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Long-term health and economic impacts of air pollution in Greater Geneva

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ABSTRACT

Introduction: We estimated the health and economic impacts of chronic exposure to air pollution for the Swiss part of the Greater Geneva area from 2016 to 2018.

Materials and methods: We extracted from fine-scale modelled concentration maps for two pollutant indicators, particulate matter $PM_{2.5}$ and nitrogen dioxide. Then, we performed a quantitative health impact assessment of the health burden attributable to anthropogenic-origin air pollution, and estimated the benefits of compliance with the federal Ordinance on Air Pollution Control (OAPC) limit values. Finally, we computed the economic impacts of these health effects.

Results: Exposure to fine particles of anthropogenic origin was responsible for 7.5% of annual mortality (280 deaths or 5,900 life years lost), for 14 lung cancers and for 68 strokes annually in the Canton of Geneva. Compliance with the OAPC limit value of 10 µg/m³ as an annual average would reduce annual mortality by 1.5% (62 deaths avoided or 1,300 life years gained). Exposure to anthropogenic-origin NO_2 was associated with 5.3% of annual deaths (approximately 200 deaths per year). The estimated total negative economic impacts of anthropogenic-origin fine particles were at least CHF_{2017} 1.3 billion per year, whereas compliance with the OAPC limit values would result in annual economic benefits of at least CHF_{2017} 290 million.

Conclusion: We confirmed that air quality remains a health issue on which stakeholder mobilisation is vital. Action plans should tackle emissions from freight and personal mobility, heating, industry and agriculture, while seeking to improve knowledge on health risks from air pollution exposure.

Introduction

More than 99 % of the world's population is exposed to air pollution levels exceeding the World Health Organization (WHO)'s guideline limits, with serious health consequences [1]. According to the Health Effect Institute, exposure to Particulate Matter (PM) is the major environmental cause of mortality and the 4th-ranked risk factor for early death worldwide, leading to 4.14 million premature deaths in 2019 [2], mostly in Asia. There are also documented causal links between air pollution and ischemic heart disease [3], cardiovascular risk [4],

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chronic lung disease, stroke, emergency room visits for asthma, all with substantial economic impacts [5] [6]. In addition, negative impacts are suspected on diabetes, pregnancy and the central nervous system [7], while some health events where PM exposure is implicated, such as respiratory discomfort or irritation, are not included in any health indicator.

In Switzerland, as in many European countries, concentrations of PM with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$), of NO_2 and of O_3 remain too high, despite a drastic reduction since 1986, when the Ordinance on Air Pollution Control (OAPC) was enforced [8]. This reduction lowered the early-death risk-factor ranking of air pollution in Switzerland, from 8th position in 1990 to 11th in 2019 [9]. Over the last ten years, annual means for PM_{10} measured at stations of the National Air Pollution Monitoring Network (NABEL) have been below the Ambient Limit Value (ALV) of 20 µg/m^3 specified in the OAPC. Similarly, concentrations of NO_2 have remained below 30 µg/m^3 in urban/suburban and rural areas, as required by the OAPC.

Yet the economic attractiveness of the Canton of Geneva has lured cross-border workers living in France to work in Switzerland, about 200,000 in 2016 [10]. In 2011, an average of 230,000 people crossed the Canton's border with an individual motor vehicle every working day, some 61,000 from the Canton of Vaud [11]. By heating, moving and working, all emit pollutants which, combined with the high population density, accentuate the health effects of air pollution in Greater Geneva. Close to busy roads, NO_2 concentrations exceed the ALV. In addition, an ALV of 10 µg/m^3 for $PM_{2.5}$ was introduced in 2018. Overall, there is a clear need for a health and economic impact evaluation of these two pollutants to inform decision-makers and address a societal concern.

Maintaining good air quality in Greater Geneva is challenging: the population is growing; the area is very dynamic economically and its air belongs to an inter-cantonal and cross-border region. Although improving air quality demands constant commitment and monetary investments, however, it is justified by concern over health and economic impacts. Air quality ranks high in the Organization for Economic Co-operation and Development (OECD) indicator of better living, based on its impact on health and life expectancy. Moreover, the importance of air quality for the quality of life in Geneva was underlined by 91% of respondents to the "Geneva 2050" consultation in 2019 [12] and local residents and associations regularly request Quantitative Health Impact Assessments (QHIA) (see [13] for Geneva international airport's development plan).

This article presents the results of the first study to assess both health and economic impacts of $PM_{2.5}$ and NO_2 ambient air pollution on the Swiss part of Greater Geneva, during the period 2016-2018 [14]. The QHIA method used here is supported by the WHO and was used by the regional unit of Santé publique France (SpF) on the French part of Greater Geneva [15].

The objectives of this study were first to characterize air pollution on a cross-border scale through harmonised concentration mapping. Second, this characterisation was used to compute a population-weighted concentration per municipality, and estimate the health impacts based on three "pollutant-health effect" pairs recommended by SpF [16]: total mortality for adults over 30 years old with $PM_{2.5}$ and NO_2 concentration and incidences of lung cancer and stroke for all ages with $PM_{2.5}$ concentration. Third, we estimated the air pollution health burden due to anthropogenic activities above background annual levels (5.5 µg/m^3 for $PM_{2.5}$ and 1.8 µg/m^3 for NO_2) and the benefits to be expected from compliance with OAPC ALVs (10 µg/m^3 for $PM_{2.5}$ and 30 µg/m^3 for NO_2). Finally, we computed the economic impacts (intangible and direct medical costs) associated with the health effects.

Materials and methods

We begin by describing the sample and data used, detailing the variables chosen and their measurement. Economic evaluation of the health impacts of air pollution proceeds in two stages. First, for each municipality of the study area, the concentrations of the pollutants under consideration are modelled and the population's exposure is computed. Then, the attributable health impacts are estimated under two exposure variation scenarios , using the AirQ+ [17, 18]. Second, economic unit values are applied to the numbers of cases attributable to each scenario. The section ends with details of how uncertainty is accounted for in these two steps.

Sample and data

The selected study period was 2016, 2017 and 2018, for which environmental and health data at the scale of Greater Geneva (including the French part) already exist.

