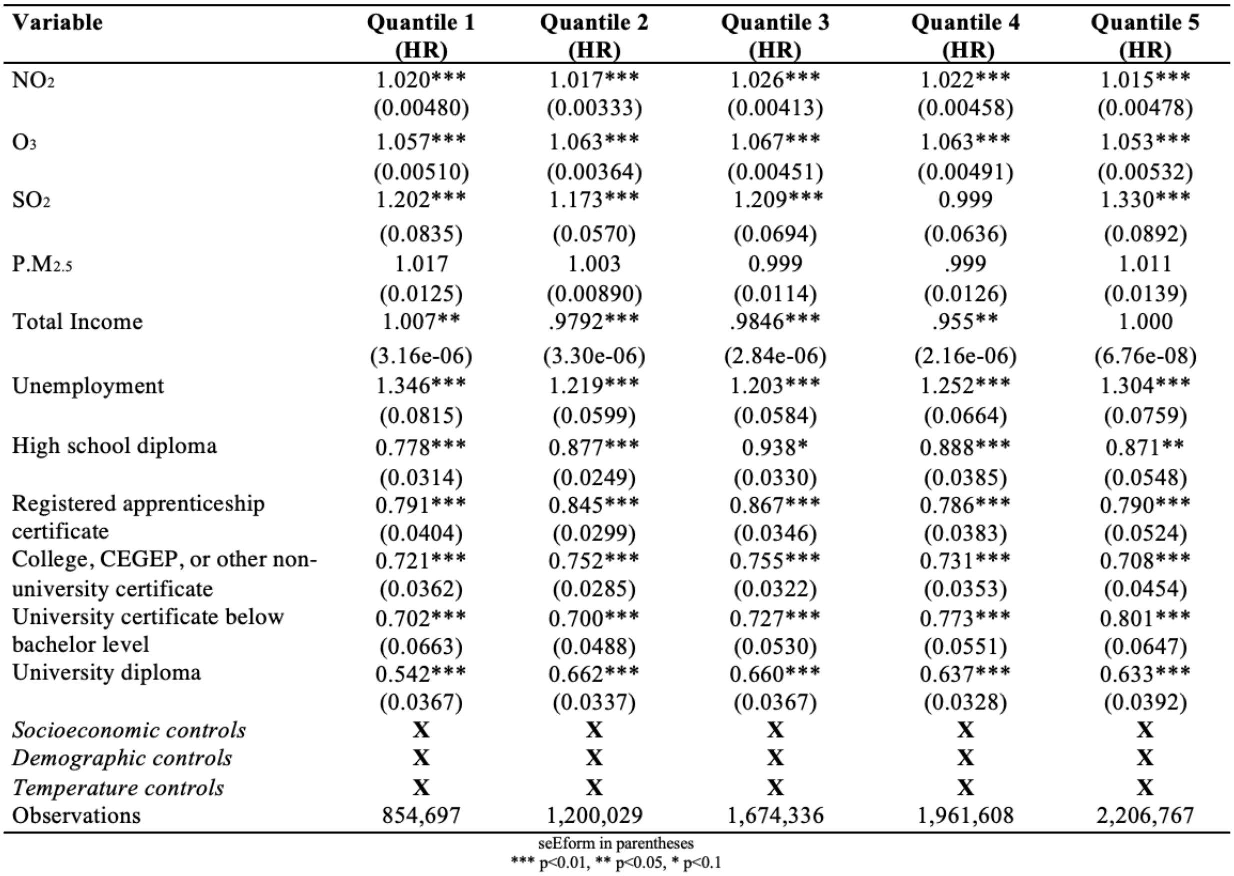
In this section, we analyze how the effect of air pollution on mortality hazards ratio varies across quantiles of income, by doing a regression for each group. A pooled regression would have been a better option as it would have interaction terms, but due to limited access to data sets, we could not perform this method. In **Table 6**, the columns are in ascending order of income quantiles. At first, we find that NO_2, O_3 and SO_2 increase the risk of mortality in all quantiles, at a 1% level of significance, except for SO_2 in the fourth quantile.

Second, individuals in the third and fourth quantile of income have the highest hazards ratio of mortality related to NO_2 of 2.6% and 2.2%, respectively. However, individuals in the first and second quantiles are following closely with hazards of 2% and 1.7%. The lowest risk of mortality appears for individuals with higher incomes with 1.5%, which is in line with our hypothesis that potentially most deprived individuals bear a higher burden of the impacts of air pollution on health and counterbalances the fact that they are overall more exposed to the pollutant as seen in **Figure 1**. The higher hazards of mortality of the low to middle income individuals may be explained by the fact that they have more sensitivity factors as living in unsuitable housing, having an unhealthy lifestyle, being employed in environmental hazardous jobs, to name a few. For the ground-level ozone pollution, we observe similar patterns, whereas quantiles 2,3 and 4 have the highest risk of mortality by 6.3%, 6.7% and 6.3% respectively, followed by the poorest quantile with a risk of 5.7%. Again, the richest group of individuals is also impacted by O_3 but with the lowest ratio of 5.3%. These findings suggest the existence of health disparities associated with air pollution with respect to income. However, we observe different results for SO_2, whereas individuals in the richest quantile of income have the highest impact of SO_2 on mortality with a hazard of 33%, followed by the third quantile with 20.9% and no significant results for the fourth group. The SO_2 seems to impact less the poorest set of the population, with the first quantile having an increased risk of 20.2% and the second quantile of 17.3%.

These disparities can be partially explained by the non-linearity in the effect of pollution on mortality. As we observe in **Figure 3**, individuals with higher levels of income are exposed to higher levels of average concentration of SO_2. Therefore, an effect of a one unit increase of SO_2 might result in an exponential effect on risk of mortality. At last, the particulate matter results are all insignificant. This may be explained by the correlation between O_3 and NO_2 which may bias the result obtained for $PM_{2.5}$. Or, as we only account for 2011-2016, the variation in the data sets may not be sufficient to obtain significant results and, that even if in the single and multiple pollutant model, hazards of mortality related to $PM_{2.5}$ showed significant results.

