École Polytechnique Fédérale de Lausanne

Extreme Environments Research Laboratory

Master Thesis

URBTREES – Quantifying and mapping the impact of urban trees on air quality in Geneva, Switzerland

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Summary - Tropospheric ozone (O_3) and coarse particulate matter (PM_{10}) are two air pollutants that pose a serious threat to human health. Urban trees interact with the atmosphere via their leaves and can regulate urban O_3 and PM_{10} concentrations. Trees emit many different biogenic volatile organic compounds (BVOC), some of which are highly reactive and can, in the right conditions, contribute to O_3 formation. On the other hand, with their leaves, trees can act as filters and remove pollutants from the atmosphere, thus improving air quality in cities. In this study, we use a large tree inventory to characterize and map the urban trees' impact on air quality in the Canton of Geneva, Switzerland. Based on a literature research, emission rates of isoprene, monoterpenes and sesquiterpenes, three reactive BVOCs emitted by trees, were associated with the most common tree species in the data set. According to this study, the urban forest structure (*e.g.*, number of trees and species composition) in Geneva is not optimal for improving air quality. This is due to the dominant tree species in the city that are high BVOC emitters and deciduous, meaning that they will have a reduced ability to capture air pollutants during their leafless period. However, urban trees still removed 82 t of PM_{10} in 2019, compared to estimated annual anthropogenic emissions of 631 tons. Also, they removed 179 t of O_3 in 2019, but under ideal atmospheric conditions, they can contribute to the formation of 1,153 t of O_3 per year. The pollution removal and ozone-forming potential (OFP) were mapped on a 100x100m grid across the Canton of Geneva. These maps showed that the air pollution reduction and OFP were heterogeneous over the study area, depending on the absolute number of trees, species distribution, leaf area and leaf biomass per hectare. To the best of the authors' knowledge, this study is the first attempt in Switzerland that maps and assesses the air pollution removal capacity and OFP from urban trees. The results of this work could help urban planners to better manage vegetation and plan future large-scale planting programs.

Keywords - Air pollution, Air pollutant removal, Urban trees, Environmental assessment, mapping, PM_{10}, O_3, Switzerland

Résumé - *L'ozone troposphérique (O_3) et les particules fines (PM_{10}) sont deux polluants atmosphériques qui menacent la santé humaine. La végétation urbaine, en particulier les arbres, interagit avec l'atmosphère via ses feuilles et régule les concentrations d'O_3 et de PM_{10}. Les arbres émettent de nombreux composés organiques volatils (COV), dont certains sont très réactifs et peuvent, dans les bonnes conditions, contribuer à la formation d'O_3. D'autre part, grâce à leurs feuilles, les arbres agissent comme des filtres et éliminent les polluants de l'atmosphère, améliorant ainsi la qualité de l'air dans les villes. Dans cette étude, nous utilisons un large inventaire d'arbres élaboré par les autorités du canton de Genève en Suisse, afin de quantifier et cartographier l'impact des arbres urbains sur la qualité de l'air. Sur la base d'une recherche dans la litérature scientifique, des facteurs d'émission d'isoprène, de monoterpènes et de sesquiterpènes, trois COV réactifs émis par les arbres, ont été associés aux espèces d'arbres les plus courantes dans le jeu de données. Les résultats montrent que la structure (e.g., nombre d'arbres et composition des espèces) de la forêt urbaine genevoise n'est pas optimale dans un but d'amélioration de la qualité de l'air. Ceci est dû au fait que les espèces d'arbres les plus répandues dans le canton sont de grands émetteurs de COV et sont à feuilles caduques, signifiant que leur capacité à capturer des polluants sera fortement réduite une fois qu'ils auront perdu leurs feuilles. Cependant, les arbres urbains ont tout de même retiré 82 t de PM_{10} de l'atmosphère en 2019, alors que les émissions anthropiques annuelles de PM_{10} sont estimées à 631 t. Durant la même année ils ont également retiré 179 tonnes d'O_3. Mais, dans des conditions atmosphériques idéales, ils peuvent contribuer à la dégradation de la qualité de l'air en formant 1 153 t d'O_3 par an. Le potentiel de dépollution et le potentiel de formation d'ozone (PFO) ont été cartographiés sur une grille de 100x100m dans le canton de Genève. Ces cartes ont montré que le dépôt de polluants et le PFO sont spatiallement hétérogènes en fonction du nombre absolu d'arbres, de la distribution des espèces, de la surface foliaire et de la biomasse foliaire par hectare. À la connaissance des auteurs, cette étude est la première tentative en Suisse de cartographier et d'évaluer la capacité de filtration de polluants atmosphérique et le PFO des arbres urbains. Les résultats de ce travail pourraient aider les urbanistes à mieux gérer la végétation et à planifier de futurs programmes de plantation à grande échelle.*

Mots-clés - *Pollution atmosphérique, Élimination des polluants atmosphériques, Arbres urbains, Évaluation environnementale, Cartographie, PM_{10}, O_3, Suisse*

I. Introduction

Urban air pollution is the greatest environmental risk to health for humans [1]. High concentrations of particulate matter with a diameter equal to or smaller than 10 µm (PM_{10}) are causing millions of premature deaths every year worldwide [1]. In the European Union, despite reductions in emissions and ongoing improvements in air quality, air pollution is still a major health concern. In fact, in 2020, 71% of the European urban population was exposed to levels of PM_{10} above the 2021 annual mean guideline of 15 µg/m^3 set by the World Health Organization (WHO) [2]. A similar result for O_3 was observed, where the proportion of the population exposed to levels higher than the WHO 2021 short-term (8h-mean) guideline value of 100 µg/m^3 fluctuated between 93% and 98% in the period 2013-2020 [2]. Exposure to air pollutants affects the entire body and causes premature deaths, mainly through lung and heart diseases but also increases the risk of metabolic diseases, such as type 2 diabetes [3]. Bell *et al.* [4] associated an increase in O_3 with an increase in mortality for the following week. Pascal *et al.* [5] assessed the health and monetary benefits of reducing short and long-term exposure to PM and O_3 in 25 European cities. They found that 8,000 annual hospitalizations for cardiovascular and respiratory causes could have been avoided if the cities had complied with the 2015 WHO guideline of 20 µg/m^3 (annual mean) for PM_{10}. Additionally, for the 25 cities, they found that the annual economic benefits would total €520 million if the O_3 levels were decreased by 5 µg/m^3. Reducing further the urban levels of ozone and fine particles by setting more ambitious objectives would increase life expectancy in Europe [5] and save money.

The normative assumption that urban trees will help solve many environmental problems can be attributed to the substantial evidence in the scientific literature that trees positively influence many urban issues, ranging from social to air quality aspects [6]. However, the role of urban trees should be considered with more nuance as they are both responsible for ecosystem services and disservices, such as heat mitigation, air quality modification, noise attenuation and pollen emissions. Due to urbanization, natural soils are being replaced by impervious surfaces modifying the city climate towards a drier and warmer air compared to rural areas, especially at night [7]. By shading the streets, urban trees stop solar radiations from reaching pedestrians and the surface which usually is concrete with a high heat capacity, thus reducing heat storage. Schwaab *et al.* [8] found that the surface temperature of urban trees is 8-12 K lower than urban fabric in Central Europe. Additionally, urban trees act as natural filters reducing the pollutant loads in the atmosphere, such as PM_{10} and O_3, and therefore have a positive impact on air quality. Meanwhile, they deteriorate the air quality with their emissions of BVOCs that lead to the formation of O_3 and aerosols [9, 10]. So trees play a central role in the urban ozone balance as they can both reduce or contribute to O_3 formation. The potential contribution of urban trees to higher ozone levels is called the ozone-forming potential (OFP).

Tropospheric O_3 is formed by the reaction of hydrocarbons, mainly methane (CH_4), carbon monoxide (CO) and volatile organic compounds (VOC) with nitrogen oxides (NO_x), in the presence of UV radiation [11]. VOCs are important in tropospheric chemistry as precursors to O_3 and the formation of secondary organic aerosols, which contribute to the total PM_{10} load. Identifying VOC sources becomes central to improve the air quality of an area. VOCs are emitted to the atmosphere both by natural (vegetation, soil microbes and biomass burning) and anthropogenic sources (industrial release, solvent use, fossil and biogenic fuel combustion) [12, 13]. On a global scale, natural emissions equal or exceed anthropogenic emissions, whereas in an urban area, anthropogenic sources usually dominate [12].

Plants emit a wide range of BVOCs of which a few very reactive molecules are important for air quality. From all the BVOCs emitted to the atmosphere by the vegetation, isoprene is dominating the annual global flux to the atmosphere [14]. The total annual amount of isoprene emitted to the atmosphere is comparable to total methane (CH_4) emitted [15]. Two other important BVOCs emitted by plants are monoterpenes and sesquiterpenes. Broadleaved species were found to mainly emit isoprene, while conifers mostly emit monoterpenes [16]. The study of these BVOCs is important because isoprene's breakdown produces ozone when reacting with anthropogenic NO_x, whereas monoterpenes and sesquiterpenes can contribute to particles formation [17]. Plants emit BVOCs for communication and interaction purposes, as a defense mechanism and protection against stress conditions [17]. The BVOC emission rates of trees are highly species-specific and depend on climatic conditions such as temperature, water availability and light intensities [18]. These emission rates can vary by as much as 4 orders of magnitude between species [19]. For example, tree species such as *Quercus robur* or *Populus nigra* emit high amounts of isoprene but are not among the highest monoterpenes and sesquiterpenes emitters. BVOC emissions tend to increase with temperature, light, drought periods, air pollution and plant tissue damage which can be caused by herbivores [20]. Importantly, in a global climate change scenario, some regions will see their average temperatures and drought episodes increase and urban trees will play a stronger role than ever in regulating air quality and temperature in cities. The contribution of each BVOC towards the formation of O_3 is not equal and among the BVOCs emitted by plants, isoprene contributes the most. Finally, it is very hard to evaluate the net effect urban trees have on atmospheric O_3 concentrations as their contribution to the overall O_3 budget is species-specific through their OFP and O_3 deposition potential, and dependent on many environmental factors.

In European cities, high particulate pollution episodes generally happen when there is a strong traffic load combined with stable atmospheric conditions preventing mixing and synoptic weather conditions that favor long-range transport of particles [21]. Vegetation in cities, in particular trees, can reduce PM concentrations through dry deposition processes onto the leaves' surfaces [22]. A leaf's morphology and physiology affect its capacity to remove PM from the atmosphere and leaves with abundant trichomes, waxes and wrinkled surfaces are considered more suitable for capturing pollutants [9]. It is the combination of those leaf traits that is a key factor to improve PM removal and there is not one trait alone that dominates the process [23]. Evergreen conifers such as pine trees are thought to be more efficient in capturing PM than broad-leaved species because they can accumulate pollutants throughout the year [24]. Whereas, the ability of deciduous trees to capture air pollutants will be significantly reduced during their leafless period.