Demographic and environmental data

Greater Geneva is a cross-border conurbation between Switzerland and France with a population of approximately one million (see Fig. 1) spread over approximately 200 municipalities and a territory of about 2,000 km^2. The population is growing throughout the agglomeration, particularly in the French part and in the District of Nyon [10]. Demographic data for the Swiss part are available by age, year and municipality on the Swiss Federal Statistical Office (SFSO) website [19]. The population we are interested in was the reference population for statistics: permanent residents. (The permanent resident population includes Swiss nationals with their main residence in Switzerland and foreigners with a residence permit of at least 12 months, or foreigners who have resided in Switzerland for at least 12 months). These data were then aggregated by age or by territory (District or Canton), as required by the analysis. Over the study period, the District of Nyon had 99,638 inhabitants, with 64,477 aged 30 or older (64.7%) and the Canton of Geneva had 494,751 inhabitants, with 325,476 aged 30 or older (65.8%). In total, the study area had 594,389 inhabitants, with 65.6% (389,953) aged 30 or older.

The Franco-Swiss cooperation in the Greater Geneva area enabled to characterise air pollution on a cross-border scale using harmonised concentration mapping. ATMO Auvergne Rhône Alpes' modelling provides coherent environmental data on the whole territory.

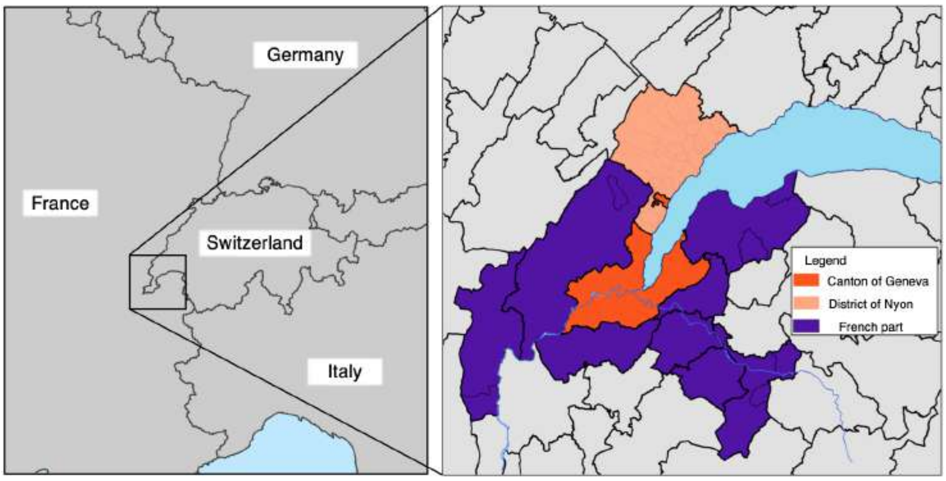

Fig. 1. Location of the study area. Left: Position of Greater Geneva in Western Europe, between France and Switzerland. Background map: Eurostat. Right: Cross-border conurbation of Greater Geneva. The Swiss part of Greater Geneva is represented in orange and the French part in purple. Background map: SITG

Health data

• Mortality: Data were obtained from the BEVNAT database and were provided by the SFSO for each year of the study period and each municipality, by 5-year age group. The average over the three years was combined with the exposure indicators, also calculated by municipality.

• Morbidity: Data were calculated from the MS database on "hospital medical statistics". This database provides data on all patients admitted to hospital (age at admission, region of residence, etc.), on diagnoses listed with ICD-10 codes and on length of stay [20]. The patient's place of residence is defined by MEDSTAT region, which depends on postal codes and whose borders differ somewhat from those of the municipalities. For this reason, health indicators related to morbidity were calculated and used at Canton or District level.

Economic data

Three components related to the cost of a health outcome can be distinguished: direct, indirect and intangible costs [21]. Direct costs cover medical and non-medical resources. The former include all medical resources consumed during patients' care (goods, services, consultations, drugs or hospitalisations, for instance). The latter include transportation, social support or major home modifications. Indirect costs cover resources lost by the patient or relatives: time off work, productivity loss, poorer access to employment, early retirement, etc. Intangible costs apply to the patient and his/her relatives and represent the loss of well-being due to fear, pain, psychological factors, loss of quality of life due to morbidity or premature mortality. As this study was part of the Geneva cantonal plan for measures for the protection of outdoor air, the point of view adopted was that of society and therefore includes all components: direct, indirect and intangible costs [21].

Because health impacts were estimated for the period 2016 to 2018 on the Swiss part of Greater Geneva, the currency chosen for cost evaluation was the Swiss franc of 2017 (CHF_{2017}). It was converted into current values based on the purchasing power parity (PPP)s provided by SFSO [22], the Harmonised Index of Consumer Prices (HICP) provided by SFSO [23] and Eurostat [24] and the euro-Swiss franc exchange rates available on the website of the cantonal statistics office (OCSTAT) [25], on average in 2017 1 CHF is equivalent to about 1 US dollar.

Measures of variables

The numerous health effects of air pollution cannot all be accounted for in a QHIA. To facilitate comparisons with our study area, we used the "pollutant-health effect" pairs recommended by the SpF guide and used by its regional unit in Auvergne Rhône Alpes for the study on the French part of Greater Geneva [15]. The long-term effects of exposure to $PM_{2.5}$ and NO_2 are expressed as Relative Risks (RR) for an air pollutant concentration increase of 10 µg/m^3, along with their 95% Confidence Interval (95%CI). Their computations rely on cohort studies observing over several years the evolving health of individuals living in differently exposed geographical areas. Confounding factors are controlled for by considering differences in individual characteristics (health status, smoking habits, chronic disease, occupational exposure, etc.).

Mortality data

We accounted for total mortality (ICD-10 codes A00-Y98) for adults over 30 years old. The long-term mortality RR for $PM_{2.5}$ (RR=1.15 [95%CI 1.05 ;1.25]) was based on the 22 European cohorts of the ESCAPE project and one French cohort (Gazel-air). It was higher than the 1.062

[95%CI 1.040 - 1.083] recommended in the HRAPIE project [26], and slightly exceeded the 1.12 [95%CI 1.06-1.19] obtained from ten European studies [27]. The long-term mortality RR for NO_2 (RR=1.023 [95%CI 1.008 ;1.037]) was similar to that used both in HRAPIE and in the latest WHO guidelines [28].

The gain in 30-year-olds' life expectancy was calculated from life tables constructed from age-specific mortality data [18]. The 92 municipalities were divided into 15 clusters of at least 20,000 inhabitants (from 20,668 inhabitants for Nyon to 200,448 inhabitants for the City of Geneva), which served as the basis for the life tables (The municipality of Céligny was included in the District of Nyon for territory continuity). The life table for each grouping was constructed by summing the age-specific mortality data for each municipality in the grouping.