Table 6

Interaction between air pollution-related mortality and quantiles of income



Variable	Quantile 1 (HR)	Quantile 2 (HR)	Quantile 3 (HR)	Quantile 4 (HR)	Quantile 5 (HR)
NO_2	1.020***	1.017***	1.026***	1.022***	1.015***
	(0.00480)	(0.00333)	(0.00413)	(0.00458)	(0.00478)
O_3	1.057***	1.063***	1.067***	1.063***	1.053***
	(0.00510)	(0.00364)	(0.00451)	(0.00491)	(0.00532)
SO_2	1.202***	1.173***	1.209***	0.999	1.330***
	(0.0835)	(0.0570)	(0.0694)	(0.0636)	(0.0892)
$P.M_{2.5}$	1.017	1.003	0.999	.999	1.011
	(0.0125)	(0.00890)	(0.0114)	(0.0126)	(0.0139)
Total Income	1.007**	.9792***	.9846***	.955**	1.000
	(3.16e-06)	(3.30e-06)	(2.84e-06)	(2.16e-06)	(6.76e-08)
Unemployment	1.346***	1.219***	1.203***	1.252***	1.304***
	(0.0815)	(0.0599)	(0.0584)	(0.0664)	(0.0759)
High school diploma	0.778***	0.877***	0.938*	0.888***	0.871**
	(0.0314)	(0.0249)	(0.0330)	(0.0385)	(0.0548)
Registered apprenticeship certificate	0.791***	0.845***	0.867***	0.786***	0.790***
	(0.0404)	(0.0299)	(0.0346)	(0.0383)	(0.0524)
College, CEGEP, or other non-university certificate	0.721***	0.752***	0.755***	0.731***	0.708***
	(0.0362)	(0.0285)	(0.0322)	(0.0353)	(0.0454)
University certificate below bachelor level	0.702***	0.700***	0.727***	0.773***	0.801***
	(0.0663)	(0.0488)	(0.0530)	(0.0551)	(0.0647)
University diploma	0.542***	0.662***	0.660***	0.637***	0.633***
	(0.0367)	(0.0337)	(0.0367)	(0.0328)	(0.0392)
Socioeconomic controls	X	X	X	X	X
Demographic controls	X	X	X	X	X
Temperature controls	X	X	X	X	X
Observations	854,697	1,200,029	1,674,336	1,961,608	2,206,767

seEform in parentheses

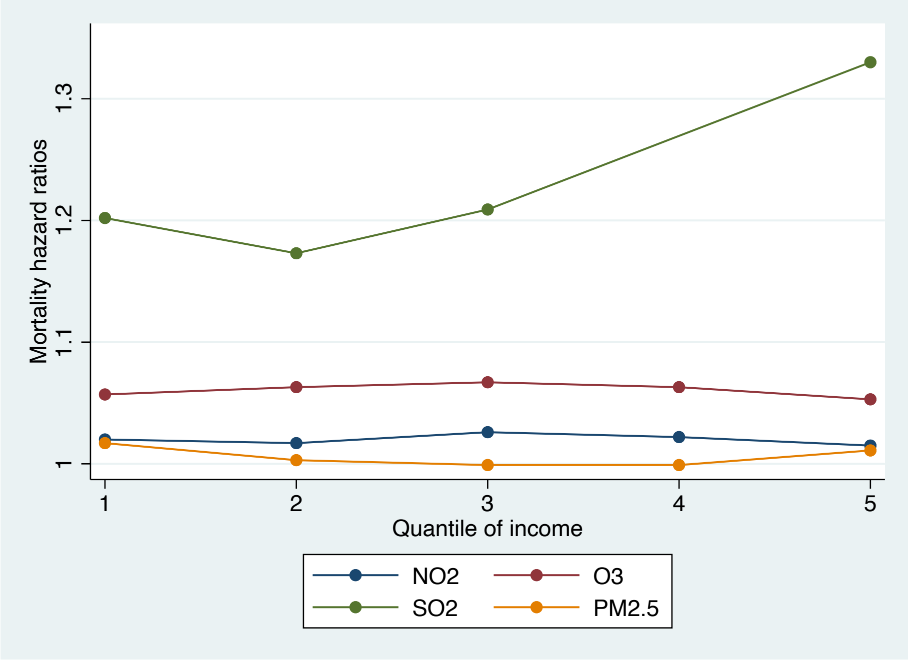
*** p<0.01, ** p<0.05, * p<0.1

Being unemployed remains a factor which increases the probability of mortality for all groups of income, however, the middle class has the lowest ratios. Consistently, total income and education is significantly and negatively associated with air pollution-related mortality throughout all income quantiles. Moreover, as we have seen in **Figures 1 and 2**, individuals in the 80th percentile of income and higher had higher exposure to NO_2 and the relationship between concentration of O_3 was positive with quantiles of income, however, richer individuals remain with lower mortality risks related to these pollutants. Potential reason may be because the richer sub-group of individuals might have better access to health care, or have better health behaviours (diet, exercising, etc.), for example. Nevertheless, we did not have access to these primary data that could affect the mortality risks. Therefore, some variables may overestimate their effects on mortality.

In brief, we find disparities in health outcomes associated to air pollution according to quantiles of income. As shown in **Figure 5**. Individuals in the highest quantile of income have lower hazards of mortality associated with NO_2 and O_3 compared to other quantiles of income. Nonetheless, the differences in ratios are not substantial, with a difference of 1.1% for the NO_2, between the least affected and the most affected and 1.4% for the O_3. Further, quantile 2 had the lowest hazards ratio of mortality related to the SO_2 pollutant, with a difference of 15.7% with the richest quantile. Note also that these disparities might also reflect non-linearities in the effect of pollution on mortality, as these income groups are exposed to different average levels of pollution (see **Figures 1-4**)

Figure 5

Hazards of mortality related to air pollution (NO_2, O_3, SO_2 and $PM_{2.5}$) by quantiles of Income