To evaluate the benefits and drawbacks of the urban forest several software tools have been developed. The Urban Forest Management Plan Toolkit website lists available tools including i-Tree Eco which is state-of-the-art, peer-reviewed and freely available. i-Tree Eco is the flagship tool from the i-Tree suite of computer programs developed through a collaborative public-private partnership and distributed by the U.S. Department of Agriculture (USDA) [25]. It is designed to estimate forest structure, ecosystem services, values, and risks related to forests and people. It was originally called the Urban Forest Effects model (UFORE). i-Tree Eco was initially only used in the United States but it has been adapted for international use. Some examples of European studies using i-Tree are presented below. Riondato *et al.* [26] assessed the potential effect of urban trees on removing particulate matter from the atmosphere by combining air quality monitoring and the i-Tree Eco (UFORE) model. Selmi *et al.* [27] used i-Tree to estimate air pollution removal through dry deposition of pollutants by urban trees in Strasbourg city. And Soares *et al.* [28] quantified the benefits and costs of Lisbon's street tree population.

i-Tree Eco is a powerful tool with many positive aspects and some drawbacks. Its main positive features are that the software is free and easy to use. This greatly facilitates its application for scientific research and allows people with a minimal environmental background to use it. On the other hand, it does not allow the user to produce detailed maps of the ecosystem services and disservices it estimates. Although a mapping option has been implemented with the latest i-Tree Eco version, it is only available for projects in the continental United States. Also, to estimate the BVOC emissions from the trees, i-Tree Eco uses EFs at the genus level, thus not considering the sometimes significant differences between two species from the same genus. It estimates hourly emissions of isoprene and monoterpenes, but not of sesquiterpenes. Finally, it does not estimate ozone formation from the BVOC emissions.

Considering the negative effects air pollutants have on human health and well-being in general, many cities actively try to reduce their concentrations by issuing policies, elaborating strategies and planning interventions. One way of mitigating urban air pollution is through city forests and trees. Even though several studies assessed the role of urban trees in their ability to ameliorate or deteriorate the air quality in cities [11, 29–31], only a few attempts were made to map these results at the city scale [22, 32].

In this work, we apply two different methods to evaluate the urban trees' functions (*e.g.*, BVOC emissions, PM_{10} deposition, O_3 deposition and OFP) in Geneva, Switzerland. The first one is a direct use of i-Tree Eco with the tree inventory (referred to in the text as the i-Tree Eco approach). For the second method, we adapt and simplify some modules of i-Tree Eco to work at the species level (referred to in the text as the species-level approach). To do this, we conduct a literature review to determine emission factors of the most potent ozone-forming BVOCs (isoprene, monoterpenes, sesquiterpenes) for different tree species based on their relative abundance in Geneva's database. We investigate both the negative and positive impacts that urban trees can have on air quality with their potential contribution to the formation of ozone through BVOC emissions and their ability to act as natural filters that remove harmful air pollutants (O_3 and PM_{10}). Note, the effect of urban BVOC emissions on PM formation is beyond the scope of this work. By using a geographic information system (GIS), our goal is to create detailed maps of air quality impacts on O_3 and PM_{10} by urban vegetation at the Geneva Canton scale. In addition, we calculate yearly estimates of total BVOC emissions, OFP, PM_{10} and O_3 deposition. Finally, we compare the results obtained through our approach with the outputs of the i-Tree Eco model.

The following objectives were formulated to produce the detailed maps:

- Perform a literature review to attribute isoprene, monoterpenes and sesquiterpenes emission factors to the most abundant tree species in Geneva's inventory
- Estimate the OFP based on the BVOC emission factors
- Estimate the PM_{10} and O_3 deposition on leaves
- Map the results

II. Data and methods

A. GIS work

All maps in this study were produced with QGIS (version 3.26.3-Buenos Aires). This is a free and open-source geographic information system.

B. Study area

The study area covers the entire Canton of Geneva (46°13'N, 6°09' E), extending over 282.48 km^2, located in the westernmost part of Switzerland next to lake Geneva and north of the Alps (Figure 1). The Canton includes the city of Geneva itself as well as the agricultural areas surrounding it and a few minor cities. About 506,343 inhabitants live in the Canton, of which 203,856 are living in the city. Geneva has a population density of 12,797 inhabitants/km^2. This places Geneva in the top 40 cities with the highest population density in Europe and is comparable to Stockholm or Dublin. The elevation varies between 369 and 458 m a.s.l.

The Canton of Geneva has a temperate climate, mainly influenced by the Atlantic Ocean, and is classified as an oceanic climate (Cfb) according to the Köppen climate classification. Over the reference period from 1991 to 2020, the coldest month was January with a mean temperature of 2.1°C and the warmest month was July with a mean temperature of 20.6°C [33]. Climate change will have a significant impact on the temperatures and precipitations in Geneva. By 2060, the yearly mean temperatures in Geneva are expected to increase by 1.2°C or 2.3°C compared to the reference period 1981-2010 according to the RCP2.6 scenario (climate mitigation measures are taken) and RCP8.5 scenario (no climate mitigation measures are implemented) respectively [34].

C. Data - plant material

The BVOC emissions, OFP, PM_{10} and O_3 removal estimations are based on an open-source tree inventory prepared by the Canton of Geneva [35]. This data set is updated regularly and starting in 1976, centralizes all existing surveys of isolated trees located outside forests. It contains 237,191 trees with their associated characteristics such as diameter at breast height (DBH), trunk height, coordinates (EPSG:2056/ CH1903+/LV95) and crown diameter. It was estimated that the Canton of Geneva contains approximately 1,000,000 trees in total of which 500,000 are isolated trees, thus the data set contains about half of all the isolated trees [36].

D. i-Tree Eco

For this study, we used i-Tree Eco combined with Geneva's tree inventory to derive the leaf area and leaf dry weight of each tree, two key variables for further calculations (see sections II-F, II-G and II-H). But i-Tree Eco has certain limitations regarding the importation of a full tree inventory. For example, species names must match exactly with a predefined species list that the software uses. If the data set contains trees that are unknown to i-Tree Eco they will not be imported and used for calculations. The original data set provided by the Canton of Geneva had many missing values such as DBH, species name and crown diameter. Those had to be estimated or completed to avoid losing a big portion of the valuable data set. For transparency reasons all manipulations and estimations made on the data set are detailed in Table I.

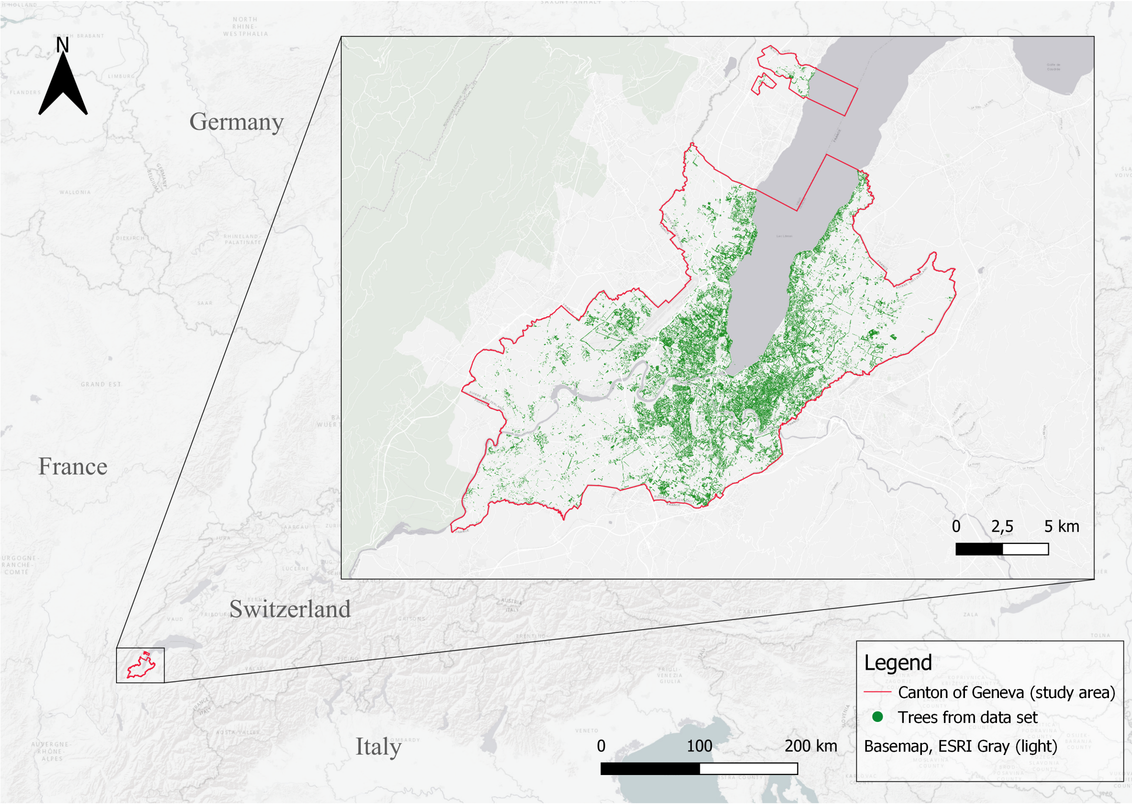


Figure 1: Location of the Canton of Geneva (study area) in Switzerland with neighbouring countries. Each green dot represents a tree from Geneva's database (available here).

All methods and equations that i-Tree Eco uses are detailed in the "2021 Summary of Programs and Methods" manual written by D.J. Nowak [37].

Leaf biomass and leaf area are two output variables from i-Tree Eco that we used to calculate OFP, PM_{10} and O_3 removal. Thus, the equations to calculate these parameters are presented in this section.

The leaf area of a tree is calculated according to the following regression equation [38]:

$$ln(Y) = -4.33 + 0.29H + 0.73D + 5.72S - 0.01C \quad (1)$$

where Y is the leaf area in m^2, H is crown height in m, D is the average crown diameter in m, S is the average shading factor for the individual species (percent light intensity intercepted by foliated tree crowns), C is based on the outer surface area of the tree crown ($\pi D(H + D)/2$).

Leaf biomass (leaf dry weight) is calculated from the leaf area using species-specific conversion factors:

$$L_{dry\ weight} = Y * f \quad (2)$$

where $L_{dry\ weight}$ is the leaf dry weight, Y is the tree leaf area and f is a species-specific conversion factor (see annex of [37]).

i-Tree Eco also calculates BVOC emissions, PM_{10} deposition and O_3 deposition at the tree level. The equations are not detailed here but can be found in the i-Tree manual [37]. i-Tree Eco uses weather and pollution data to estimate PM_{10} and O_3 deposition and BVOC emissions. The most recent available year for weather and pollution data was 2014. For BVOC emissions, i-Tree uses a base genus emission rate. If genus-specific information is not available, median emission values for the family, order, or superorder are used. So the model does not use species-specific emission rates as we applied in our comparative method (see section II-E). i-Tree Eco does not estimate OFP.