Finally, the total number of years of life gained was calculated for the entire population of the different parts of the territory using the same groupings of municipalities. This calculation is the product of the gain in life expectancy at age 30 by the number of people over 30 years old for each group of municipalities [29] [30], approximated by the number of people in the class [30 years; 34 years] divided by 5.

Morbidity data

- Lung cancer: We accounted for the incidence of lung cancer (specific algorithm) for all ages (RR=1.09 [95%CI 1.04 ;1.14]), calculated based on the Geneva Tumor Registry for the Canton of Geneva. It represents the number of new cases diagnosed as "lung cancer" and does not take into account deaths. The incidence provided was a crude rate averaged over the years 2016 and 2017, i.e., without standardisation, calculated following the methodology published on the University of Geneva website [31]. It was impossible to obtain lung cancer incidence for the District of Nyon, since data are only available for the entire Canton of Vaud.
- Stroke: We accounted for the incidence of stroke (ICD-10 codes I60-I64) for all ages (RR=1.13 [95%CI 1.04 ;1.23]), as calculated by the Swiss Health Observatory (OBSAN) for the District of Nyon and the Canton of Geneva. Stroke incidence was averaged over the years of the study period. Because the MEDSTAT region boundaries do not correspond to those of Cantons and Districts, a population-based allocation key was used to assign stroke cases to the Canton of Geneva, the District of Nyon, or the rest of the Canton of Vaud. The calculated incidence rate took into account the first occurrences of stroke in hospital, delimited by ICD-10 codes I60-I64, adding all deaths where ICD-10 diagnosis codes I60-I64 were involved, and subtracting deaths occurring in hospital [32]. This rate considered the first occurrences of stroke for each patient since 2012 and was calculated per 100,000 population (crude rate).

Economic data: central monetary values

- Mortality: The standard framework for assessing the economic impact associated with mortality was based on either the Value of a Prevented Fatality (VPF) or the value of a life year (VOLY). To assess the intangible costs associated with mortality, we used both approaches, employing the values proposed by [29]. The central VPF of CHF_{2017} 6 million was the value recommended for the socio-economic evaluation of public investments in France [33], itself derived from an international meta-analysis [34]. The central VOLY was the average of i) the value of CHF_{2017} 226,000 proposed in [33] from the VPF considered as a flow of discounted life years and ii) the value of CHF_{2017} 85,300 obtained from surveys of the population on their willingness to pay to increase their life expectancy by one year [35]. We therefore used a VOLY of CHF_{2017} 157,000, which was consistent with the values obtained from a sample of 179

Swiss citizens [36], which ranged from CHF_{2005} 46,200 to 86,000 (i.e., from CHF_{2017} 92,000 to 172,000) depending on the scenario.

- Morbidity: For lung cancer, the value of CHF_{2017} 180,610 was derived from a study conducted for the Federal Office of Public Health [37], and took into account all medical costs per lung cancer patient throughout the patient's care. For stroke, the value of CHF_{2017} 94,651 [86,274; 103,557] took into account all direct medical costs related to the management of a patient with ischemic stroke in Germany, from the onset of the disease to the death of the patient [38]. The use of German data for a Swiss evaluation was justified by the similarity of the Swiss and German health care systems and of health expenditure conditions [37]. However, these monetary values will not be applied to all strokes attributable to $PM_{2.5}$ exposure, but only to those where death occurred in a health care facility and where there was a medical cost. This represents 98% of the cases in the District of Nyon and 94.5% in the Canton of Geneva.

Models and data analysis

Modelling of air pollutant concentrations

We were interested in the health effects of two pollution indicators: $PM_{2.5}$, which can be of natural origin (pollen, volcanic ash, Sahara sand, etc.) or anthropogenic origin (road traffic, mechanical abrasion, heating, waste incineration, industrial processes, etc.); and nitrogen dioxide (NO_2), which is mainly produced by combustion processes (motor vehicles for example). Their concentrations depend on various factors like meteorology (temperature, humidity, wind), local and regional topography, human activities. These two indicators were chosen because OAPC ALVs covering them have not been respected in recent years in Geneva's urban environment, and because of the availability of concentration maps produced by ATMO Auvergne Rhône Alpes.

The pollutant concentrations were first modelled on a regional scale, based on the register of western Switzerland (CADERO) and on that of France (spatialized regional inventory, ATMO Auvergne Rhône Alpes), with data provided per hectare or per km^2. They relied on a simulation model of pollutants in the common air basin of Greater Geneva developed in the Interreg project PACT'Air (Programme d'Actions Transfrontalier pour la qualité de l'Air du Grand Genève). These data were fed into the chemistry-transport model CHIMERE with meteorological and topographical data, yielding a raw regional map with a resolution of the order of a km. The data of this regional map were adjusted following a geostatistical approach, using the data of the measurement stations.

Finer-scale modelling was then performed, starting from the regional scale and adding the description of the streets and buildings as well as the road traffic emissions. This finer-scale modelling was based on the SIRANE model specific to urban and interurban environments, which provides geo-referenced data on pollutant concentrations as an annual average with a spatial resolution of 10 m.

Computation of indicators of population exposure

We assumed that exposure at place of residence is the best way to represent an individual's average exposure, as is standard in most epidemiological studies [16]. The population-weighted concentration per municipality was estimated by cross-referencing the spatial distribution of the population with that of the air pollution concentrations. Geo-referenced population data were provided by the SFSO for the year 2016, at a one-hectare resolution. These data were then disaggregated on a 10 m grid and the pollutant exposure indicators per municipality were calculated by cross-checking the population grid against the pollutant concentration map for that year in the municipality relative to the intersecting areas [16]. This yielded an exposure indicator for $PM_{2.5}$ and NO_2 per municipality for 2016, 2017 and 2018. The indicator used to estimate the health impacts over the whole study period per municipality was the average of the indicators per year.

Computation of health effects

Health effects were computed for each "pollutant-health effect" pair assuming a reduction of population exposure to air pollutant concentrations. This reduction was based on target values (annual average) for two scenarios in a counterfactual impact evaluation at the municipality level.