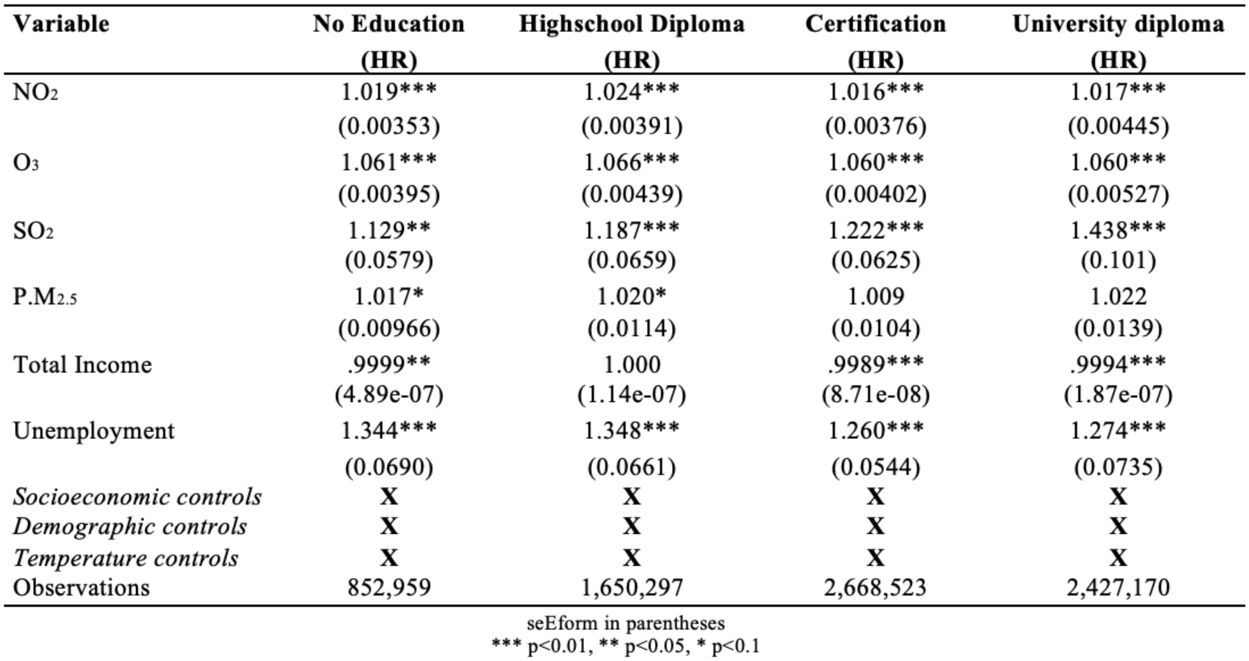


1.5.2.2 Interaction between air pollution-related mortality and education level

Education and health are intrinsically linked. Research demonstrates a strong association between education and life expectancy and health behaviours. Ross et al (1995) demonstrated that well-educated individuals are less likely to be unemployed, are more likely to occupy fulfilling and rewarding jobs, have higher incomes and have low economic hardship. In turn, these social achievements significantly improve health in all analyses. Further, the well-educated report a greater sense of control over their lives and their health, leading to better health outcomes. In our previous models, we observed that education was negatively and significantly related to mortality. Going further in our analysis of SES disparities in air pollution-related mortality, we divided individual educational achievement into four categories: the first category being individuals with no diploma, certificate, or degree, the second being individuals who possess a high school diploma or equivalency certificate followed by individuals with a registered certificate and other non-university certificate or diploma, and lastly individuals with university diploma of bachelor level and higher. In **Table 7**, the objective is to observe whether higher educational achievement could mitigate the impacts of exposure to air pollution on health.

Table 7

Interaction between air pollution-related mortality and educational level achievement



Variable	**No Education (HR)**	**Highschool Diploma (HR)**	**Certification (HR)**	**University diploma (HR)**
NO_2	1.019***	1.024***	1.016***	1.017***
	(0.00353)	(0.00391)	(0.00376)	(0.00445)
O_3	1.061***	1.066***	1.060***	1.060***
	(0.00395)	(0.00439)	(0.00402)	(0.00527)
SO_2	1.129**	1.187***	1.222***	1.438***
	(0.0579)	(0.0659)	(0.0625)	(0.101)
$P.M_{2.5}$	1.017*	1.020*	1.009	1.022
	(0.00966)	(0.0114)	(0.0104)	(0.0139)
Total Income	.9999**	1.000	.9989***	.9994***
	(4.89e-07)	(1.14e-07)	(8.71e-08)	(1.87e-07)
Unemployment	1.344***	1.348***	1.260***	1.274***
	(0.0690)	(0.0661)	(0.0544)	(0.0735)
Socioeconomic controls	**X**	**X**	**X**	**X**
Demographic controls	**X**	**X**	**X**	**X**
Temperature controls	**X**	**X**	**X**	**X**
Observations	852,959	1,650,297	2,668,523	2,427,170

seEform in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

In sum, NO_2, O_3 and SO_2 all increases significantly the risk of mortality. Whereas $PM_{2.5}$ has no significant results. Debuting with the nitrogen dioxide, we observe that individuals with no education and with only a high school diploma experience higher hazards of mortality related to NO_2 of 1.9% and 2.4%, respectively, compared to individuals with a certificate or a university diploma, having ratios of 1.6% and 1.7%, respectively. For the ozone, we observe the same pattern in the disparities of hazards between group. However, the magnitude of the effect of O_3 is almost the same throughout the four groups. Regardless of the small differences between hazard ratios related to NO_2 and O_3, these results demonstrate that higher levels of education may help mitigate some negative effects of pollution and that there is a higher vulnerability in groups of individuals with lower SES. As in **Table 6**, we observe the inverse of the impacts for SO_2, whereas an individual with higher levels of educational achievement is experiencing extensively higher hazards of mortality. Individuals with a certificate have a risk of mortality of 22.2%, and individuals with a university diploma experience the double of this risk, with a hazard ratio of 43.8%. On the other hand, individuals with no education have a probability of mortality of 12.9% and the ones with high school diplomas of 18.7%. Disparities in the results may be explained by the level of physical activities individuals at study perform. Potentially, individuals with higher education are more likely to have the information on the benefits of exercising, and consequently are more active. However, people who exercise outdoor have higher exposure to Sulphur dioxide than people who are less active (U.S. National Park Service (NPS)).

1.5.2.3 Interaction between air pollution-related mortality and labour occupation

Certain workplaces have a higher presence of hazardous substances, especially airborne pollution. If exposure continues over longer periods, even at a low level, such workplace pollutants may affect workers' health. In **Table 8**, we observe if a variation in the concentration of air pollution leads to differences in hazards of mortality according to labour categories (see Appendix A). We created categories of labour occupation based on the North American Industry Classification System of 2007 and the labour employment are regrouped based on exposure to outdoor air pollution. We have regrouped individuals working in professional and management sectors in a model of low exposure to air pollution. The following categories: Agriculture, forestry, fishing and hunting, Mining, quarrying, oil and gas extraction, construction, manufacturing, wholesale trade, retail trade and transportation and warehousing are analyzed separately as we presume those occupations occur more extensively outside whereas exposure to outdoor air pollution may be higher. As results, we observe that individuals with jobs considered as being less exposed to air pollution have an increased risk of mortality associated to NO_2 of 2.6%, at 1% level of significance. Jobs in agriculture have an increased risk of mortality of 3.7%, at 10% level of significance and individuals working in construction of 2.2% at a 5% level of significance. The other categories of labour have increased hazards of mortality related to NO_2 but with no significance in the results. On the other hand, the effect of O_3 significantly increased the risk of mortality for every labour category, with manufacturing, agriculture and wholesale being the most affected with 7.7%, 7% and 6.7% respectively. In terms of SO_2, individuals working in low pollution exposure jobs and manufacturing have 31.1% and 31.5% increased risk, at 1% level of significance, respectively. The rest of labour categories have increased hazards of mortality related to SO_2, but with no significance in the results. In sum, individuals in agriculture are disproportionately affected by NO_2 and O_3 and workers in manufacturing have the highest ratios of hazards related to O_3 and SO_2. That is potentially due to higher exposure to pollution at work (which can be unrelated to exposition in the postal code of residence). We also observe that the low-pollution exposure category has significant and increased ratios of mortality related to NO_2, O_3 and SO_2, even if the jobs classified in this labour category are consider as being in high SES and low exposure to outdoor pollution. Our results suggest that those individuals may live in areas with high exposure to air pollution or possess other sensitivity factors that affect their health outcomes, as their ability to take care of their health or have timely access to health care. Finally, our analysis does not take into consideration indoor pollutants that have the potential to harm human health and may be correlated with both income and outdoor pollution, leading to the possibility of a biased result.