Table I: Modifications and corrections applied to variables of the original data set with detailed procedures. All the work listed in this table was done by Paganini Romana, a master's student at EPFL. For detailed explanations and further information please see Paganini's report.

Step	Parameter affected	Modification performed
1	Scientific name	Removal of all taxonomic ranks inferior to the species level (subspecies and variety). If the species of a tree is unknown by i-Tree Eco then only the genus is kept. If the genus is still unknown then the whole tree is removed from the data set.
2	DBH	When the DBH value was not measured or 0, the tree was associated with the average DBH of all the trees of its genus. If no tree of a specific genus had any DBH value, all the trees of that genus were deleted.
3	Total tree height	The same approach as for the DBH was applied for missing values and 0. Additionally, in many cases, the trunk height was equal to or greater than the total tree height. For those cases, the total tree height was made 1m larger than the trunk height.
4	Land use	The data set contained a field similar to the land use approach that i-Tree Eco uses. However, this field was in french and the descriptions had to be adapted to the preset values that i-Tree Eco accepts.
5	Crown size	The crown size is parameterized by the height to live top, height to crown base, crown width and percent crown missing. - Height to live top was assumed to be equal to the total tree height - Height to crown base was assumed to be equal to trunk height - Crown width was assumed to be equal to crown diameter. For missing and 0 values the same procedure as for the DBH was applied. It was also assumed that the crown diameter was the same in both the N-S and E-W direction. - Percent crown missing was set to 0% (crown is always complete)
6	Crown health	The data set contained a field assessing the vitality of the tree that had to be matched with the predefined values of i-Tree Eco. The information provided by the inventory was matched to i-Tree Eco values as follows: Excellent = 100%, Good = 82%, Mediocre = 62%, Bad = 42%, Very bad = 22%, NaN = 82%.

E. BVOC emissions

A literature review was conducted to gather emission factors (EF) for isoprene, monoterpenes and sesquiterpenes for the most common tree species in the data set. All EFs found in the literature along with their references are listed in Table VI in the annex. For this literature review, twelve sources were used to attribute EFs. All EFs are standardized values at 30°C leaf temperature and 1000 µmol m^{-2} s^{-1} Photosynthetic Photon Flux Density (PPFD, *e.g.*, the number of photosynthetically active photons that fall on a given surface per second). In the literature, the EFs are usually reported in µg gdw^{-1} h^{-1} (meaning the mass of BVOC emitted per gram of leaf dry weight per hour). The dry weight of a leaf is measured after the leaf is dried at temperatures higher than ambient temperature, thus without its water content. These EFs are species-specific and can vary from one study to another. When several EFs were found for the same species, the average was calculated. Many entries in the original data set had only the genus of the tree documented. For those trees, a weighted mean within the tree genus was performed (see Table VII in the annex). The weights were attributed according to the absolute number of trees for each species, this gives the highest weight to the species most present within one genus. The assumption behind this approach is that the probability of a tree being the same species as the most common tree of its genus is higher than that of the tree being a completely new species not present in the data set. Also, to facilitate the management, city planners tend to use the same species leading to the abundance of certain species compared to others. Finally, the emissions of isoprene, monoterpenes and sesquiterpenes of each tree were integrated over a year, taking into account if the tree was deciduous or evergreen.

F. Ozone-forming potential

The theoretical upper limit of ozone formation can be calculated by multiplying the mass emission rate of a hydrocarbon by its maximum incremental reactivity (MIR). In reality, less ozone may be formed because of meteorological conditions and NO_x availability. In this study, however, it was assumed that NO_x and meteorological conditions were not limiting factors for ozone production.

OFP was calculated for each tree according to Benjamin *et al.* [39] as:

$$OFP = B * \sum_i EF_i * MIR_i \quad (3)$$

where *B* is the biomass factor (the total leaf dry weight of a tree) [gdw tree^{-1}] obtained with i-Tree Eco (equation 2), EF_i is the species-specific mass emission factor obtained by the literature review [μg gdw^{-1} h^{-1}] for $BVOC_i$ and MIR_i is the maximum incremental reactivity [g_{O_3} $g_{VOC}{}^{-1}$] for $BVOC_i$, *i* stands for the three BVOC categories considered in this study, namely isoprene, monoterpenes and sesquiterpenes. The OFP was integrated over a year with consideration of the trees' leaf regime (deciduous or evergreen) and we assumed that deciduous trees would emit BVOCs for 183 days (leaf-on season) per year and evergreens for 365 days.

The *MIR* is compound-specific and indicates the mass of O_3 produced under optimum climatic and air chemistry conditions per mass of BVOC. The *MIR* for each BVOC category was calculated using the speciation file from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) database [40] and the *MIR* values for each chemical compound associated to a BVOC category from Carter *et al.* [41]. For each BVOC category a weighted mean *MIR* was calculated. Table II summarizes the *MIR* values used to calculate the OFP and shows the values used by two other studies.

Table II: Comparison of MIRs [g_{O_3} $g_{VOC}{}^{-1}$] calculated in this study with two other studies.

	This study	Benjamin *et al.* [39]	Calfapietra *et al.* [29]
$MIR_{isoprene}$	10.61	9.1	9.1
$MIR_{monoterpenes}$	4.18	3.8	3.1
$MIR_{sesquiterpenes}$	2.42	-	-

To calculate the annual total OFP, a 100x100m grid was created over the Canton of Geneva and the contribution of each tree per grid cell was summed as follows:

$$OFP_{total} = \sum_{j=0}^{N} OFP_j \quad (4)$$

Where *N* is the number of trees in a grid cell and OFP_j is the OFP during one year of tree *j*.

Finally, it is important to mention that in this study, we calculate the maximum potential of ozone production when all conditions are ideal and that in reality the amount of O_3 formed may be different as the process is more complicated than accounted for here, and therefore hard to quantify.

G. Estimation of PM_{10} deposition

The annual dry deposition of PM_{10} for each tree was calculated according to the methodology applied by [9, 32] with the following equation:

$$PM_{10}\ deposition = V_d * C_i * A_L * T_i * 24 * 3600 * 0.5 * 10^{-9} \quad (5)$$

Where V_d is the dry deposition velocity of PM_{10} set to an average of 0.0064 m/s based on the median deposition velocity from the literature [42]; a 50% particle resuspension rate back to the atmosphere was assumed [9, 32]; C_i is the mean yearly PM_{10} concentration [μg/m^3], A_L is the total leaf area [m^2] of a tree, obtained by i-Tree Eco (equation 1), T_i is the number of days per year during which the trees have leaves and 10^{-9} is a dimensional adjustment factor. C_i was set to a value of 16.99 μg/m^3 for the year 2019, this concentration was obtained on the official air quality website of Geneva [43].

Finally, as for the OFP, the PM_{10} deposition was aggregated in a 100x100m grid, summing the contribution of each tree in a grid cell, according to the following equation:

$$RPM_{10} = \sum_{j=0}^{N} PM_{10}^{j} \quad (6)$$

Where *N* is the number of trees in a grid cell and PM_{10}^j is the dry deposition of tree *j*.

H. Estimation of O_3 deposition

Stomatal O_3 fluxes were calculated according to the species-specific equation reported by Manes *et al.* [44]:

$$F_{O_3} = g_s * [O_3] * 0.613 \quad (7)$$

Where F_{O_3} is the instantaneous stomatal O_3 flux in nmol m^{-2} s^{-1}, g_s is the species-specific stomatal conductance to water vapor (mol m^{-2} s^{-1}), $[O_3]$ is the annual ozone concentration in ppb (nmol mol^{-1}) and 0.613 is the diffusibility ratio between O_3 and water vapor. The annual O_3 concentration was 22.85 ppb for the year 2019 (value obtained on the air quality website of Geneva). Stomatal conductance values were attributed to the most common tree species in the data set through a literature review. As for the EFs, when only the genus of the tree was available in the data set, a weighted mean was used to attribute the g_s values.

The instantaneous fluxes were used to calculate the total annual cumulated O_3 flux for each tree species with equation 8.

$$F_{O_3}cum = F_{O_3} * Ph * N * 3600 * 10^{-9} \tag{8}$$

Where $F_{O_3}cum$ is the annual cumulated stomatal O_3 flux in mol m^{-2} y^{-1}, *Ph* is the photoperiod (h day^{-1}), N is the number of days per year during which the trees have leaves and 10^{-9} is a dimensional adjustment factor. We assumed that the stomatal O_3 flux corresponds to 30% of the total potential O_3 removal consisting in both stomatal and non-stomatal processes (Equation 9), this ratio was considered by Baraldi *et al.* (2019). Manes *et al.* (2012) reported that this ratio ranged from 29% to 43% and similar values, ranging from 21% to 33%, were reported by Mikkelsen *et al.* (2004) for conifers.

$$F_{O_3}t = F_{O_3}cum/0.3 \tag{9}$$

Finally, to obtain the annual mass of O_3 deposited on the leaves, the following equation was used:

$$R_{O_3} = F_{O_3}t * A_L * 47.997 \tag{10}$$

Where R_{O_3} is the annual mass of O_3 removed through stomatal and non-stomatal processes in g y^{-1}, A_L is the leaf area in m^2 (equation 1) and 47.997 is the molar weight of O_3 in g mol^{-1}.

III. Results

A. Structure of Geneva's urban forest

By structure of the urban forest, it is meant the number of trees and species distribution. The data set contains 274 tree genera of which the three most common are *Quercus* (Oak) with 10.7%, *Acer* (Maple) with 10.4% and *Pinus* (Pine) with 7.5%. The data set contains 1,128 tree species. The three most common species in the data set are *Quercus robur* (Common Oak) with 5.26%, *Carpinus betulus* (European hornbeam) with 3.98% and *Fraxinus excelsior* (European ash) with 2.27%. Figure 2 shows the seven most common genera of isolated trees in Geneva that add up to 52.2% of all the trees in the data set. In total, 48,196 trees (20%) are evergreens, 174,619 (74%) are deciduous and 14,376 trees (6%) were not associated with either class.

Figure 3 shows the spatial distribution of the isolated trees aggregated in a 100x100m grid. Values range from 1 to 408 trees per hectare with a mean of 8.15 trees per hectare. Grid cells that have 0 isolated trees are transparent. Most of the isolated trees are located in urbanized zones and along the shoreline of the lake. The spatial distribution is heterogeneous with some identifiable hot spots. For instance, in the northern and south-eastern (Commune Chêne-Bougeries) part of the city center and south (Commune of Onex and Lancy) of the city. In general, as the distance to the city increases, the number of trees per hectare decreases as the land use changes to be more agricultural. Most of the forests are outside of the city and along the river Rhône.