- **Anthropogenic-origin burden:** This scenario explored the weight of pollution related to anthropogenic activities; a feasible approach due to the absence of threshold effects of air pollution: there is no minimum air pollution concentration for observing impact [39]. The reference value for this scenario corresponded to the background pollution that would exist if all anthropogenic emissions were removed. To ensure comparability with the SpF study on the French part of Greater Geneva, the reference values for the " Anthropogenic-origin burden" scenario were based on air quality levels in a rural measurement station in the French department of Drôme, far from anthropogenic pollution sources. The reference pollutant concentration annual levels were 5.5 µg/m^3 for $PM_{2.5}$ and 1.8 µg/m^3 for NO_2.
- **Benefits from compliance with the OAPC:** This scenario examined the benefits that could be expected every year if each municipality's exposure indicator respected the OAPC ALVs, i.e., 10 µg/m^3 for $PM_{2.5}$ and 30 µg/m^3 for NO_2.

Computation of economic impacts

The economic valuation only considered health impacts associated with $PM_{2.5}$ exposure. For each scenario, intangible costs were estimated by multiplying the health benefit in terms of avoidance of deaths attributable to $PM_{2.5}$ exposure by the VPF, and by multiplying the health benefit in terms of life years gained by the VOLY. The direct medical costs were estimated by multiplying the cases attributable to $PM_{2.5}$ exposure by the direct medical cost of each patient with lung cancer or stroke. Overall, we obtained the monetary burden associated with exposure to anthropogenic-origin fine particles, and the monetary benefits from compliance with the OAPC ALV.

Accounting for uncertainties

Uncertainties in the estimation of health effects

The uncertainties involved in estimating health effects are related to those encountered in epidemiological studies, estimation of exposure indicators or data collection.

A first source of uncertainty, related to the selected RRs, is quantified statistically by the 95%CI derived from epidemiological studies and meta-analyses. An additional source concerns the transposability of an RR constructed for a specific pollution mixture and population to the conditions of the present study. While this uncertainty is limited by the choice of "pollutant-health effect" pairs from meta-analyses concerning populations close to the one studied, transposability remains a source of uncertainty regarding the mainly rural municipalities of the North of the Nyon District and the South-West municipalities of the Canton of Geneva, since the cohort studies were mainly carried out in an urban environment.

A second source of uncertainty concerns the estimation of populations' exposure to pollutants, which depends on the capacity of the model to reproduce actual pollution levels and on the modelling-based assessment of exposure. Model quality depends on the quality of the input data

(emission inventories, reliability of pollutant measurements, traffic model, geographical distribution of the population per hectare), and it is difficult to quantify this uncertainty precisely.
A third source comes from hospital data collection: follow-up of stroke patients, the imperfect overlap of MEDSTAT regions and borders of the Canton of Geneva and the District of Nyon.
Overall, the 95%CI can reasonably be considered to cover all the uncertainties related to exposure and health data [29].

Uncertainties in the monetary valuation of health effects

For monetary valuation, uncertainty in the estimation of health effects adds to that associated with each impact's monetary valuation. For the largest component of the economic benefits expected from an improvement in air quality, mortality, the uncertainty is more of a subjective than a purely scientific nature. Mortality valuation is not based on market prices and depends not only on the context of the death, which is taken into account in the valuation, but also on the population studied.
The techniques used to account for this uncertainty (use of the median and mean values as an interval, of a triangular-type probability distribution or of one constructed under the assumption of normality from an empirical standard deviation, of an uncertainty factor expressed in percentage of the central value) generally lead to a factor of around +/- 33%, as recommended by CAFE [40] or Aphekom [21]. We applied it strictly for the VPF, thus considered CHF_{2017} 6 [4; 8] million; we also applied it to value a case of lung cancer, thus considered CHF_{2017} 180,610 [120 407; 240, 813]. We proceeded in a different way to represent the uncertainty associated with VOLY, using the two values that led to the construction of the central value as bounds, i.e., a VOLY of CHF_{2017} 157,000 [85,300; 226,000]; and for a case of stroke, since the study in question [38] proposed a confidence interval of approximately -/+ 10%, i.e., a unit cost of CHF_{2017} 94,651 [86,274; 103,557].

Comprehensive consideration of uncertainties

We performed an independent uncertainty assessment, taking the central estimates as well as the 95%CI for the health effects, and applying to them the central monetary values as well as their upper and lower bounds. It should be noted that a comprehensive uncertainty assessment, which would jointly take into account all sources in an integrated Monte Carlo simulation approach [40], is methodologically preferable (see [41] for a detailed discussion). However, it seems that an independent assessment gives a reasonable approximation of the joint assessment (they differ by less than 20% in [42] ; by less than 3% in [43]).

Results and discussion

$PM_{2.5}$ and NO_2 exposure evaluation for each municipality

The annual average of the population-weighted $PM_{2.5}$ exposure indicator is 11.1 μg/m^3. Fig. 2a shows that 37 of the 45 municipalities of the Canton of Geneva and 16 of the 57 municipalities of the District of Nyon exceed the OAPC ALV (10 μg/m^3). We estimated that about 482,000 inhabitants of the Canton of Geneva (97% of the population) and 66,000 inhabitants of the District of Nyon (66% of the population) were exposed to annual $PM_{2.5}$ concentrations above the OAPC ALV. However, it should be noted that the concentration values in Geneva were higher than the concentrations observed more recently, in particular in 2020 and 2021 [44] [45], which indicates an improvement in air quality.

The annual average of the population-weighted NO_2 exposure indicator was 25.4 μg/m^3 for the whole study area. Fig. 2b shows that only the municipalities of the City of Geneva and Carouge exceeded the annual OAPC ALV (30 µg/m^3), i.e., municipalities with an average population of 222,000. It should be noted, however, that since NO_2 is a locally influenced pollutant, the average exposure indicator for a municipality can be lower than 30 µg/m^3 even when the ALV is not respected throughout the municipality. For this pollutant as well, a clear downward trend was observed in 2020-21 for NO_2 concentrations over the whole territory [44, 45], partially due to the exceptional health situation which helped reduce anthropogenic pollutant emissions.