1.5.2.4 Interaction between air pollution-related mortality and ethnic groups

The analysis of the interaction between ethnic groups, air pollution and mortality has the potential to contribute to the growing literature on environmental justice issues, particularly the one on environmental racism in Canada. This issue refers to the fact that polluting industries or other environmental hazards may be disproportionately found in Aboriginal, Afro-Canadian, and other ethnic communities. We can already witness some of those phenomena in Canada. An example is the well-known case of environmental racism in Nova Scotia called Africville. Since 1960, a fertilizer plant, a slaughterhouse, a tar plant, a stone and coal crushing plant and a cotton mill were all established in this neighbourhood predominantly inhabited by Afro-Canadians immigrants (LaPresse, 2021). Whereas in Montreal, Québec, heat islands[5] are mainly found in neighbourhoods with a higher density of ethnic minor visibility communities (U.S. EPA, 2022). The health of these populations is put at risk; however, little investigation of the impacts is being assessed. Going further, we are interested to observe whether some ethnic groups bear disproportional risk of mortality following a variation in the concentration of air pollution.

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[5] Heat islands are urbanized areas that experience higher temperatures than outlying areas. Structures such as buildings, roads, and other infrastructure absorb and re-emit the sun's heat more than natural landscapes such as forests and water bodies. Urban areas, where these structures are highly concentrated and greenery is limited, become "islands" of higher temperatures relative to outlying areas. Daytime temperatures in urban areas are about 1–7°F higher than temperatures in outlying areas and nighttime temperatures are about 2-5°F higher.

We will analyze current disparities of the air pollution-related mortality of the following ethnic visible minority groups: Afro-Canadians, Latinos, and Asians compared to Caucasians. This step contributes to the quantification of the impacts of environmental hazards on ethnic communities in Canada. In the first column of **Table 9**, Afro-Canadians have no significant impacts on their hazards of mortality related to NO_2 and O_3. However, they are disproportionately affected by SO_2 compared to individuals that are not part of the ethnic visible minority category. In the second column, we observe that Latinos have a significant increased risk of mortality related to NO_2, O_3 and SO_2, with HR of 14.3% related to NO_2 and 53.6% related to SO_2, compared to 1.9% and 20.2% of the not ethnic visible minority group. Latinos also increased risk of 5.4% related to O_3, however, Caucasians have an even higher risk of non accidental mortality of 6.3%. In the third column, we observe that individuals originally from Asia have an increased risk of mortality related to NO_2, O_3 and SO_2. Their NO_2 ratios are twice higher than the one of Caucasian's and ratios related to SO_2 are of 32.1%. Nevertheless, we observe a slightly smaller risk of 10% for the O_3 pollutant. At last, only the Caucasians have a positive hazard of mortality related to $PM_{2.5}$ of 1.7%. Based on these observations, we are interested to investigate why some ethnic groups are impacted by one pollutant and not another.

The association between an ethnic group and health outcomes related to specific pollutants may be intertwined with ancestry and heritage, as well as cultural, structural, economic and institutional factors that we could not take into account in this analysis (Flanagin et al. 2021). Several studies demonstrate that there are differences in the health responses to pollutants across different ethnic groups. For example, Dehmo et al (2021) investigated the relationship between fine particulate matter ($PM_{2.5}$) exposure and cardiovascular disease (CVD) mortality among different ethnic groups in the United States and they found that $PM_{2.5}$ exposure was associated with a higher risk of CVD mortality in non-Hispanic blacks and Mexican Americans compared to non-Hispanic whites. Moreover, Astell-Burt et al (2013) investigated the effects of air pollution exposure on respiratory health outcomes among different ethnic groups in New York City. The study found that non-Hispanic blacks and Mexican Americans were more likely to experience respiratory symptoms such as coughing and wheezing compared to non-Hispanic whites. However, they highlight the need for further research in this area to understand the underlying mechanisms of the present health disparities.

Possibly, a person's genetics may convey certain health-related predispositions, or it can bear a disproportionate burden of disease compared to other ethnic groups, making them more vulnerable to a certain pollutant. Or, because the effect of exposure to air pollution is not linear nor constant, the effect of a little variation in the concentration of a pollutant may have exponential effects on health. If certain ethnic groups are clustered in areas that are not near pollution sources of NO_2, for example. They are less likely to experience substantial effects of a variation of the pollutant versus a highly exposed group.

Table 9

Interaction between air pollution and ethnic group

Variable	Afro Canadian (HR)	Latino (HR)	Asian (HR)	Not visible minority (HR)
NO_2	1.006	1.143***	1.040***	1.019***
	(0.0158)	(0.0312)	(0.00743)	(0.00209)
O_3	1.004	1.023	1.054***	1.063***
	(0.0231)	(0.0442)	(0.0106)	(0.00228)
SO_2	2.482***	5.487***	1.536***	1.202***
	(0.635)	(2.916)	(0.241)	(0.0350)
$P.M_{2.5}$	0.948	0.933	0.951	1.017***
	(0.0537)	(0.109)	(0.0312)	(0.00589)
Total Income	.99897***	1.0002	.9991	.9993***
	(3.35e-06)	(4.36e-06)	(8.04e-07)	(1.34e-07)
Unemployment	1.466	1.564	1.157	1.312***
	(0.350)	(0.705)	(0.152)	(0.0341)
High school diploma	0.906	1.182	1.016	0.878***
	(0.152)	(0.379)	(0.0757)	(0.0162)
Registered apprenticeship certificate	0.762	0.762	0.808	0.826***
	(0.148)	(0.330)	(0.107)	(0.0178)
College, CEGEP, or other non-university certificate	0.712*	0.738	0.789**	0.726***
	(0.134)	(0.312)	(0.0816)	(0.0160)
University certificate below bachelor level	0.710	0.708	0.881	0.724***
	(0.205)	(0.452)	(0.103)	(0.0263)
University diploma	0.739	0.636	0.721***	0.609***
	(0.163)	(0.284)	(0.0638)	(0.0151)
Socioeconomic controls	X	X	X	X
Demographic controls	X	X	X	X
Temperature controls	X	X	X	X
Observations	109,957	49,759	642,499	6,529,352