B. BVOC emissions

EFs for isoprene and monoterpenes were found for 51 species and for sesquiterpenes for 38 species (Table VI in the annex). EFs for sesquiterpenes are much less common in literature. Considering that their contribution to OFP is much lower compared to isoprene and monoterpenes this is not problematic. Isoprene emission rates range from 0 to 70 µg gdw^{-1} h^{-1}. The three highest isoprene emitters are *Quercus robur* (European oak), *Populus nigra* (black poplar) and *Populus tremula* (European aspen), all three are native to Europe. For monoterpenes, values range from 0 to 43 µg gdw^{-1} h^{-1}. The three highest monoterpenes emitters are *Quercus ilex* (evergreen oak, native to the Mediterranean region), *Fagus sylvatica* (European beech, native to Europe) and *Liquidambar styraciflua* (American sweetgum, native to temperate areas of eastern North America). For sesquiterpenes, values range from 0.1 to 6.94 µg gdw^{-1} h^{-1}. With the available 51 tree species, EFs could be attributed to about 87% of the trees in the database. Table III shows the average EFs for each species and their rank according to their total BVOC emissions by applying the classification system by Benjamin *et al.* [19]. Based upon these definitions, 17 species (33%) are high emitters, 21 (41%) are moderate emitters and 13 (26%) are low emitters.

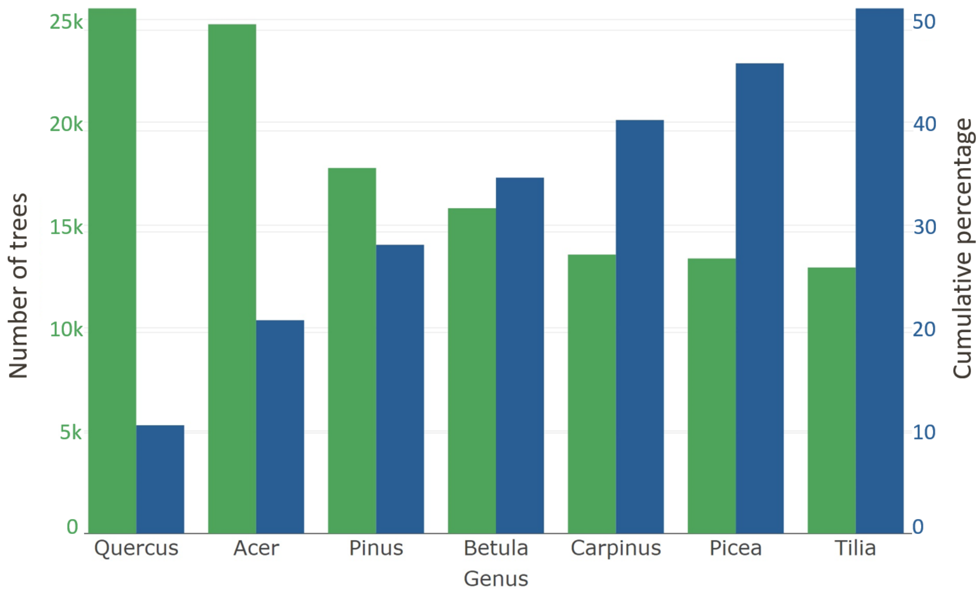


Figure 2: The seven most common tree genera of Geneva's data set. In green, the absolute number of trees per genus and in blue the cumulative percentage of these genera considering the entire data set.

Figure 8 in the annex shows the annual emissions of BVOCs (sum of isoprene, monoterpenes and sesquiterpenes) in the Canton of Geneva. The BVOC emissions of each tree were aggregated in 100x100m grid. In total, the urban trees in the Canton of Geneva emit 130 t of BVOCs per year. In the city center, rather low values of BVOC emissions are estimated. This can be explained by the combination of three factors, first the low density of trees (see Figure 3), second the low EFs of the species present in the area and third the total leaf biomass.

C. *Ozone-forming potential*

Figure 4 shows the annual OFP in the study area where the individual contribution of each tree is aggregated in a 100x100m grid. Values range from 0 to 1,662 kg of O_3 produced per hectare per year, with a mean of 88 kg/y. The total annual OFP is 1,153 t of O_3. The city center has rather low values of OFP, with most grid cells ranging between 0 and 57 kg/y. The actual OFP of an individual tree depends on hourly mass emission rates, environmental factors and leaf biomass. As the environmental factors were not considered in this study, high OFP is expected to occur at locations where trees have high emission rates and high leaf biomass. Thus, the OFP map shows very similar patterns to the BVOC emissions map (see Figure 8 in the annex).

D. *Ozone and PM_{10} removal*

Figure 5 shows the annual O_3 removed from the atmosphere by Geneva's urban trees calculated over a 100x100m grid, for the year 2019. Values range from 0 to 391 kg of O_3 removed per hectare with a mean of 13 kg/ha/y. The total ozone removed in 2019 is 179 t, this value can be compared with a study in Strasbourg by Selmi *et al.* (2016) who found a removal of 56 t.

Figure 6 shows the annual PM_{10} removal of Geneva's urban trees for the year 2019. Values per hectare range from 0 to 94 kg removed per year with a mean of 6 kg per year and hectare. The deposition is not homogeneous over the total area, some hot spots appear on the map; one is just south-east of the city, in the Commune Chêne-Bougeries and another one is north of the city. The amount of PM_{10} deposited will greatly depend on the leaf area, so regions with older, bigger trees will have more deposition. Another important factor is the leaf regime of the trees, deciduous trees are leafless during the winter period, nullifying their deposition potential. In 2019, trees in Geneva removed about 82 t of PM_{10}.

To estimate the contribution of Geneva's urban forest to the cleaning of the local atmosphere, we used the Emissions Database for Global Atmospheric Research (EDGAR [45]), which provides present-day anthropogenic emissions of air pollutants, to estimate the total emitted PM_{10} by anthropogenic sources. When using

Table III: Tree species with average standardized EFs for isoprene, monoterpenes and sesquiterpenes (µg gdw^{-1} h^{-1}) and ranked by the sum of their hourly EFs according to the classification proposed by Benjamin *et al.* (1996), where “low-“, “moderate-“, and “high-emitters” were defined as those species emitting less than 1 µg gdw^{-1} h^{-1}, between 1-10 µg gdw^{-1} h^{-1} and greater than 10 µg gdw^{-1} h^{-1}.

Species	Iso.	Mono.	Ses.	Iso. + Mono. + Ses.	Class
Quercus robur	39.89	1.79	0.10	41.78	high
Carpinus betulus	0.00	3.00	0.10	3.10	moderate
Fraxinus excelsior	0.00	0.45	0.10	0.55	low
Acer platanoides	0.06	2.95	0.10	3.11	moderate
Acer campestre	0.00	1.25	0.10	1.35	moderate
Malus domestica	0.07	1.60	0.10	1.77	moderate
Prunus avium	0.00	0.18	0.10	0.28	low
Acer pseudoplatanus	3.90	0.50		4.40	moderate
Taxus baccata	0.00	1.10		1.10	moderate
Pinus sylvestris	0.18	1.53	0.10	1.81	moderate
Aesculus hippocastanum	0.00	12.00		12.00	high
Pinus nigra	0.05	3.83	0.10	3.98	moderate
Juglans regia	0.00	1.00	0.10	1.10	moderate
Fagus sylvatica	0.00	21.14	0.10	21.24	high
Prunus domestica	0.00	0.00		0.00	low
Betula pendula	0.05	2.63	2.00	4.68	moderate
Robinia pseudoacacia	16.00	0.50	0.10	16.60	high
Tilia platyphyllos	0.09	7.70	0.10	7.89	moderate
Tilia cordata	0.00	1.70	0.10	1.80	moderate
Platanus acerifolia	18.50	0.10		18.60	high
Pyrus communis	0.00	0.00	0.10	0.10	low
Populus nigra	70.00	2.30	0.10	72.40	high
Picea abies	1.00	2.10	0.10	3.20	moderate
Platanus hispanica	18.50	0.10		18.60	high
Cedrus atlantica	0.00	1.00	0.10	1.10	moderate
Celtis australis	0.01	7.60		7.61	moderate
Acer saccharinum	0.10	0.50		0.60	low
Ulmus minor	0.10	0.10	0.10	0.30	low
Liquidambar styraciflua	17.00	20.00		37.00	high
Prunus cerasifera	0.50	0.48		0.98	low
Salix alba	37.20	1.10	0.10	38.40	high
Cupressus sempervirens	0.00	0.70	0.10	0.80	low
Ginkgo biloba	0.60	0.10		0.70	low
Quercus rubra	35.00	0.10	0.10	35.20	high
Quercus petraea	45.00	0.30	0.10	45.40	high
Quercus ilex	0.10	43.00	0.10	43.20	high
Quercus cerris	0.10	0.60	0.10	0.80	low
Aesculus carnea	0.00	12.00		12.00	high
Alnus glutinosa	0.30	1.10		1.40	moderate
Prunus padus	0.00	0.10	0.10	0.20	low
Betula pubescens	0.00	1.71	4.47	6.18	moderate
Salix caprea	18.90	0.10	0.10	19.10	high
Populus tremula	60.00	0.00	0.10	60.10	high
Juglans nigra	0.00	1.00	0.10	1.10	moderate
Populus alba	60.00	0.00	0.10	60.10	high
Fraxinus angustifolia	0.00	0.00	0.10	0.10	low
Acer monspessulanum	0.00	1.50	0.10	1.60	moderate
Fraxinus ornus	0.00	0.02	0.10	0.12	low
Acer opalus	0.10	1.50	0.10	1.70	moderate
Pinus pinea	0.00	3.00	0.10	3.10	moderate
Platanus orientalis	18.5	0.10	0.10	18.70	high