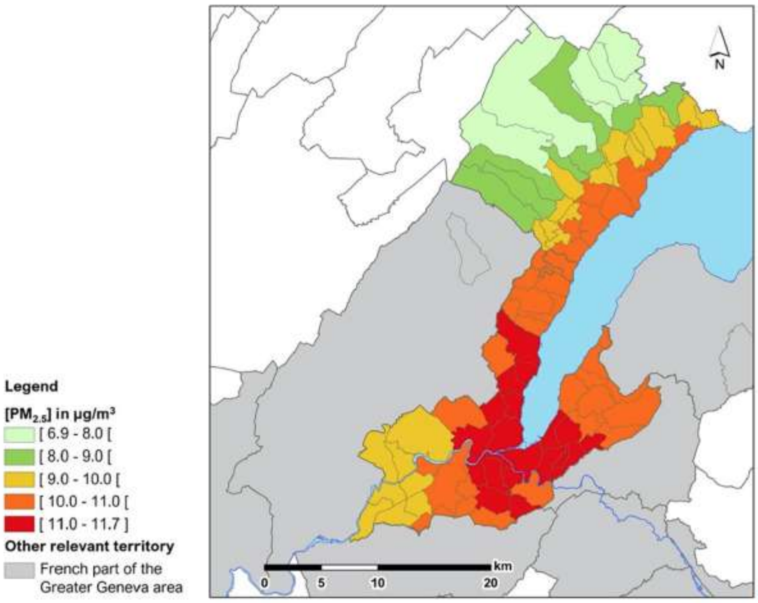

Fig. 2a. Annual average of population-weighted $PM_{2.5}$ concentrations per municipality in the Greater Geneva area from ATMO modelling, averaged over 2016, 2017 and 2018. Background map: SITG

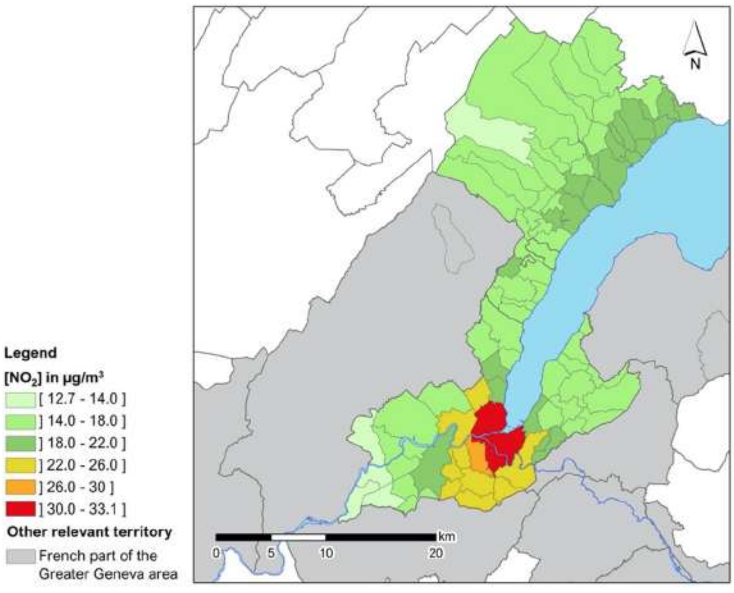

Fig. 2b. Annual average of population-weighted NO_2 concentrations per municipality in the Greater Geneva area from ATMO modelling, averaged over the years 2016, 2017 and 2018. Background map: SITG

Expected health impacts

Table 1 presents the annual outcomes attributable to chronic exposure to $PM_{2.5}$ and NO_2 for both mortality and morbidity indicators.

Mortality

• *Expression in terms of attributable deaths ($PM_{2.5}$ and NO_2):*

In the anthropogenic-origin burden scenario, exposure to $PM_{2.5}$ was responsible for 284 deaths [95%CI 102; 443], or 7.5% of the mortality of Greater Geneva's population aged 30 or more. Compliance with the OAPC ALV for $PM_{2.5}$ appeared to lower this to 62 deaths [95%CI 22; 98], or 1.5% of the mortality of those aged 30 or more. This difference underlines the health benefit that can be achieved by lowering $PM_{2.5}$ concentrations, even below the OAPC ALV. For NO_2, since the population-weighted average concentrations in each territory were below the OAPC ALV (30 µg/m^3), only the anthropogenic-origin burden was considered. In the Swiss part of Greater Geneva, about 201 deaths [95%CI 72; 315] (or 5.3% of deaths) were attributable to NO_2 exposure. It should be noted, however, that these indicators represented an average exposure that masks the heterogeneity of NO_2 concentrations within the municipalities: compliance with the OAPC ALV throughout each municipality would still lead to a health benefit.

• *Expression in terms of life expectancy ($PM_{2.5}$ only):*

Based on an analysis dividing the municipalities into 14 groupings, for the anthropogenic-origin burden scenario, on average 7.9 months of life expectancy were lost in the Swiss part of Greater Geneva (8.3 for the Canton of Geneva and 5.8 for the District of Nyon). Fig. 3a shows that all municipalities in the Swiss part of Greater Geneva could increase the average gain in life expectancy at age 30 by lowering concentrations to 5.5 µg/m^3 $PM_{2.5}$, with a gain of over 8 months for the City of Geneva, Vernier, Lancy and Carouge. If all municipalities complied with the OAPC ALV, we estimated that the study area's inhabitants would gain on average 1.4 months of life expectancy at age 30. Fig. 3b shows that the expected gains are more pronounced in the Canton of Geneva (almost 2 months), while they are zero for the municipalities in the northern part of the District of Nyon, which are exposed to $PM_{2.5}$ concentrations below the ALV (population-weighted average of 8.8 µg/m^3).

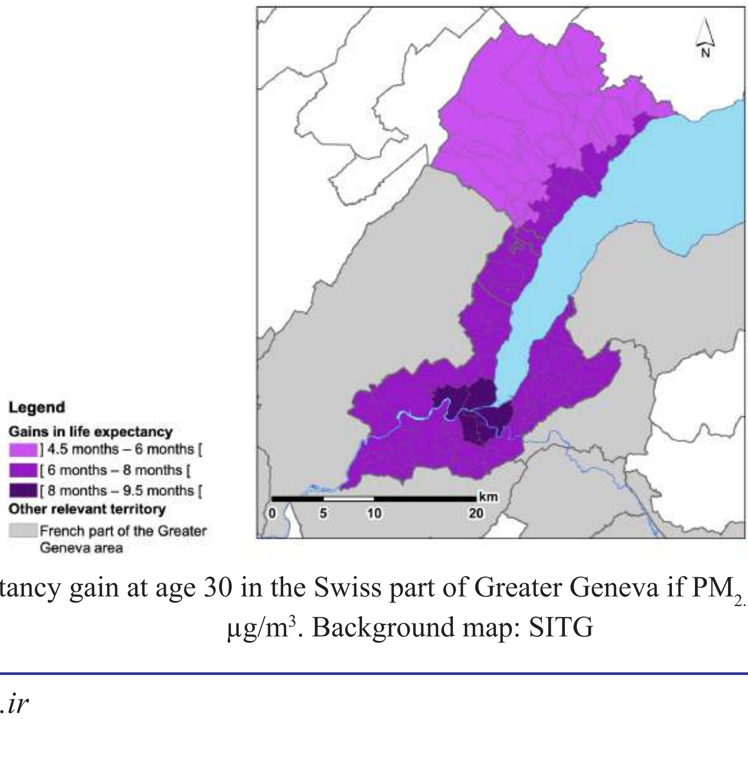

Fig. 3a. Life expectancy gain at age 30 in the Swiss part of Greater Geneva if $PM_{2.5}$ concentrations were 5.5 µg/m^3. Background map: SITG