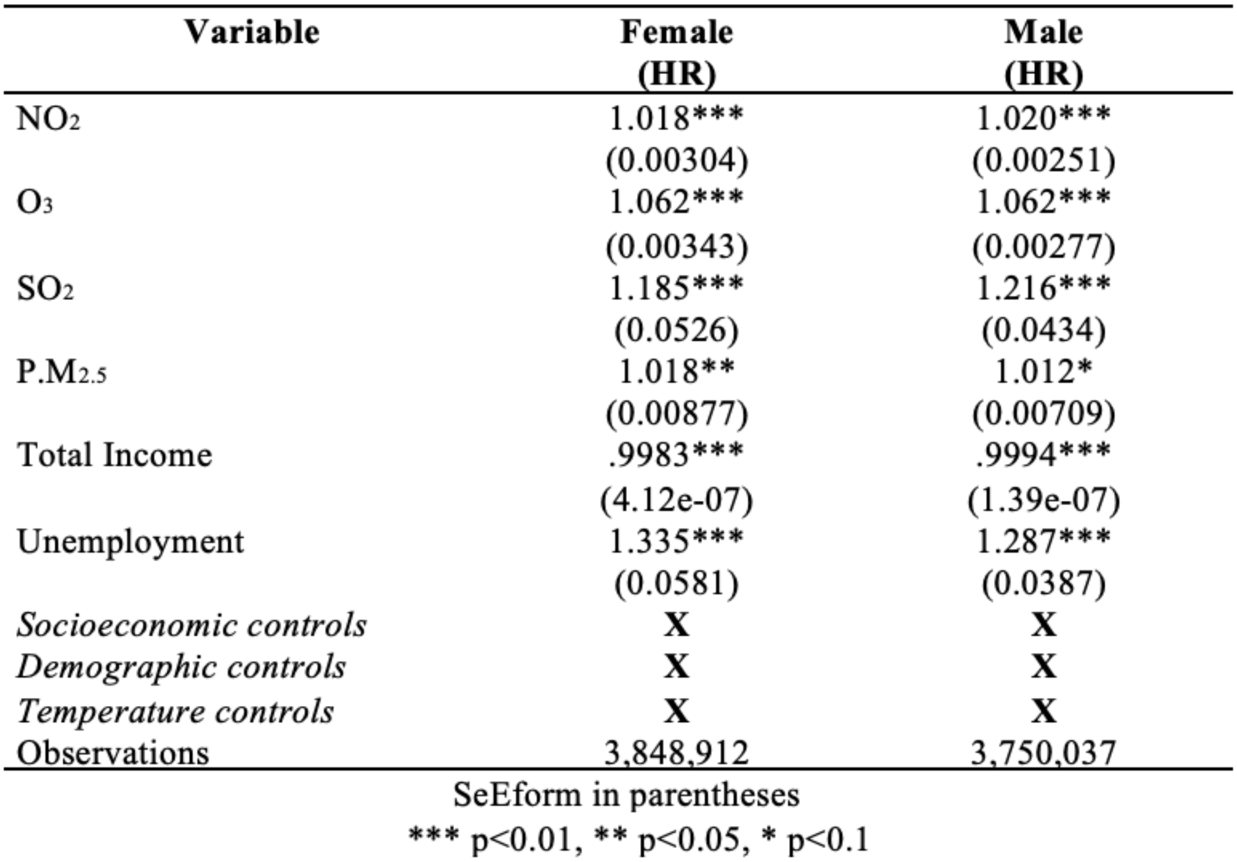
seEform in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

1.5.2.5 Gender analysis(female and male)

In the context of mapping environmental hazard risks across the Canadian population, we examine the relationship between air quality and mortality hazard ratios for females and males, separately. Notice, the NHS 2011 data sets do not include non binary and ungendered categories. In **Table 1**, the female incidence rates of mortality are lower than those of males, however, in **Table 10** estimates, we are interested to analyze which sex may be more vulnerable to air pollution-related mortality. While both genders are affected by air pollution, hazard ratio related to NO_2 and SO_2 are higher for males. For the O_3 pollutant, both sexes have an increased impact of 6.2% and hazards of females related to $PM_{2.5}$ are higher, with an increased risk of 1.8%, at a 5% level of significance, versus 1.2%, at a 10% level of significance for men. The health disparities observed within gender between the different air pollutants may be attributable to socially derived gender exposures, to sex-linked physiological differences, or the combination of the two (Clougherty 2010).

Table 10
Gender analysis



Variable	Female (HR)	Male (HR)
NO_2	1.018***	1.020***
	(0.00304)	(0.00251)
O_3	1.062***	1.062***
	(0.00343)	(0.00277)
SO_2	1.185***	1.216***
	(0.0526)	(0.0434)
$P.M_{2.5}$	1.018**	1.012*
	(0.00877)	(0.00709)
Total Income	.9983***	.9994***
	(4.12e-07)	(1.39e-07)
Unemployment	1.335***	1.287***
	(0.0581)	(0.0387)
Socioeconomic controls	X	X
Demographic controls	X	X
Temperature controls	X	X
Observations	3,848,912	3,750,037

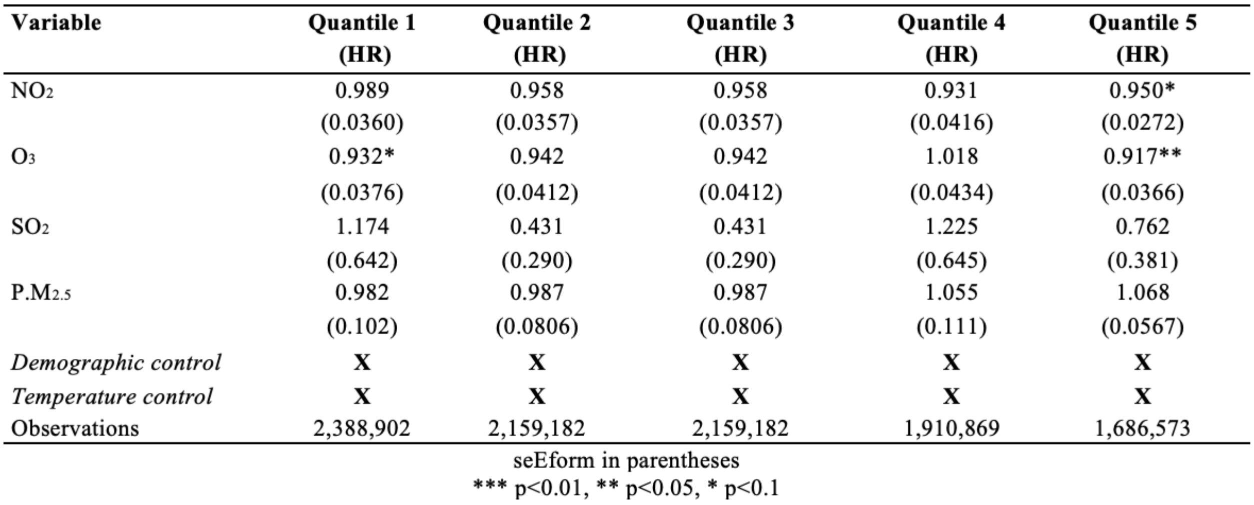
SeEform in parentheses
*** p<0.01, ** p<0.05, * p<0.1

1.5.2.6 Interaction between atmospheric pollution and area-level socioeconomic status

To contribute to the environmental inequality literature, we will analyze the socioeconomic disparities of health related to air pollution according to area-level SES metrics. Here, we address the methodological issue of the persistent use of whether individual or area-level SES metrics in health studies. Using both level data may allow a better understanding of the role of SES in the air pollution-health association. To date, only several studies have included both levels of data and only studies from Canada on air pollution inequalities have not embraced the use of an SES index (Hajat et al 2015, p.446). Therefore, we explore the relationship between mortality outcomes and area-level marginalization by using the census- and geographically based material deprivation index. The material deprivation index "has been demonstrated to be associated with health outcomes including hypertension, depression, youth smoking, alcohol consumption, injuries, body mass index and infant birthweight" (citation: Can-Merge user guide, 2012). The index has been constructed based on six indicators: Proportion of the population aged 20+ without a high-school diploma, families who are lone parent families, receiving government transfer payments, aged 15+ who are unemployed, considered low-income and proportion of the population of households living in dwellings that need a major repair. In **Table 11**, quantiles are in ascending order, with quantile 1 being the least deprived and quantile 5 being the most deprived. We found almost no significant results for either of our pollutants. For individuals being in the most deprived quantile, we found counter-intuitive results, where an increase in NO_2 and O_3, reduces the risk of mortality by 5% at a 10% level of significance, and by 8,3% at a 5% level of significance, respectively.