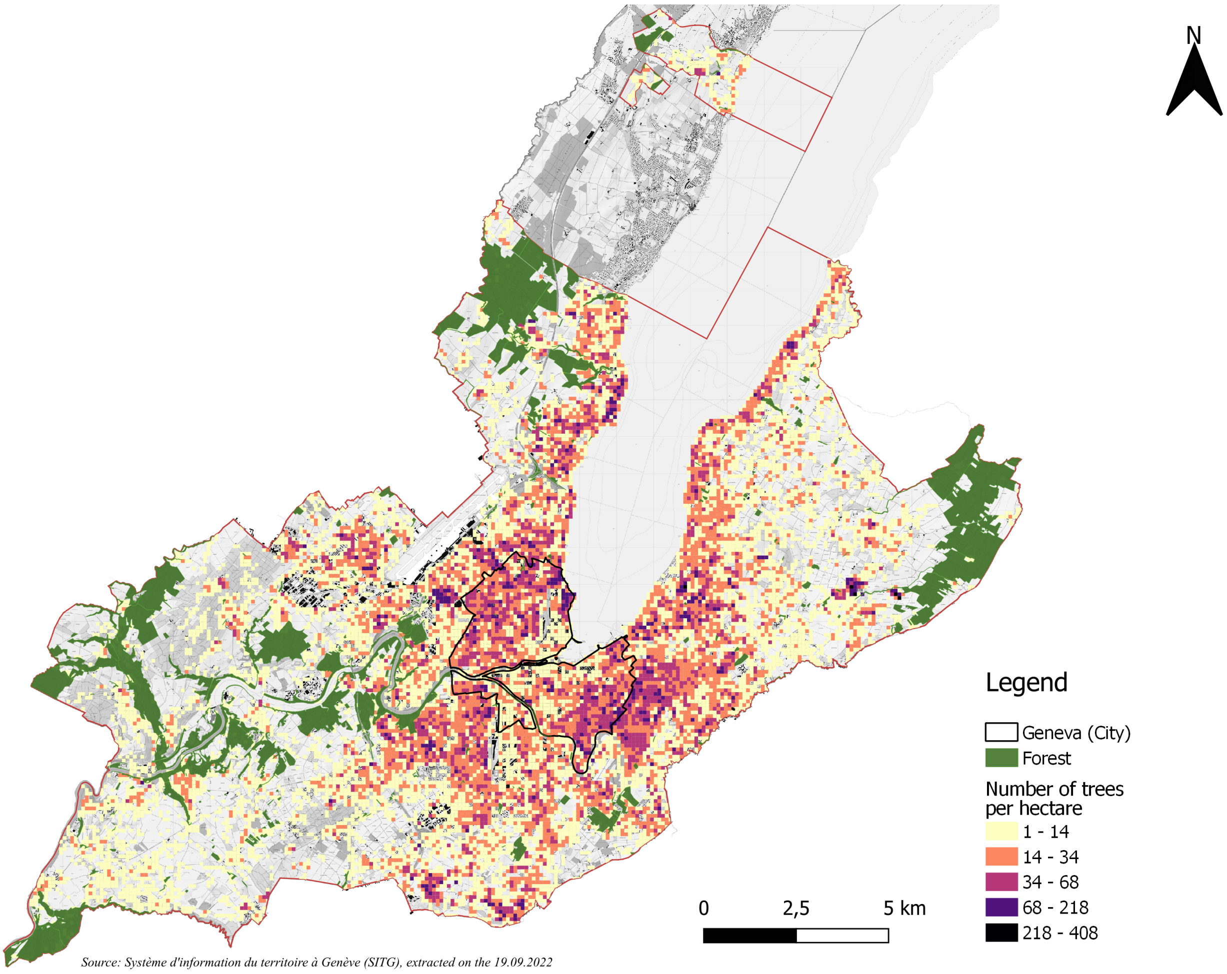


Figure 3: Map of the tree density in Geneva, calculated on a 100x100m grid, forests are shown in dark green patches and the city of Geneva is shown with a black outline. Topographic background, present in all subsequent maps, is freely available on the swisstopo website.

EDGAR, it can be estimated that the Canton of Geneva emitted approximately 631 t of PM_{10} in 2018 (2018 is the latest available year). So the fraction of total emitted PM_{10} removed by Geneva's urban trees is 12.98%.

IV. Discussion

A. *Interpretation of the urban trees' structure and functions*

The current species' distribution of Geneva's urban forest is not ideal from an air quality point of view. Among the five most abundant tree species, one is a high BVOC emitter, three are moderate emitters and one is a low emitter. Indeed, *Quercus robur* (European oak) is the most common species with 10,708 individuals (4.5% of all the trees in the data set) and is a high BVOC emitter that has the potential to deteriorate the air quality by increasing O_3 concentrations. Most of the *Quercus* (oak) trees have high BVOC EFs [31] and they represent 25,534 individuals (10.8%) of Geneva's urban trees. Taha *et al.* [46] showed that the net effect of increased urban vegetation in the Californian South Coast Air Basin would be a decrease in ozone concentrations if the additional trees are low BVOC emitters. Their simulations showed that tree species emitting more than 2 µg gdw^{-1} h^{-1} of isoprene and 1 µg gdw^{-1} h^{-1} of monoterpenes should not be introduced.

Moreover, from the 23 most common tree genera in Geneva's inventory (90% of all the trees in the data set) 17 are deciduous tree genera and only 6 evergreens. This will heavily impact the urban vegetation's ability to remove pollutants from the atmosphere in winter as deciduous trees are leafless during several months.

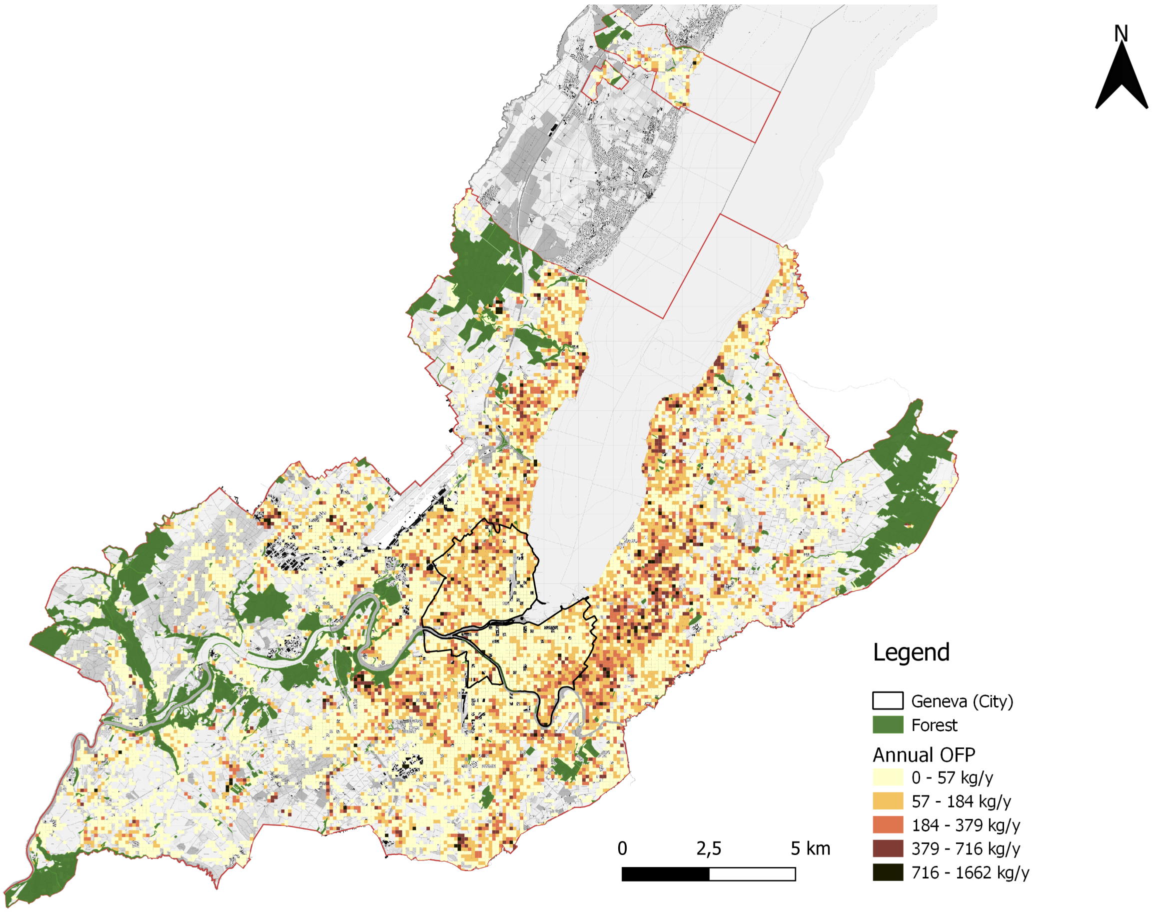


Figure 4: Map of the annual OFP, aggregated in a 100x100m grid. Values are in kg of O_3 potentialy produced per year.

Usually, evergreen trees are more efficient in capturing air pollutants than broad-leaved species [47] because they keep their foliage during winter. Selmi *et al.* [27] showed that the urban forest of Strasbourg removed in total 88 t of pollutants during a one-year period. The filtering capacity of urban trees is thus an important aspect for air quality.

Also, the way city planners tend to their urban trees needs to be considered. For instance, since the beginning of 2022, Geneva's authority responsible for urban trees decided to gradually abandon the pruning of its trees [48]. Stopping the heavy pruning will most probably have a positive impact on the air quality as it will lead to more canopy cover. This will in turn increase the air pollution filtering capacity of the trees, mitigate the urban heat island effect and increase biodiversity. However, it will also increase the amount of BVOCs emitted by the trees because of increasing leaf biomass. Consequently, not all trees should suddenly be stopped pruning, but they should be carefully selected to avoid an increase in BVOC emissions. To avoid such an increase, the authorities could continue to prune high BVOC emitting species such as *Quercus robur* (European oak) and *Populus nigra* (black poplar).

In this study, to estimate the PM_{10} deposition we used an average PM_{10} concentration over the entire area, thus spatial differences in PM_{10} deposition will solely depend on the leaf area of trees. It is however a simplified approach as the PM_{10} concentration would vary spatially with higher concentrations being close to the main sources of emissions (roads, industry). The estimation would be more precise if hourly or daily averages of PM_{10} concentrations were used. Therefore, in Figure 6 the city center does not show the highest PM_{10} deposition even though the atmospheric concentrations of PM_{10} can be expected to be high there because of traffic load. We estimated that the urban forest removed about 82 t of PM_{10} in 2019, representing about 13% of the

