Tree Distribution in Geneva

A Study of the Influence of Trees on Ozone and PM_{10} absorbtion in the city of Geneva

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Computational Methods and Tools

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1 Deviations from Project Proposal

Initially, our plan was to analyze hypothetical tree distributions across the regions of Geneva and Zurich to determine the most effective tree-planting strategies for enhancing air quality. The idea was to create a grid containing information about local pollutant concentrations, placing trees at different locations within the grid, and analyzing how this would impact pollutant levels.
We quickly realized that obtaining spatially resolved maps of pollutant concentrations would be challenging, as air quality in Switzerland is mainly monitored by local sensors, requiring interpolation for a full spatial map. Instead of modeling our own tree distribution, we used existing data on the actual tree distribution across a city to analyze its impact on pollutant concentrations. Our work is based on a study conducted in Geneva by Kofel, Donato, et al., *URBTREES – Quantifying and Mapping the Impact of Urban Trees on Air Quality in Geneva, Switzerland*, 2023 [7]. This study provides formulae to calculate the *OFP* (ozone-forming potential), PM_{10} deposition, and O_3 removal by trees, using species-specific parameters and the mean yearly concentrations of pollutants.
Due to different formats and contents, writing a program adaptable to the provided data of different cities turned out to be very difficult. Since the study and formulae were based on Geneva, we decided to focus exclusively on this city. The study also provides results that enable us to compare our final outcomes.

2 Introduction

In this project, we analyze the influence of isolated trees within the canton of Geneva on ozone (O_3) and PM_{10} concentrations. The term "PM_{10}" is used for particulate matter with a diameter less than 10 μm [15]. Both are components that have a strong influence on human health by affecting cardiovascular and respiratory systems [11]. Due to the danger imposed by these compounds, there exists a certain interest on removing them from the air. Urban trees are proposed as solution: besides providing heat mitigation, ecosystem services, and other benefits, they also improve air quality [4].
This project investigates the dual effect of trees: they absorb air pollutants like ozone and PM_{10}, improving air quality, but they can also emit *Biogenic Volatile Organic Compounds* (*BVOCs*), which may transform into ozone, thereby impairing air quality [1]. This contribution to air mitigation is called the ozone-forming potential (*OFP*). We try to answer the question of whether trees eventually have a positive or This project takes the outstanding work of Kofel, Donato, et al. [7] as guidance. This master thesis, written and published at EPFL, is a study using the i-Tree Eco tool to model the impact of isolated trees on air quality in the canton of Geneva. In this project, we tried to recreate the results imposed by Kofel, Donato, et al. by writing a program using the languages C and Python. This allows for comparison between data computed using our code with that in [7] to evaluate the correctness of our computations. In a first step, the approach and data used in this project will be presented, while underlining eventual differences with Kofel, Donato, et al. We will then explore how air quality is impacted in the canton of Geneva. In a next step, the results of this study can be compared to those of Kofel, Donato, et al., which used older concentrations of PM_{10} and O_3. Finally, we are going to outline the limits and power of the model used and provide the reader with an outlook on improvements for further usage of the model used.

3 Approach

3.1 Modeling

Our project is based on the formulae found in the thesis of Kofel, Donato, et al. [7]. They are part of a physical, mechanistic, and deterministic model that allows forward modeling using empirical data. In fact, calculations are based on underlying physical, biological, and chemical processes and produce predictable results from given inputs. These formulae eventually allow us to calculate the yearly OFP of a single tree, its yearly PM_{10} deposition, and its cumulated annual stomatal O_3 flux. Below are some of the most important formulae, presented in the same original notation as in [7]. The names of some variables have been modified in the code.

Ozone-forming potential (*OFP*) of one tree for one hour in $\mu g(O_3)/h$:

$$OFP = B \cdot \sum_i EF_i \cdot MIR_i \tag{1}$$

B, in $[gdw\ tree^{-1}]$, is the biomass factor or total dry leaf weight of a tree. EF_i, expressed in $[\mu g\ gdw^{-1}\ h^{-1}]$, is a species-specific mass emission factor for $BVOC_i$. MIR_i is the maximum incremental reactivity in $[g_{O_3}\ g_{VOC}^{-1}]$. i represents the tree $BVOC$ categories considered in the study: isoprene, monoterpenes and sesquiterpenes.

Estimation of PM_{10} deposition for one tree over one year in $\mu g(PM_{10})/y$:

$$PM_{10}\ deposition = V_d \cdot C_i \cdot A_L \cdot T_i \cdot 24 \cdot 3600 \cdot 0.5 \cdot 10^{-9} \tag{2}$$

The dry deposition velocity V_d of PM_{10} was set to 0.0064 m/s. C_i is the mean yearly PM_{10} concentration in $[\mu g/m^3]$. A_L is the total leaf area in $[m^2]$ and T_i is the number of days per year during which the tree has leaves. The 0.5 factor corresponds to a 50% particle resuspension rate back to the atmosphere, and 10^{-9} is a dimensional adjustment factor.