Table 11

Interaction between air pollution and area-level socioeconomic status



Variable	**Quantile 1 (HR)**	**Quantile 2 (HR)**	**Quantile 3 (HR)**	**Quantile 4 (HR)**	**Quantile 5 (HR)**
NO_2	0.989	0.958	0.958	0.931	0.950*
	(0.0360)	(0.0357)	(0.0357)	(0.0416)	(0.0272)
O_3	0.932*	0.942	0.942	1.018	0.917**
	(0.0376)	(0.0412)	(0.0412)	(0.0434)	(0.0366)
SO_2	1.174	0.431	0.431	1.225	0.762
	(0.642)	(0.290)	(0.290)	(0.645)	(0.381)
$P.M_{2.5}$	0.982	0.987	0.987	1.055	1.068
	(0.102)	(0.0806)	(0.0806)	(0.111)	(0.0567)
Demographic control	**X**	**X**	**X**	**X**	**X**
Temperature control	**X**	**X**	**X**	**X**	**X**
Observations	2,388,902	2,159,182	2,159,182	1,910,869	1,686,573

seEform in parentheses
*** p<0.01, ** p<0.05, * p<0.1

1.6 Discussion

This research comports several important limitations. The first limitation is in the NHS dataset, it only has information on social characteristics for the 2011 year. Thus, we could not account for changes from 2011 to 2016 in the total income, education achievements, labour occupation, to name a few that could have affected the impacts of changes in air pollution on health. Further, due to the unavailability of the data, we could not include behavioural information of the subjects at study. Even if we have integrated some proxies for lifestyle, possible bias remains in our estimates because information on smoking and alcohol consumption, diet, obesity, and physical activity can have direct effects on health outcomes. Individual-level genetic factors can also have an incidence on mortality. Some subjects may have disadvantageous baseline health status. They could be immunosuppressed or severally ill due to genetic reasons, making them highly vulnerable to air pollution (Yang et al, 2009). As a result of the lack of information on individuals' health status, the mortality hazards ratio can be biased, and some pollutants and SES effect on the impact on mortality could be overestimated. Further, we could not include proximity to health institutions in our analysis as the data in CANUE was only available for 2019. The additional information on accessibility to health care can explain at some extend the variation in the health outcomes related to air pollution.

Also, our analysis excludes populations with indigenous identity to alleviate the analysis as their integration required various considerations. To produce more inclusive research in the future in the Canadian context, we must include indigenous population so as individuals aged $1-24$ years old. Further, there is relevance in integrating indoor air pollution into the analysis. High rates of concentration of air pollution are found in households and exposure to harmful air pollutants in the home results in an estimated 2 to 31 million deaths per year globally (The Lancet, 2021). Moreover, the inclusion of workplace indoor air pollution, such as gases or particulate matter, can contribute to expanding the analysis of the distribution of air pollution-related mortality by category of labour occupation.

1.7 Conclusion

This research had two primary objectives. At first, we have investigated whether air pollution, controlling for socioeconomic status at the individual-level had an impact on the mortality hazards ratio. Second, we have analyzed the interaction between multiple socioeconomic status and mortality related to air pollution. The purpose was to observe if there is variation in mortality due to specific social characteristics. These hypotheses were tested by performing a Cox Proportional Hazard model. We found that NO_2, O_3, SO_2 and $PM_{2.5}$ significantly increases the risk of mortality in both the simple and multiple pollutant models. These results showcase the negative impacts of atmospheric pollution on health and shed light on the importance of implanting policies for better air quality and projects of energy transition, such as the electrification of road transports. Moreover, we found disparities in health effects related to air pollution in different socioeconomic groups in the Canadian population. While individuals in all quantiles of income and all levels of education are impacted by air pollution, the richest and the most educated have the lowest hazard ratio related to NO_2 and O_3, but the highest ratios related to SO_2. Also, compared to males, females had only a higher ratio of mortality related to the $PM_{2.5}$.

These findings can be used for making better choices in terms of public policies. More adapted measures could have extensive implications for population's health and national healthcare expenses. In conclusion, this research is part of the growing literature on environmental inequality in Canada. The stake for public policies is potentially major, as we could reduce health inequalities by reducing environmental inequalities (Larrère et al. (2017). As more work is needed on the links between environmental and social inequities, Canada could benefit of a better understanding of environmental inequities by instituting an institution which brings together epidemiological studies on the health consequences of environmental factors in the public sector. For future research, it would be interesting to continue to investigate the interaction between social characteristics and the impacts of air pollution on different health outcomes, such as cancer, hospitalization, and occupation-linked diseases.

Acknowledgments

Calculated Nitrogen dioxide data, ozone metrics, SO_2 metrics and $PM_{2.5}$ metrics were indexed to DMTI Spatial Inc. postal codes and were provided by CANUE (Canadian Urban Environmental Health Research Consortium).

Conclusion générale

Traduction litterale de la conclusion en version anglaise, afin de satisfaire aux exigences de la M.Sc. Pour la correction du memoire, se referer a 1.7 Conclusion.

Cette recherche avait deux objectifs principaux. Premièrement, nous avons cherché à savoir si la pollution de l'air, en contrôlant le statut socio-économique au niveau individuel, avait un impact sur le ratio des risques de mortalité. Deuxièmement, nous avons analysé l'interaction entre le statut socioéconomique et la mortalité liée à la pollution de l'air. Le but était d'observer s'il existe une variation de la mortalité due à des caractéristiques sociales spécifiques. Ces hypothèses ont été testées en réalisant un modèle de risque proportionnel de Cox. Nous avons que les polluants NO_2, O_3, SO_2 et $PM_{2.5}$ augmenter les risques de mortalité dans les modèles singulier et multiple de polluants (**Table 3-4**). Ces résultats montrent les impacts négatifs de la pollution atmosphérique sur la santé et mettent en lumière l'importance d'implanter des politiques pour une meilleure qualité de l'air et de prioriser des projets de transition énergétique, tels que l'électrification des transports routiers. De plus, nous avons observé des disparités dans les effets sur la santé liés à la pollution atmosphérique dans différents groupes socioéconomiques de la population canadienne. Alors que les individus de tous les quantiles de revenus et de tous les niveaux d'éducation sont affectés par la pollution de l'air, les plus riches et les plus éduqués ont le ratio de risque le plus faible lié au NO_2 et au O_3 et les ratios les plus élevés liés au SO_2. Aussi, par rapport aux hommes, les femmes ont seulement un ratio de mortalité plus élevé lié aux $PM_2, 5$.