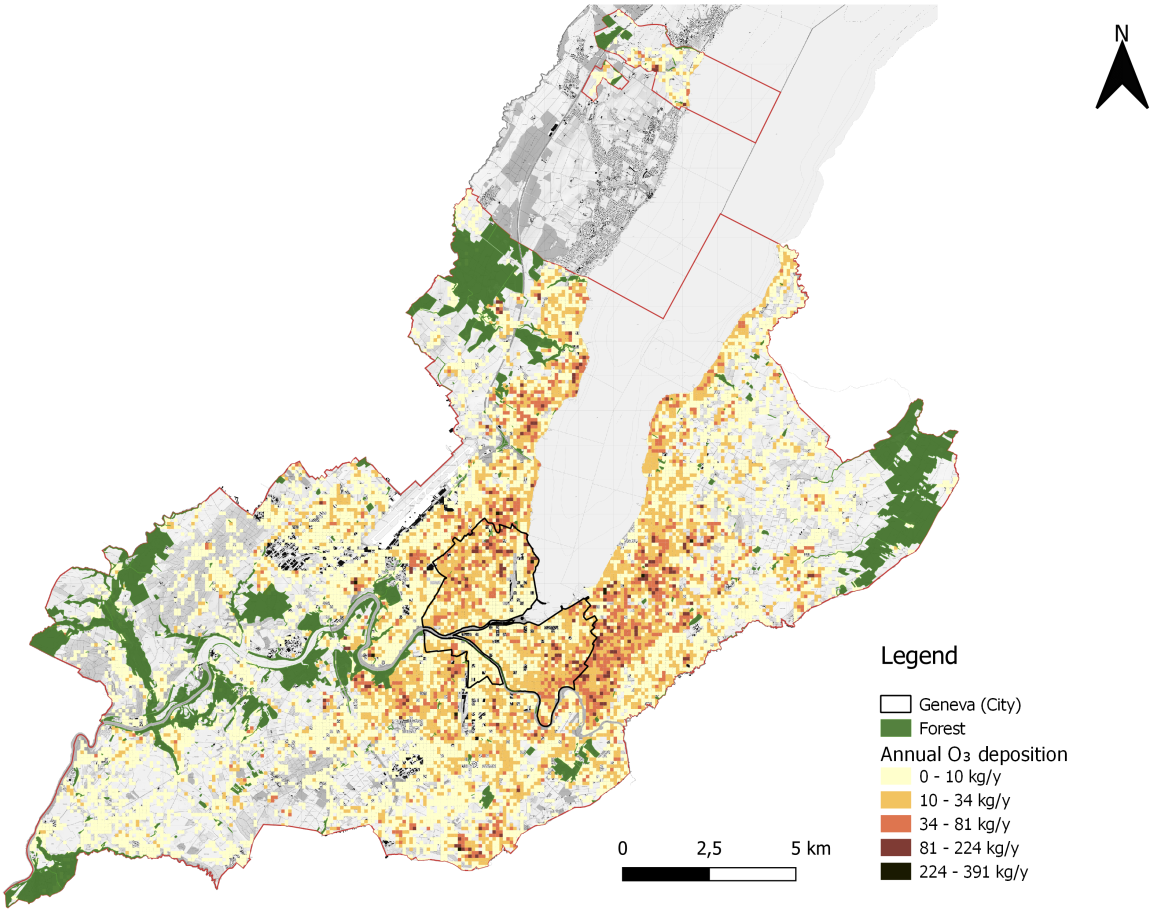


Figure 5: Map of the annual O_3 removal in 2019, values are in kg/y aggregated in a 100x100m grid.

anthropogenic emissions. A similar study in Strasbourg estimated that trees removed 11.76 t of PM_{10} in one year which represents 7% of the anthropogenic emissions [27]. The two cities are comparable in many aspects such as population, climate, number of trees and region. However, the study area of Strasbourg covers 7,830 ha (with 2,750 ha canopy cover) whereas Geneva covers 28,248 ha (with 1,160 ha canopy cover). Urban trees cover about 19.02% and 4.11% of the city area in Strasbourg and Geneva, respectively. Geneva's canopy cover does not include the forests in the Canton as those trees were not surveyed. With the non-urban forests, this value would increase from 4.11% to 19.38%. Overall the estimations show that Geneva's urban trees perform better than Strasbourg's trees do.

Concerning the ozone-forming potential, by using the MIR we estimated the maximum amount of ozone that the urban trees can possibly produce in ideal atmospheric conditions. Therefore, NO_x was not a limiting factor. However, in reality, NO_x would be a limiting factor at the city scale and its concentrations are not uniform over the study area.

To conclude about Geneva's urban trees' functions and structure, the most common tree species in the Canton of Geneva emit large amounts of BVOCs and are deciduous, which leads to the formation of unwanted O_3 and reduces the ability of the urban vegetation to capture atmospheric pollutants. In the future, if a large planting program is planned, it would be of interest to carefully select the species used. In this study, we showed that the "best" trees are those with low BVOC emissions and a high leaf area. However, it is important to stress that this study solely focuses on the impact of the urban forest on air quality, but the selection of tree species should also consider other important factors such as noise attenuation potential, evapotranspirative cooling, environmental stress tolerance, carbon sequestration, pest tolerance and biodiversity. Tiwary *et al.* [49] propose a performance index that uses some of the aforementioned factors to evaluate the performance of street vegetation.

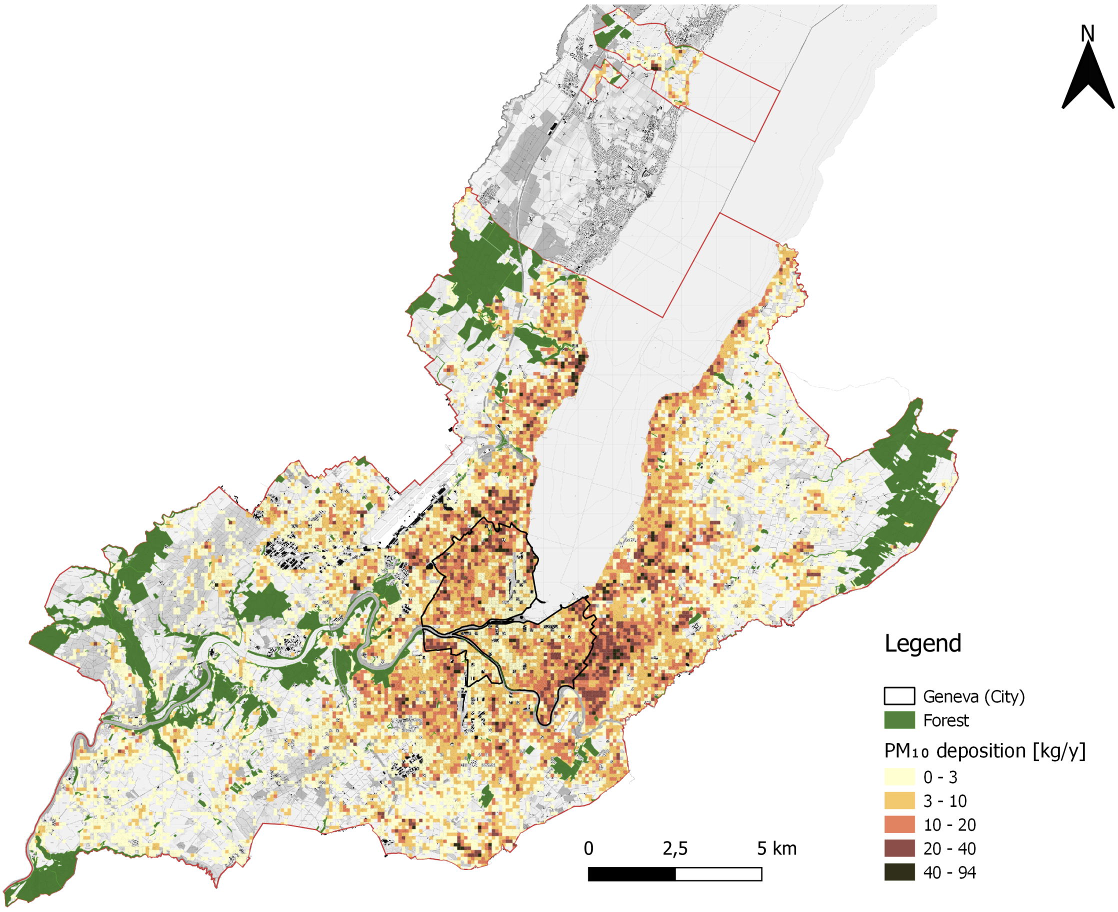


Figure 6: Annual removal of PM_{10} for the year 2019, the contribution of each tree was aggregated in a 100x100m grid, values are in kg/y.

Classifying Geneva's tree species according to their air quality performance (deposition of PM_{10} and O_3, and OFP) will be an important aspect of future research. A new performance index can be elaborated or one from the scientific literature can be directly used or adapted to the needs of the local authorities.

To the authors' knowledge, it is the first time that estimations for PM_{10} deposition, O_3 deposition and OFP were done and mapped for a city in Switzerland based on an urban trees inventory. For comparison purposes, it would be important that this methodology, or a similar one, is applied to other big Swiss cities.

B. Comparison to i-Tree Eco outputs

One advantage of this study is the completeness and size of Geneva's inventory. Indeed, most trees are identified at the species level and this inventory contains about 25% of all the trees in the Canton, including forests. This allows us to treat BVOC emissions at a finer scale compared with studies and i-Tree Eco that work at best at the genus level. Indeed, i-Tree Eco uses a base genus emission rate and if genus-specific information is not available, median emission values for the family, order, or superorder are used. Therefore studies that use i-Tree Eco or UFORE model components will also treat the BVOC emissions at the genus level.

One goal of this study was to compare the results of our approach to i-Tree Eco outputs and to understand where the potential differences come from. i-Tree Eco estimated that Geneva's trees removed 13.6 t of PM_{10} in 2014. Whereas with the approach presented in section II-G we estimated the deposition to be around 82 t of PM_{10} for the year 2019. The mean yearly PM_{10} concentration for 2014 was about 18 $\mu g/m^3$ compared to 16.99 $\mu g/m^3$ in 2019. Both concentrations are thus very similar. However, it is important to note that i-Tree Eco models pollution removal based on hourly measured pollution concentrations. To get the pollution concentrations, the model uses weather and pollution data from two different stations. The weather station is located in Geneva Cointrin (46°14'13.0884" N and 6°6'33.0582" E) at the international airport and the pollution data comes from a station located in Gaillard (46°11'37.2048" N and 6° 12' 53.2548" E), a small French city located at the border with Switzerland and 5 km away from Geneva. The location of the weather station should not be problematic, as it is very close to the city and meteorological variables would not change significantly over such a distance. However, the pollution data from Gaillard would only partly match the concentrations in Geneva. Gaillard is a small town, with approximately 11,000 inhabitants, which belongs to the larger agglomeration of Annemasse. The measuring station is located directly at the border to Switzerland in an urban area, next to a road. Gaillard has no heavy industry that could significantly influence pollutant measurements. As the station is located directly at the border and next to other cities, the levels of PM measured will be influenced by the other cities and will also depend on wind direction as particles can be transported in the atmosphere. To summarize, the pollution measurements in Gaillard do not perfectly match Geneva's air pollution. However, both cities are only 5 km apart and have a similar urban setting making it an acceptable station to be used by i-Tree Eco.

i-Tree Eco estimated that the urban trees emit 50.4 t of BVOCs (isoprene and monoterpenes only) per year. With the species-level approach, we estimated that the annual BVOC (isoprene, monoterpenes and sesquiterpenes) emissions would be about 130 t. Our estimation is thus about 2.6 times greater than i-Tree Eco's estimation. This difference can be explained by the following reason. To estimate BVOC emissions from a tree, i-Tree Eco calculates the leaf biomass of the tree and then multiplies it by genus-specific or family-specific emission factors and by a meteorological correction factor. The meteorological correction factor takes into account air temperature and light conditions. Meanwhile, for simplification reasons we do not consider climate conditions in our species-level approach. It is thus possible that the overestimation is due to that simplification and because we consider sesquiterpenes which i-Tree does not. However, the species-level approach has the advantage over i-Tree Eco to consider EFs at the species level whereas i-Tree uses EFs at the genus level from literature without giving the references and also from unpublished studies. The best combination would be to use species-specific EFs and consider the weather conditions.