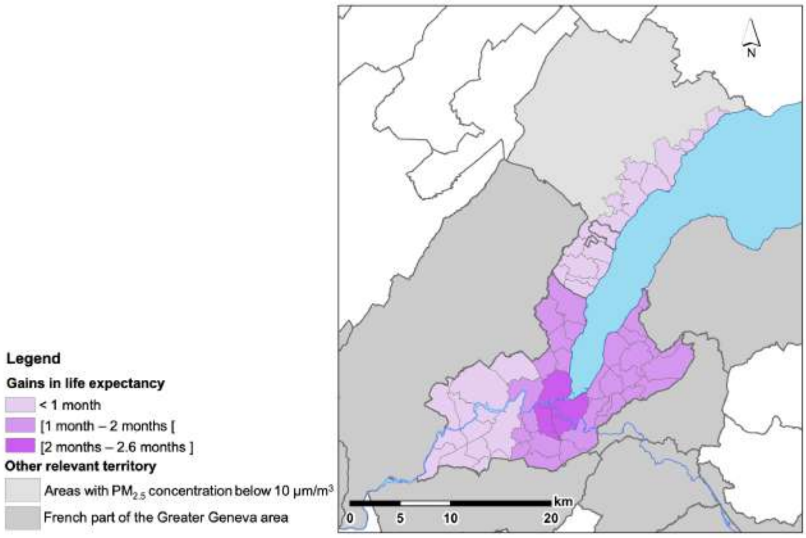

Fig. 3b. Life expectancy gain at age 30 if all municipalities complied with the federal ordinance on air pollution control limit values (OAPC ALVs). Background map: SITG

Table 1. Annual health outcomes attributable to chronic exposure to particulate matter and nitrogen dioxide

Health outcome	Nyon District		Canton of Geneva		Total Swiss part of Greater Geneva	
Scenarios	Anthropogenic burden	OAPC ALV compliance	Anthropogenic burden	OAPC ALV compliance	Anthropogenic burden	OAPC ALV compliance
Number of deaths[a] ($PM_{2.5}$)	28 [10 ; 44]	1 [0 ; 2]	256 [92 ; 399]	61 [21 ; 96]	284 [102 ; 443]	62 [22 ; 98]
Number of life-years[a] ($PM_{2.5}$)	574 [197 ; 916]	19 [7 ; 30]	5 289 [1 838 ; 8 458]	1 278 [459 ; 1 994]	5 864 [2 036 ; 9 373]	1 297 [466 ; 2 025]
Months of life expectancy[b] ($PM_{2.5}$)	5.8 [2.0 ; 9.2]	NA	8.3 [2.9 ; 13.2]	1.9 [0.6 ; 3]	7.9 [2.8 ; 12.6]	1.4 [0.5 ; 2.4]
Number of deaths[a] (NO_2)	17 [6 ; 27]	NA	183 [66 ; 288]	NA	201 [72 ; 315]	NA
Incidence of lung cancer ($PM_{2.5}$)	NA	NA	14 [7 ; 21]	3 [1 ; 5]	14 [7 ; 21]	3 [1 ; 5]
Incidence of stroke ($PM_{2.5}$)	8 [3 ; 13]	NA	68 [22 ; 113]	16 [5 ; 27]	76 [25 ; 126]	16 [5 ; 27]

Notes: OAPC ALV for Ordinance on Air Pollution Control Ambient Limit Value. NA for Not Assessed (see text).
Average over 2016, 2017 and 2018. [95%CI]. [a] for people aged 30 or more. [b] At age 30.

- *Expression in terms of life years gained ($PM_{2.5}$ only):*

The total number of life years gained per year can be calculated using the same groupings of municipalities. In the anthropogenic-origin burden scenario, 5,864 [95%CI 2,036; 9,373] life years were lost each year: 5,289 [95%CI 1,838; 8,458] for the Canton of Geneva and 574 [95%CI 197; 916] for the Nyon district. Compliance with the OAPC ALV could yield a gain of 1,297 [95%CI 466; 2,025] life years each year in the study area: 1,278 [95%CI 459; 1,994]) for the Canton of Geneva and 19 [95%CI 7; 30] for the District of Nyon. Note that the result for the Canton of Geneva may be slightly underestimated in the OAPC ALV compliance scenario due to the grouping of municipalities.

Morbidity due to $PM_{2.5}$ exposure

- *Lung cancer:*

The decrease in fine particle concentrations would result in a small but significant decrease in lung cancer cases in the Canton of Geneva. The anthropogenic-origin burden scenario would lead to 14 [95%CI 7; 21] cases of lung cancer, i.e., about 5% of cases, while compliance with the OAPC ALV could avoid 3 [95%CI 1; 5] cases.

- *Stroke:*

For the whole Canton of Geneva, the anthropogenic-origin burden scenario would lead to 68 [95%CI 22; 113] cases, i.e., about 7%. Compliance with the OAPC ALV would prevent 16 [95%CI 5; 27] stroke cases. This value may be slightly underestimated, because the municipalities with an exposure indicator below the ALV pull down the Canton's $PM_{2.5}$ exposure estimate. Any such underestimation will be small, however, since the exposure indicators for the municipalities in the southwestern part of the Canton remain above 9 $\mu g/m^3$. For the Nyon District, only the anthropogenic-origin burden scenario was quantified, since the OAPC ALV is respected on average. (However, the expected benefit from compliance with the OAPC ALV is not zero, since 16 of the 47 municipalities of the Nyon District have an indicator above this ALV). The number of stroke cases attributable to this scenario was 8 [95%CI 3; 13], i.e., about 5% of cases.

Economic valuation

Table 2 shows the estimated intangible costs based on mortality as well as the direct medical costs based on morbidity for both scenarios, and provides uncertainty intervals in parentheses.