Ces résultats peuvent être utilisés pour faire de meilleurs choix en matière de politiques publiques. Des mesures plus adaptées pourraient avoir des implications importantes sur la santé de la population et les dépenses nationales de santé. En conclusion, cette recherche s'inscrit dans la littérature sur les inégalités environnementales au Canada. L'enjeu pour les politiques publiques est potentiellement majeur, puisque nous pourrions réduire les inégalités de santé en réduisant les inégalités environnementales (Larrère et al. (2017).
Comme il est nécessaire de poursuivre les travaux sur les liens entre les inégalités environnementales et sociales, le Canada pourrait bénéficier d'une meilleure compréhension des inégalités environnementales en instituant une institution qui rassemble les études épidémiologiques sur les conséquences sanitaires des facteurs environnementaux dans le secteur public. Pour les recherches futures, il serait intéressant de continuer à étudier l'interaction entre les caractéristiques sociales et les impacts de la pollution atmosphérique sur différents résultats de santé, tels que le cancer, l'hospitalisation et les maladies liées à la profession.

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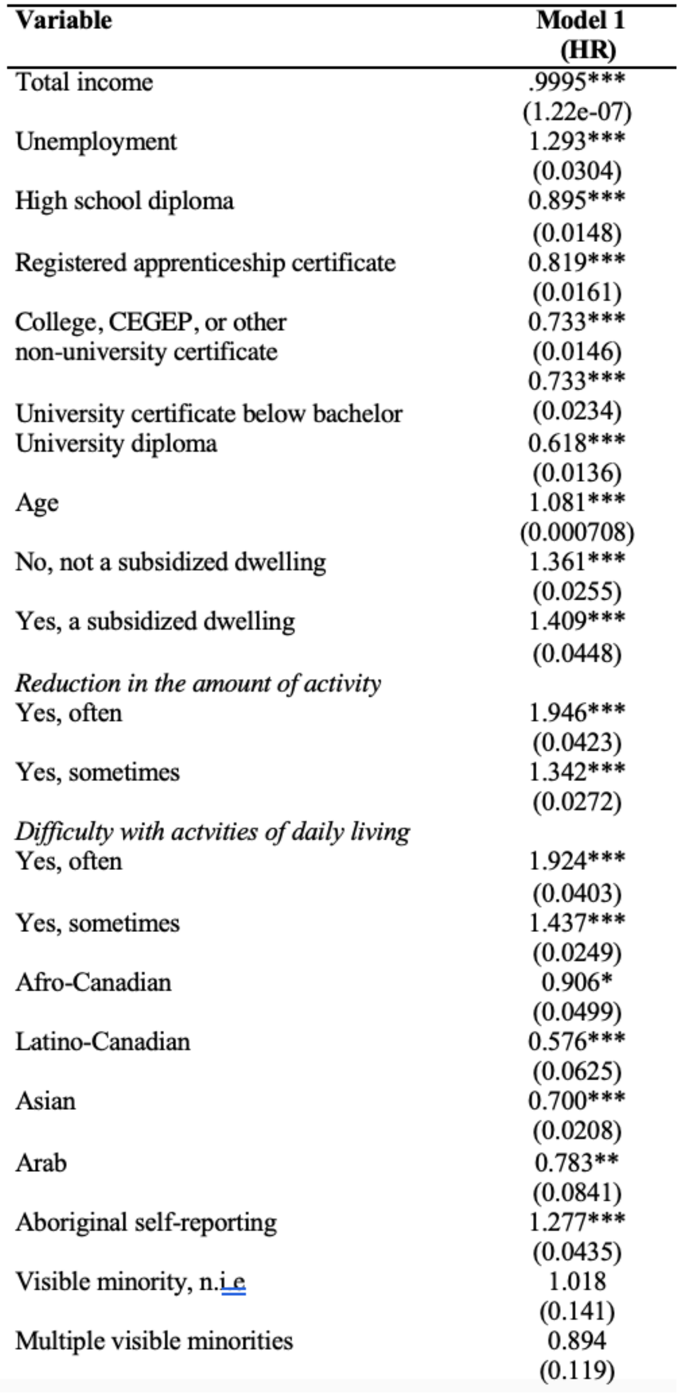
Appendix A

Table 2

Simple model of mortality



Variable	Model 1 (HR)
Total income	.9995*** (1.22e-07)
Unemployment	1.293*** (0.0304)
High school diploma	0.895*** (0.0148)
Registered apprenticeship certificate	0.819*** (0.0161)
College, CEGEP, or other non-university certificate	0.733*** (0.0146)
University certificate below bachelor	0.733*** (0.0234)
University diploma	0.618*** (0.0136)
Age	1.081*** (0.000708)
No, not a subsidized dwelling	1.361*** (0.0255)
Yes, a subsidized dwelling	1.409*** (0.0448)
Reduction in the amount of activity	
Yes, often	1.946*** (0.0423)
Yes, sometimes	1.342*** (0.0272)
Difficulty with actvities of daily living	
Yes, often	1.924*** (0.0403)
Yes, sometimes	1.437*** (0.0249)
Afro-Canadian	0.906* (0.0499)
Latino-Canadian	0.576*** (0.0625)
Asian	0.700*** (0.0208)
Arab	0.783** (0.0841)
Aboriginal self-reporting	1.277*** (0.0435)
Visible minority, n.i.e	1.018 (0.141)
Multiple visible minorities	0.894 (0.119)

Individual has an apartment	1.032*
	(0.0178)
Individual lives in mobile house	1.185***
Sex	1.747***
	(0.0230)
Immigrants	0.839***
	(0.0149)
Non-permanent residents	0.798
	(0.117)
Low-income person (below LIM-MI)	1.125***
	(0.0167)
Age 85yo and plus	1.278***
	(0.0332)
Marital status controls	**X**
Labour industry sectors controls	**X**
Temperature controls	**X**
Observations	8,563,583