C. Comparison to other studies

The PM_{10} and O_3 deposition of the three most common tree species in Geneva (*Quercus robur*, *Carpinus betulus* and *Fraxinus excelsior*) were compared with other studies in order to evaluate our results. Table IV contains the species mean yearly PM_{10} deposition in g plant^{-1} y^{-1} for these trees from the species-level approach, i-Tree Eco approach, Baraldi *et al.* [9] and Paoletti *et al.* [50]. At first glance, the values are not uniform between the different studies. For instance, PM_{10} depositions for *Carpinus betulus* range from 2.6 to 346.9 g plant^{-1} y^{-1}. The results reported by Baraldi *et al.* [9] are close to what i-Tree Eco estimates. One reason for these differences may be the PM_{10} concentrations in the different study areas, as the deposition of particulate matter is directly dependent on the load of particles in the atmosphere. However, Paoletti *et al.* [50] reported a PM_{10} concentration of 34.6 µg/m^3 which is about twice as great as Geneva's 16.99 µg/m^3. It is thus surprising that Paoletti *et al.* [50] obtain the lowest values of PM_{10} deposition. Another reason that could explain the differences is the leaf area of the trees. Unfortunately, the studies do not provide this variable. The method we used (see section II-G) produces the highest values of PM_{10} depositions.

Concerning O_3 deposition (see Table V), Paoletti *et al.* [50] also report the lowest values. While both approaches of this study and Baraldi *et al.* [9] resulted in closer deposition values, with the exception of *Quercus robur* that shows a high mean ozone deposition when using the species-level approach. Baraldi *et al.* [9] use the same method as we do to estimate O_3 depositions therefore the values are close to each other. As for PM_{10} deposition, i-Tree Eco uses weather and pollution data to estimate O_3 deposition. Our comparative approach does not use weather or pollution data, we only use an annual average O_3 concentration for the entire study area (see Section II-H). It is thus interesting to see that even with some simplifications the estimations for *Carpinus betulus* and *Fraxinus excelsior* are so close between both methods.

After comparing deposition values at the species level, it is interesting to see how urban trees in Geneva perform in total and over an entire year compared with other cities. The PM_{10} deposition estimation by i-Tree Eco is closer to what Selmi *et. al* (2016) observed in Strasbourg (11.76 t) than to what we found in this study. Nowak *et al.* (2006) estimated the PM_{10} and O_3 removals

Table IV: Comparison of PM_{10} deposition values of the three most common tree species in the data set with two studies and i-Tree Eco. In the study by Paoletti *et al.* (2011) the average PM_{10} concentration was 34.6 µg/m^3 and for Baraldi *et al.* (2019), the concentration used is unknown.

	Species mean PM_{10} deposition (g plant^{-1} y^{-1})			
	This study			
Species	**Species-level**	**i-Tree Eco**	**Paoletti et al. (2011)**	**Baraldi et al. (2019)**
Quercus robur	423.8	87.0	37.8	-
Carpinus betulus	346.9	71.4	2.6	68.6
Fraxinus excelsior	390.1	80.3	-	90.3

Table V: Comparison of the O_3 deposition values of the three most common tree species in the data set with two studies and i-Tree Eco.

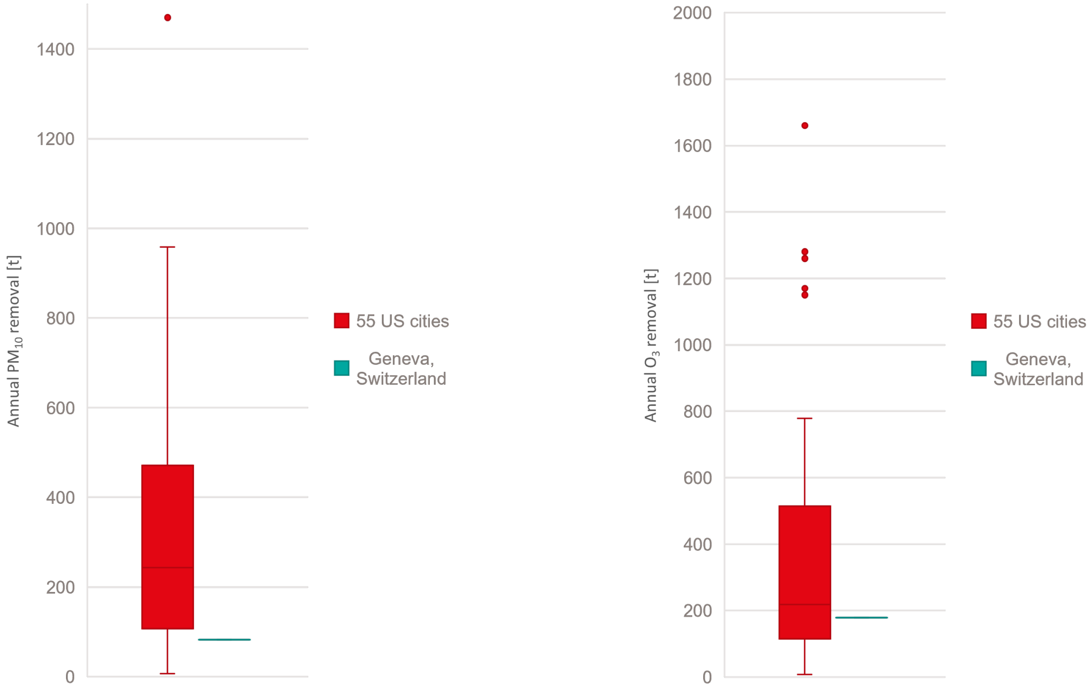
	Species mean O_3 deposition (g plant^{-1} y^{-1})			
	This study			
Species	**Species-level**	**i-Tree Eco**	**Paoletti et al. (2011)**	**Baraldi et al. (2019)**
Quercus robur	2904.1	331.8	18.8	-
Carpinus betulus	237.6	279.2	1.1	140.3
Fraxinus excelsior	320.7	312.7	-	130.6

of 55 cities in the US (Figure 7). Considering PM_{10} deposition, Geneva's performance is in the lower part of the graph (see Figure 7a), this could be due to higher PM_{10} concentrations in those cities. As this study only investigated the performance of the isolated trees in the Canton that represent about 25% of the total trees, forests would increase total air pollution removal in the study area, but these trees cannot be easily surveyed. Future research focusing on air pollution removal by the entire tree cover is recommended to quantify ecosystem services provided by all the trees in the Canton of Geneva. This study makes a first attempt at estimating the total PM_{10} removed in Geneva and can be improved if all the trees, the pollution and weather conditions are considered. Figure 7b shows the annual O_3 removal from Geneva's urban trees compared with 55 US cities. With the removal of 179 t of O_3, Geneva places itself very close to the median of the 55 US cities.

D. Spatial analysis

The fine mapping of the air quality variables is a significant advantage over other studies that do not consider the spatial component. The different maps showed that the urban forest did not perform uniformly over the study area, but rather that some hot spots of OFP or air pollutant removal appeared. To obtain clear and representative maps we made the decision to represent the variables on a 100x100m grid. Tests were made by using larger or smaller grids, but when a finer grid (*e.g.*, 50x50m) was used the details would mask spatial trends and hot spots. On the other hand, when a larger grid (*e.g., 200x200m*) was used, the grid cells did not faithfully represent the neighbourhoods anymore. The choice of the grid size is therefore crucial and will impact the interpretations. In general, the maps showed certain repetitions in their patterns, meaning that the same hot spots appeared for different variables. This can be explained by two factors. First, because we sum the contributions of each tree to the environmental variables (PM_{10} and O_3 deposition and OFP) the final performance will directly depend on the number of trees present per grid cells. Second, whether for PM_{10} and O_3 deposition or for OFP, all three equations use a variable that depends directly on the age of a tree, namely leaf area or leaf biomass. Some hot spots are thus expected at locations where the density of trees and the average age of trees are high. But the species distribution also plays a major role as some grid cells can have many trees but if all of them are low BVOC emitters, the OFP will also be low.

In this study, the focus was set on air quality and on the interactions between urban trees with the atmosphere. But, the spatial approach could be used for many different purposes such as the heat mitigation potential of the urban trees and pollen emissions. A spatial approach can



(a) **(b)**

Figure 7: Comparison of PM_{10} and O_3 removal between Geneva and 55 US cities [51]. (a) Annual PM_{10} removal in t for 55 US cities compared to Geneva. (b) Annual O_3 removal in t for 55 US cities compared to Geneva.

help urban planners to better understand the dynamics in place and could help them focus their efforts on areas that need air quality improvement. The spatial analysis done in this work is rather superficial and it would be interesting to apply further spatial analysis methods to identify clustering or spatial correlation.

V. Conclusion

In this study, we used two different approaches to estimate OFP, PM_{10} and O_3 deposition. The first approach was a direct use of i-Tree Eco with Geneva's tree inventory. For the second, we applied a well-documented methodology, also used in other papers, to estimate the OFP of an urban forest based on species-specific BVOC emission rates. Also, we estimated the atmospheric removal of PM_{10} and O_3 based on a dry deposition equation and stomatal uptake, respectively. All results are mapped at the Canton scale in a 100x100m grid providing a spatial overview and allowing spatial analysis.

We showed that Geneva's air quality suffers from its urban forest structure as it is dominated by tree species that are both high BVOC emitters and deciduous. We estimated that Geneva's urban forest removed 82 t of PM_{10} and 179 t of O_3 for the year 2019. Also, we estimated that the urban trees emit 130 t of BVOCs per year, that under ideal conditions would lead to the formation of 1,153 t of O_3. Meanwhile, i-Tree Eco estimated that the urban trees removed 13.6 t of PM_{10} in 2014 and that they emit 50.4 t of BVOCs per year. These values can be compared to what Selmi *et al.* [27] found for the city of Strasbourg which has a similar urban forest than Geneva. They found that the urban trees in Strasbourg removed about 11.76 t of PM_{10} and 56 t of O_3 from July 2012 to June 2013. The two approaches and the study considered here show very different values. The differences between the species-level approach and i-Tree Eco can be attributed to the following factors. i-Tree Eco uses weather data to estimate BVOC emissions which for simplification reasons were not used in the species-level approach. Second, i-Tree Eco uses BVOC emission factors at the genus level compared to the species level for the other approach. Concerning the differences between our results and the study by Selmi *et al.* [27], the same remarks can be made as the authors of the study also used i-Tree Eco and in addition, the structure of Strasbourg's urban forest is different from

Geneva's.

Even though the species-level approach has some simplifications compared with i-Tree Eco, the results still show that urban trees play an important role in the removal of major air pollutants and that the drawback of OFP should not be underestimated. For future planting programs, it would be important to choose species that emit low amounts of BVOC to minimize the formation of O_3. This study is a first step in assessing the impact of Geneva's urban forest on air quality and the fine grid GIS approach can allow urban planners to focus on certain neighbourhoods where air quality is an issue. This allows solutions to be tailored to the local needs and unnecessary interventions can be avoided, saving time and money for the city.

The aim of this work is not to purposefully tarnish the image of urban trees but to propose a more complete approach to the challenge of urban greening. Planting trees will in most cases be beneficial to the well-being of citizens but if the species are carefully selected and planted at the right places their positive impact can be improved even further.