Intangible costs associated with mortality

The first part of Table 2 shows the estimated intangible costs based on mortality. When expressed in life years, the total burden of anthropogenic-origin $PM_{2.5}$ exposure for the inhabitants of the study area was estimated at CHF_{2017} 921 [95%CI 320; 1,472] million per year at central value and using the VOLY. The benefits from compliance with the OAPC ALV were estimated at CHF_{2017} 204 [95%CI 73; 318] million per year, about 22% of the burden.

Table 2. Annual economic valuation of health impacts attributable to $PM_{2.5}$ exposure in the Swiss part of Greater Geneva. In million CHF_{2017}

Scenarios	Anthropogenic-origin burden			Benefits of OAPC ALV compliance		
Boundaries	95CI-	Central	95CI+	95CI-	Central	95CI+
Intangible costs based on …						
… life years	320 (174; 460)	921 (500; 1325)	1 472 (800; 2118)	73 (40; 105)	204 (111; 293)	318 (173; 458)
… premature deaths	612 (408; 816)	1 704 (1136; 2272)	2 658 (1772; 3544)	132 (88; 176)	372 (248; 496)	588 (392; 784)
Direct medical costs based on …						
… lung cancer[a]	1.3 (0.87; 1.73)	2.5 (1.67; 3.33)	3.8 (2.53; 5.07)	0.18 (0.12; 0.24)	0.54 (0.36; 0.72)	0.90 (0.60; 1.20)
… stroke[b]	2.2 (1.98; 2.42)	6.8 (6.12; 7.48)	11 (9.9; 12.1)	0.47 (0.42; 0.52)	1.4 (1.26; 1.54)	2.4 (2.16; 2.64)

Notes: OAPC ALV for Ordinance on Air Pollution Control Ambient Limit Value. 95CI- for the lower bound of 95%CI. 95CI+ for the upper bound or 95%CI. Uncertainty intervals are in parentheses [a] Only Canton of Geneva. [b] Only in health care facility.

The intangible costs estimated from deaths attributable to $PM_{2.5}$ exposure were about 1.8 times higher: about CHF_{2017} 1,704 [95%CI 612; 2,658] million per year at central value for the anthropogenic-origin burden scenario, and CHF_{2017} 372 [95%CI 132; 588] million per year for the compliance with the OAPC ALV scenario. This difference resulted from the population structure and the choice of monetary values for each approach. We propose to use the geometric mean between the two approaches, i.e., a central value of CHF_{2017} 1.3 billion per year for the anthropogenic-origin burden (CHF_{2017} 130 million for the district of Nyon, and CHF_{2017} 1.2 billion for the Canton of Geneva) and a benefit of CHF_{2017} 288 million per year for the compliance with the OAPC ALV scenario (CHF_{2017} 4.5 million for the District of Nyon and CHF_{2017} 285 million for the Canton of Geneva).

Direct medical costs

The second part of Table 2 shows the estimated direct medical costs based on morbidity.

- *Lung cancer in the Canton of Geneva:*

The anthropogenic-origin burden scenario would lead to direct costs of CHF_{2017} 2.5 [95% CI 1.3; 3.8] million per year using the central value for the cost of a lung cancer. Compliance with the OAPC ALVs would reduce direct costs by approximately CHF_{2017} 0.54 [95%CI 0.18; 0.90] million. A factor of -/+ 33% should be applied to the above monetary values to obtain lower and upper bounds taking into account the uncertainty on monetary values.

- *Stroke cases in the Swiss part of Greater Geneva:*

We computed the number of cases in a health care facility to estimate the direct medical costs of a stroke (see section Economic data: central monetary values). Thus, for the district of Nyon, the number of cases for the anthropogenic-origin burden scenario was 8 [95%CI 2; 13]. For the whole Canton of Geneva, the anthropogenic-origin burden scenario would lead to 64 [95%CI 21; 107] cases of stroke, and compliance with the OAPC ALVs would prevent 15 [95%CI 5; 25] cases. From these figures, and for the Swiss part of Greater Geneva, the anthropogenic-origin burden was estimated at CHF_{2017} 6.8 [95%CI 2.2; 11] million per year. The scenario of compliance with the OAPC ALVs would reduce direct costs by approximately CHF_{2017} 1.4 [95%CI 0.47; 2.4] million. A factor of -/+ 10% should be applied to the above monetary values to account for the uncertainty on monetary values (see section Uncertainties in the monetary valuation of health effects).

Discussion

What can reliably be stated is that $PM_{2.5}$ and NO_2 pollution have a real impact on the health of inhabitants in the Swiss part of Greater Geneva. We provided a minimum estimate of the health and economic burden of anthropogenic-origin air pollution and of the benefits to be expected from compliance with the OAPC ALVs.

Any comparison of our results with those of other studies needs to take into account methodological differences in the approach used, the study area and period, the "pollutant-health effect" relationships chosen and the reference levels adopted for the scenarios considered. The closest QHIA in terms of methodology is the one conducted on the French part of Greater Geneva [15]. It covers the same period, the same pollution indicators, a contiguous territory, uses the same RR and the same scenarios and models exposure with the same pollutant mapping. The major methodological difference lies in the population grid, provided per hectare in the Swiss part, but with a 10m x 10m grid for the French part. The QHIA conducted on the French side estimates that 8.7% of deaths were attributable to $PM_{2.5}$ exposure, only slightly higher than the 7.5% found in our study, due to the higher $PM_{2.5}$ concentrations found on the French side. NO_2 exposure, on the other hand, was responsible for 3.6% of mortality on the French side, compared to 5.3% on the Swiss side. This difference is explained by the lower concentrations found in the French part: the municipality with the highest NO_2 exposure in the French part had an average indicator below 25 $\mu g/m^3$, while that of the City of Geneva exceeded 33 $\mu g/m^3$.

The burden of air pollution was also recently assessed in mainland France for the years 2016 to 2019 [46], yielding an estimate comparable to ours. Exposure to $PM_{2.5}$ accounts for 7.1% of annual mortality, but 8.4% in cities with more than 100,000 inhabitants. The percentage of annual mortality attributable to NO_2 exposure, however, was lower: 1.2% compared to 5.3% in our study. This difference is mainly explained by the reference value used in the "air pollution burden" scenario: 10 $\mu g/m^3$ (i.e., the 25th percentile of the distribution) for the mainland France study, compared with 1.8 $\mu g/m^3$ in our study. Moreover, the exposure indicator for NO_2 was lower: around 17 $\mu g/m^3$ on average for French cities with more than 100,000 inhabitants compared to 33 $\mu g/m^3$ on average for the city of Geneva.