seEform in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3

Simple pollutant model and non accidental mortality

Variable	Model 1 (HR)	Model 2 (HR)	Model 3 (HR)	Model 4 (HR)
NO$_2$	1.007***			
	(0.00152)			
O$_3$		1.053***		
		(0.00190)		
SO$_2$			1.274***	
			(0.0350)	
P.M$_{2.5}$				1.036***
				(0.00460)
Total Income	.9994 ***	.9994***	.9994***	.9994***
	(1.23e-07)	(1.24e-07)	(1.32e-07)	(1.23e-07)
Unemployment	1.296***	1.305***	1.287***	1.299***
	(0.0305)	(0.0307)	(0.0318)	(0.0306)
High school diploma	0.893***	0.890***	0.886***	0.892***
	(0.0148)	(0.0147)	(0.0154)	(0.0147)
Registered apprenticeship certificate	0.818***	0.820***	0.813***	0.817***
	(0.0161)	(0.0161)	(0.0168)	(0.0161)
College, CEGEP, or other non-university certificate	0.732***	0.725***	0.732***	0.731***
	(0.0146)	(0.0144)	(0.0153)	(0.0145)
University certificate below bachelor level	0.733***	0.740***	0.730***	0.730***
	(0.0234)	(0.0236)	(0.0245)	(0.0233)
University diploma	0.613***	0.623***	0.613***	0.614***
	(0.0135)	(0.0137)	(0.0142)	(0.0135)
Age	1.081***	1.081***	1.081***	1.081***
	(0.000708)	(0.000707)	(0.000745)	(0.000708)
No, not a subsidize dwelling	1.361***	1.353***	1.362***	1.356***
	(0.0255)	(0.0254)	(0.0267)	(0.0254)
Yes, a subsidized dwelling	1.409***	1.415***	1.400***	1.409***
	(0.0448)	(0.0451)	(0.0466)	(0.0449)
Reduction in the amount of activity				
Yes, often	1.944***	1.936***	1.923***	1.948***
	(0.0423)	(0.0421)	(0.0441)	(0.0424)
Yes, sometimes	1.344***	1.336***	1.349***	1.344***
	(0.0272)	(0.0270)	(0.0287)	(0.0272)
Difficulty with actvities of daily living				
2. Yes, often	1.927***	1.908***	1.913***	1.929***
	(0.0404)	(0.0400)	(0.0421)	(0.0404)
3. Yes, sometimes	1.435***	1.428***	1.421***	1.441***
	(0.0250)	(0.0248)	(0.0260)	(0.0250)
Afro-Canadian	0.894**	0.943	0.905*	0.903*
	(0.0493)	(0.0519)	(0.0540)	(0.0497)
Latino-Canadian	0.568***	0.600***	0.588***	0.570***
	(0.0617)	(0.0652)	(0.0688)	(0.0619)
Asian	0.690***	0.739***	0.692***	0.701***
	(0.0206)	(0.0220)	(0.0219)	(0.0208)

Arab	0.775**	0.814*	0.750**	0.775**
	(0.0832)	(0.0874)	(0.0871)	(0.0831)
Aboriginal self-reporting	1.279***	1.348***	1.244***	1.281***
	(0.0436)	(0.0460)	(0.0445)	(0.0441)
Visible minority, n.i.e	1.008	1.027	1.049	1.022
	(0.139)	(0.142)	(0.159)	(0.141)
Multiple visible minorities	0.865	0.934	0.802	0.892
	(0.116)	(0.125)	(0.122)	(0.119)
Legally married	0.725***	0.702***	0.721***	0.726***
	(0.0137)	(0.0133)	(0.0142)	(0.0137)
Separated, but still legally married	0.888***	0.862***	0.887***	0.891***
	(0.0322)	(0.0313)	(0.0337)	(0.0323)
Divorced	0.919***	0.896***	0.915***	0.918***
	(0.0211)	(0.0206)	(0.0219)	(0.0211)
Widowed	0.846***	0.819***	0.841***	0.846***
	(0.0216)	(0.0209)	(0.0225)	(0.0216)
Individual has an apartment	1.011	1.101***	1.034*	1.008
	(0.0180)	(0.0192)	(0.0186)	(0.0176)
Individual lives in mobile house	1.191***	1.228***	1.182***	1.201***
	(0.0510)	(0.0525)	(0.0528)	(0.0514)
Sex	1.749***	1.752***	1.741***	1.748***
	(0.0230)	(0.0230)	(0.0240)	(0.0230)
Immigrants	0.826***	0.840***	0.840***	0.829***
	(0.0150)	(0.0149)	(0.0159)	(0.0148)
Non-permanent residents	0.791	0.799	0.782	0.790
	(0.116)	(0.117)	(0.123)	(0.116)
Low-income person	1.128***	1.128***	1.130***	1.131***
	(0.0167)	(0.0167)	(0.0176)	(0.0168)
	(17.30)	(17.55)	(20.14)	(17.35)
Age 85yo and plus	1.279***	1.277***	1.284***	1.279***
	(0.0332)	(0.0332)	(0.0351)	(0.0333)
Marital status controls	**X**	**X**	**X**	**X**
Labour industry sectors controls	**X**	**X**	**X**	**X**
Temperature controls	**X**	**X**	**X**	**X**
Observations	8,542,388	8,563,583	7,608,426	8,558,159

seEform in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 8

Interaction between air pollution and Labor Occupation

Variable	**Low pollution exposure(HR)**	**Agriculture (HR)**	**Mining (HR)**	**Construction (HR)**	**Manufacturing (HR)**	**Wholesale trade (HR)**	**Retail trade (HR)**	**Transportation (HR)**
NO_2	**1.026*****	1.037*	0.991	1.022**	1.014	1.011	1.013	1.007
	(0.00580)	(0.0201)	(0.0234)	(0.00999)	(0.00910)	(0.0115)	(0.00854)	(0.0109)
O_3	1.066***	1.070***	1.062***	1.060***	1.077***	1.067***	1.055***	1.052***
	(0.00689)	(0.0140)	(0.0225)	(0.0107)	(0.00970)	(0.0134)	(0.00925)	(0.0115)
SO_2	1.311***	1.121	1.334	0.802	1.315**	1.059	1.137	1.122
	(0.118)	(0.216)	(0.293)	(0.115)	(0.159)	(0.178)	(0.135)	(0.167)
$P.M_{2.5}$	1.009	0.949	1.032	0.973	1.031	1.064*	1.035	1.049
	(0.0178)	(0.0340)	(0.0527)	(0.0262)	(0.0256)	(0.0361)	(0.0244)	(0.0314)
Total Income	.9993***	1.000	.9993	1.000***	.9982 ***	.9994	.9989*	.9975**
	(2.37e-07)	(7.44e-07)	(7.55e-07)	(7.65e-08)	(6.72e-07)	(4.76e-07)	(5.98e-07)	(1.13e-06)
Unemployment	1.214***	1.247**	1.167	1.339***	1.187**	1.268*	1.255***	1.308***
	(0.0701)	(0.138)	(0.210)	(0.0992)	(0.0977)	(0.156)	(0.105)	(0.127)
Highschool diploma	0.861**	0.969	1.166	0.897	0.874*	0.976	0.888	0.827**
	(0.0619)	(0.0982)	(0.225)	(0.0838)	(0.0670)	(0.109)	(0.0650)	(0.0726)
Certificates	0.908	1.014	0.891	0.883	0.834**	0.854	0.777***	0.763***
	(0.0756)	(0.118)	(0.174)	(0.0729)	(0.0694)	(0.116)	(0.0718)	(0.0778)
College	0.737***	0.762**	1.067	0.863	0.669***	0.756**	0.751***	0.705***
	(0.0543)	(0.102)	(0.224)	(0.0866)	(0.0607)	(0.0981)	(0.0657)	(0.0780)
University certificate below bachelor	0.785**	0.543**	1.335	0.912	0.818	1.254	0.650***	0.855
	(0.0763)	(0.150)	(0.477)	(0.186)	(0.131)	(0.222)	(0.108)	(0.165)
University diploma	0.633***	0.605***	0.539**	0.593***	0.687***	0.711**	0.607***	0.516***
	(0.0463)	(0.111)	(0.158)	(0.0951)	(0.0772)	(0.105)	(0.0680)	(0.0873)
Socioeconomic controls	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Demographic controls	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Temperature controls	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Observations	1,359,762	174,985	96,399	413,367	652,452	292,230	594,020	318,345

seEform in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$