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VI. Annex

Table VI: List of the 51 tree species used in the species-level approach, along with their absolute number of individuals, percent of the population, standardized (at 30°C leaf temperature and 1000 µmol m^{-2} s^{-1} PPFD) isoprene, monoterpenes and sesquiterpenes emission factors in µg gdw^{-1} h^{-1}. n.d. = not detected

Species	**Number of trees**	**Percent of population [%]**	**Isoprene [µg gdw^{-1} h^{-1}]**	**Monoterpenes [µg gdw^{-1} h^{-1}]**	**Sesquiterpenes [µg gdw^{-1} h^{-1}]**
Quercus robur	10,708	4.51	9.79 [52], 70[53]	2.57 [52], 1 [53]	0.1 [53]
Carpinus betulus	9,441	3.98	n.d [9], 0 [53]	3 [9]	0.1 [53]
Fraxinus excelsior	5,391	2.27	n.d [9], 0 [53]	0.9 [9], 0 [53]	0.1 [53]
Acer platanoides	5,322	2.24	0.02 [9], 0.1 [53]	4.4 [9], 1.5 [53]	0.1 [53]
Acer campestre	5,207	2.19	0 [53]	1 [9], 1.5 [53]	0.1 [53]
Malus domestica	4,662	1.97	0.07 [9]	1.6 [9]	0.1 [53]
Prunus avium	4,576	1.93	0 [39], 0 [53]	0.25 [39], 0.1 [53]	0.1 [53]
Acer pseudoplatanus	4,351	1.83	3.9 [54]	0.5 [53]	
Taxus baccata	4,166	1.76		1.1 [55]	
Pinus sylvestris	3,735	1.57	0.18 [16]	1.53 [16]	0.1 [53]
Aesculus hippocastanum	3,428	1.45	0 [56]	12 [56]	
Pinus nigra	3,363	1.42	0.051 [16]	3.83 [16]	0.1 [53]
Juglans regia	3,215	1.35	0 [53]	1 [53]	0.1 [53]
Fagus sylvatica	2,961	1.25	0 [57]	21.14 [57]	0.1 [53]
Prunus domestica	2,856	1.20	0 [19]	0 [19]	
Betula pendula	2,483	1.05	0.05 [54]	2.63 [54]	2 [53]
Robinia pseudoacacia	2,319	0.98	16 [9]	0.5 [9]	0.1 [53]
Tilia platyphyllos	2,319	0.98	0.09 [9]	7.7 [9]	0.1 [53]
Tilia cordata	2,297	0.97	n.d [9], 0 [53]	3.4 [9],0 [53]	0.1 [53]
Platanus acerifolia	2,156	0.91	18.5 [29]	0.1 [29]	
Pyrus communis	2,043	0.86	0 [53]	0 [53]	0.1 [53]
Populus nigra	1,890	0.80	70 [57]	2.3 [57]	0.1 [53]
Picea abies	1,504	0.63	1 [57]	2.1 [57]	0.1 [53]
Platanus hispanica	1,453	0.61	18.5 [29]	0.1 [29]	
Cedrus atlantica	1,138	0.48	0 [53]	1 [53]	0.1 [53]
Celtis australis	1,019	0.43	0.01 [9]	7.6 [9]	
Acer saccharinum	977	0.41	0.1 [54]	0.5 [54]	
Ulmus minor	778	0.33	0.1 [57] , 0.1 [53]	0.1 [53]	0.1 [53]
Liquidambar styraciflua	749	0.32	17 [19]	20 [19]	
Prunus cerasifera	711	0.30	0.5 [9]	0.48 [9]	
Salix alba	600	0.27	37.2 [53]	1.1 [53]	0.1 [53]
Cupressus sempervirens	545	0.23	0 [53]	0.7 [53]	0.1 [53]
Ginkgo biloba	502	0.21	0.6 [9]	0.1 [9]	
Quercus rubra	489	0.21	35 [57]	0.1 [53]	0.1 [53]
Quercus petraea	474	0.20	45 [53]	0.3 [53]	0.1 [53]
Quercus ilex	367	0.15	0.1 [29]	43 [29]	0.1 [53]
Quercus cerris	346	0.15	0.1 [57] , 0.1 [53]	0.6 [53]	0.1 [53]
Aesculus carnea	333	0.14	0 [56]	12 [56]	
Alnus glutinosa	259	0.11	0.3 [9]	1.1 [9]	
Prunus padus	220	0.09	0 [53]	0.1 [53]	0.1 [53]
Betula pubescens	153	0.06	0 [53]	1.71 [58]	2 [53], 6.94 [58]
Salix caprea	153	0.06	18.9 [53]	0.1 [53]	0.1 [53]
Populus tremula	151	0.06	60 [57]	0 [57]	0.1 [53]
Juglans nigra	135	0.05	0 [53]	1 [53]	0.1 [53]
Populus alba	123	0.05	60 [57]	0 [57]	0.1 [53]
Fraxinus angustifolia	116	0.05	0 [53]	0 [53]	0.1 [53]
Acer monspessulanum	113	0.04	0 [53]	1.5 [57], 1.5 [53]	0.1 [53]
Fraxinus ornus	112	0.04	n.d [9], 0 [53]	0.03 [9] 0 [53]	0.1 [53]
Acer opalus	107	0.04	0.1 [57]	1.5 [57]	0.1 [53]
Pinus pinea	96	0.04	0 [53]	3 [29], 3 [53]	0.1 [53]
Platanus orientalis	29	0.01	18.5 [57]	0.1 [57]	0.1 [53]
	102,641	**43.27**			

Table VII: Number of trees per genus that only had their genus documented, along with their percent of population and weighted mean EFs in µg gdw^{-1} h^{-1}.

Genus	Number of trees	Percent of population [%]	Isoprene	Monoterpenes	Sesquiterpenes
Quercus	12,473	5.26	37.60	2.85	0.10
Betula	12,392	5.22	0.05	2.58	2.14
Picea	11,348	4.78	1.00	2.10	0.10
Pinus	9,965	4.20	0.12	2.62	0.10
Acer	7,426	3.13	1.08	1.57	0.10
Populus	6,274	2.65	68.73	2.01	0.10
Tilia	6,070	2.56	0.04	3.74	0.10
Juglans	4,515	1.90	0.00	1.00	0.10
Carpinus	4,094	1.73	0.00	3.00	0.10
Aesculus	3,718	1.57	0.00	12.00	
Fraxinus	3,706	1.56	0.00	0.43	0.10
Salix	3,296	1.39	33.70	0.91	0.10
Fagus	2,726	1.15	0.00	21.14	0.10
Ulmus	2,224	0.93	0.10	0.10	0.10
Robinia	2,116	0.89	16.00	0.50	0.10
Cedrus	2,104	0.88	0.06	1.60	
Platanus	2,037	0.86	18.50	0.10	0.10
Taxus	1,552	0.65	0.00	1.10	
Cupressus	1,041	0.44	0.00	0.70	0.10
	99,077	**39.19**			

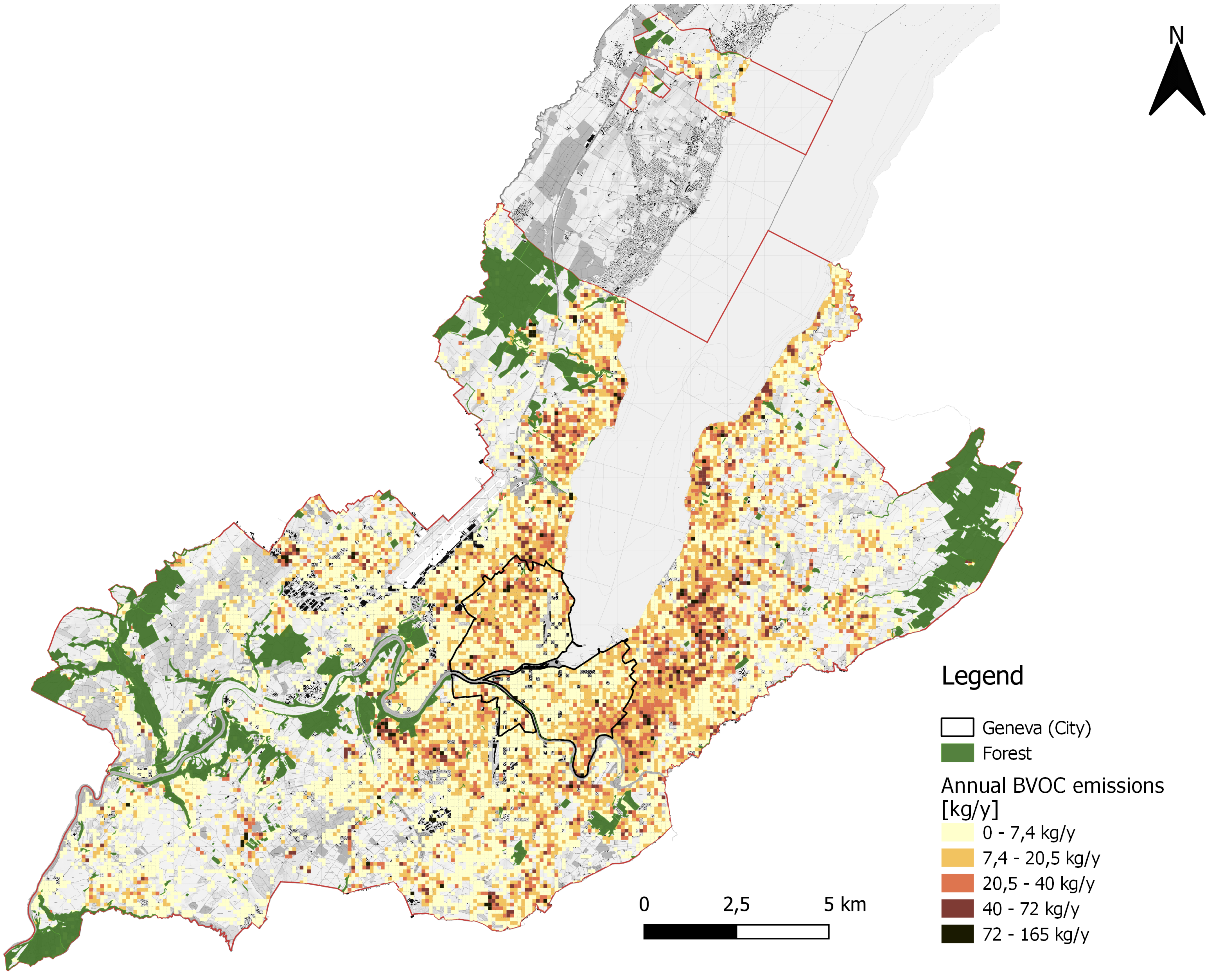

Figure 8: Annual emissions of BVOCs (sum of isoprene, monoterpenes and sesquiterpenes) from the urban trees in kg y^{-1}, the emissions of each tree were aggregated in a 100x100m grid.