In Switzerland, the 2018 report from the European Environment Agency estimated the number of premature deaths attributable to exposure to $PM_{2.5}$, NO_2 and O_3 at 3 500, 270 and 350 respectively in 2018 [47]. Note that these values were calculated on the basis of the RRs recommended in the HRAPIE project [26] i.e., 1.062 for $PM_{2.5}$ and 1.055 for NO_2. These recommended RRs were also used to estimate the impact on mortality of a decrease in exposure to PM_{10} (3.3 $\mu g/m^3$) and NO_2 (5.6 $\mu g/m^3$) between 2005 and 2015 in the Lausanne-Morges conurbation (293,000 inhabitants) [48].

Respectively 26 and 51 deaths would have been avoided annually, equivalent to 290 and 550 life years. Finally, a QHIA of Geneva international airport's development plan estimated the health effects of NO_2 air pollution on the inhabitants of the canton of Geneva and neighbouring French and Swiss territories concerned [13]. In 2014, using the RR recommended by the HRAPIE project, they were estimated at 21 premature deaths (253 life years lost) in addition to several respiratory morbidity impacts. The economic evaluation of CHF_{2014} 24.7 million (24.3 for mortality and 0.4 for morbidity) was expected to double by 2030 with the projected increases in air traffic and in population size and average age. A methodological issue regarding the economic evaluation of a QHIA deserves clarification. QHIA relies on a counterfactual approach to provide a representation of the economic impact of a change in air pollution at a given time. While the expected benefits of the OAPC ALV compliance scenario can be compared to the overall burden associated with anthropogenic-origin pollution, the economic evaluation cannot properly assess the economic benefits of a public policy aimed at reducing pollutant emissions [16] [49]. Indeed, since long-term health impacts are involved, such an assessment needs to consider the cumulative nature of health effects (cessation lag), as well as the policy/technical implementation timeframe required for the measures to achieve the targeted reduction [50]. The full health benefits will therefore only be observed after several years, and their economic assessment will also have to take into account discounting, while the costs of public policy implementation will take effect immediately.

Conclusion

This study underlined the importance of strengthening public air pollution control policies to reduce the population's exposure to pollutants, even when the OAPC ALVs are respected. The choice of a modelled exposure approach allowed us to distinguish between municipalities according to pollutant levels, enabling strategies to be targeted. In particular, our results showed that although the most densely populated municipalities in the Canton of Geneva would benefit most from a reduction in pollutant concentrations, even the less polluted municipalities in the District of Nyon, including those located to the north, would stand to gain.

Some limitations of this study deserve mention. First, our results only reflect part of the monetary impacts of air pollution, for the following three reasons. The estimation only covers health effects attributable to $PM_{2.5}$ exposure. However, other pollutants such as NO_2 and tropospheric O_3 or even indoor CO_2 [49] also have a negative impact on health, for example on hospital admissions for cardiovascular and respiratory causes. Moreover, not all the health effects of $PM_{2.5}$ were taken into account, as pointed out in the introduction. Finally, from an economic point of view, in addition to those health effects not considered despite their direct and intangible costs, the health impacts our study considered do not cover all the monetary components. Thus, no direct non-medical costs (such as home help or home improvements), no intangible components associated with suffering, grief and loss of quality of life due to stroke or lung cancer, no loss of production due to lost work days when in hospital and no activity restrictions were accounted for [48].

Second, the uncertainties from various sources discussed above affected our estimates, as in any QHIA, so that our results should be considered as orders of magnitude. For instance, the use of new therapies may affect medical cost estimates (see [51]; for lung cancer).

We should acknowledge the continuous commitment by the Cantons of Geneva and Vaud to improving air quality and achieving health benefits. The most effective strategy to reduce the population's exposure to pollutants would be to reduce $PM_{2.5}$ and NOx emissions at source. Both in the Canton of Geneva and in the District of Nyon, the four most effective levers are road traffic, heating, off-road mobile equipment and air traffic. In Geneva, previous OAPC plans have contributed effectively to reducing emissions, notably through increased control of heating installations, tax incentives for the purchase of less polluting motor vehicles or the fitting of particle filters for off-road vehicles (construction machinery). The OAPC 2018-2023 action plan for reducing emissions includes proposals for action on mobility (freight transport or individual mobility), on remediation and modernisation of heat production facilities, on identification of the link between air pollution and health [53]. One of these aims is to "raise awareness of the health risks associated with air pollution" as well as to carry out a Geneva-wide study on the costs associated with air pollution. The Canton of Geneva has also developed a strategic tool, the Air Protection Strategy 2030, whose aim is to unite the different public policies in a long-term vision for improved air quality [54]. Policies aimed at reducing the use of fossil fuels for heating according to the Energy Master Plan [55], or promoting soft mobility [56], with a double health benefit [57], are also worthy of mention. By acting on heating, industry and road traffic, it targets compliance with the OAPC ALVs throughout the Canton, limited emissions from fixed installations and NOx emissions reduced by 50% and PM_{10} by 10% by 2030, relative to 2005 levels.

Based on the latest medical and epidemiological knowledge, the WHO lowered its 2005 guideline value for $PM_{2.5}$ to 5 $\mu g/m^3$ in September 2021 (slightly below the 5.5 $\mu g/m^3$ value used in the anthropogenic-origin pollution burden scenario), and its guideline for NO_2 to 10 $\mu g/m^3$. In so doing, the WHO is urging authorities to strengthen public policies for cleaner air.

Finally, synergies can be obtained with greenhouse gas (GHG) emission reduction policies, due to the similarity of their sources (fossil fuel combustion) and the sectors concerned (agriculture, industry, transport and, depending on the type of heating, housing). Thus, actions to reduce emissions from these sources can have beneficial effects in terms both of climate change mitigation and of lowering pollutant concentrations. In the Canton of Geneva, the aim of the 2030 cantonal climate plan is to reduce GHG emissions by 60% by 2030 compared to 2012 levels and to be carbon neutral by 2050 [58]. It features actions aimed at developing thermal networks, optimising goods transport, reducing the energy needs of buildings and the proportion of individual motorised transport.

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Competing interests

All authors declare no competing interests in this paper.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc.) have been completely observed by the authors.

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