Annual mass of O_3 deposited on the leaves of one tree in $g(O_3)/y$ or annual mass of O_3 removed through stomatal and non-stomatal processes:

$$R_{O_3} = F_{O_3,\,t} \cdot A_L \cdot 47.997 \tag{3}$$

$F_{O_3,\,t}$ is the total potential O_3 removal in $[mol(O_3)\ m^{-2}\ y^{-1}]$. A_L is the leaf area in $[m^3]$, and 47.997 is the molar weight of O_3 in $[g\ mol^{-1}]$.

Finally, it is possible to calculate the **net ozone uptake** in $g(O_3)/y$ by a single tree over one year based on a formula from Manzini, Jacobon, et al. [9]:

$$Net\ O_3\ uptake = O_3\ removal - OFP \tag{4}$$

For the calculations, we use various data files containing the tree distribution in Geneva [6] and different parameters, such as *MIR* and *EF* (taken from [7]), a shading coefficent [12] and a species-specific conversion factor [13]. It is necessary to filter the trees in order to keep those for which we had corresponding parameters. Based on the coordinates of the remaining trees after filtration, we create a 100 x 100 m grid, each cell containing a certain number of trees. We iterate over each grid cell, apply all the formulas to each tree present in that cell and take the sum of *OFP*, PM_{10} deposition and O_3 removal and net uptake. Finally, we represent these final results on several plots.

3.2 Approximations

Due to the unavailability of certain measures concerning trunk height, crown height or crown diameter in the chosen data set, some parameters need to be manually adjusted. Due to time shortage, we use the average value of the data set for these values.
Moreover, data for the emission factor *EF*, shading coefficient and species-specific conversion factor are missing for some species in our trees data set. In order to still be able to work with as much data as possible, we discard only trees for which no value within the same genus could be found. Afterwards, we allocate the average value of the corresponding genus to every tree of that genus in our reduced data set.
For other approximations, such as the number of days the trees have leaves or the *MIR* values, we follow the approach used by Kofel, Donato, et al.

4 Results

In this section, we will analyze the results of our simulation for 120000 trees in the canton of Geneva. A map of Geneva is included in the annex for comparison. The annex also contains larger plots for 120000 trees, as well as plots for 60000 trees. We used a PM_{10} concentration of 15.2 $\mu g/m^3$ and a O_3 concentration of 48.09 $\mu g/m^3$, representing the yearly mean concentrations for 2023 in Geneva that can be found in [10]. After the filtering, there remained only 98107 trees.

Removal of PM_{10}:
The study of Kofel, Donato, et al. considers the deposition of PM_{10} on the leaves of each tree, which can approximately be considered as the removal of PM_{10} by that tree. Figure 1 depicts the total amount of PM_{10} removed by the trees in each 100 x 100 m grid cell.
Cream corresponds to a low value of PM_{10} removal, while dark blue represents a high value of PM_{10} removal. The highest value of PM_{10} removal that can be found in one grid cell is around 4.56 kg/y. However, the majority of the results lie between 0 and 2 kg/y. The total annual removal of PM_{10} for the entire canton of Geneva has a value of 2298 kg/y.

Ozone-forming potential (*OFP*):
The ozone-forming potential of trees corresponds to the capacity of trees to emit *BVOCs* that contribute to the formation of ground-level ozone. Indeed, O_3 formation can happen when some *BVOCs* interact with other pollutants in the presence of sunlight. The emission of *BVOCs* is part of the normal metabolic processes of trees. The *OFP* can approximately be seen as the capacity of the trees to emit O_3. In figure 2, one can see the total *OFP* of each grid cell.
Low *OFP* values are shown in cream and high *OFP* values are shown in dark blue. The maximum *OFP* of a grid cell, i.e. the maximum amount of ozone that could be produced, is around 832 kg/y. Most *OFP* values are between 0 and 200 kg/y. The total annual *OFP* of the canton is 71294 kg/y.

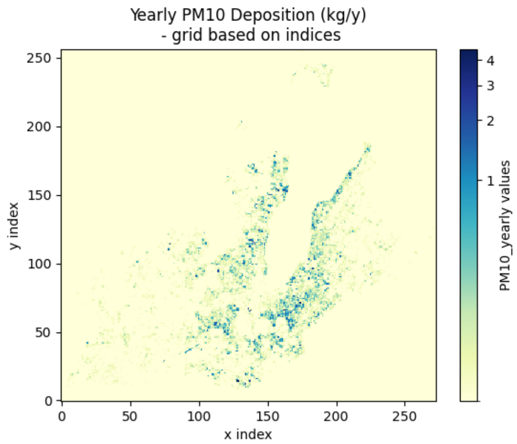

Figure 1: Removal of PM_{10} for 120000 trees

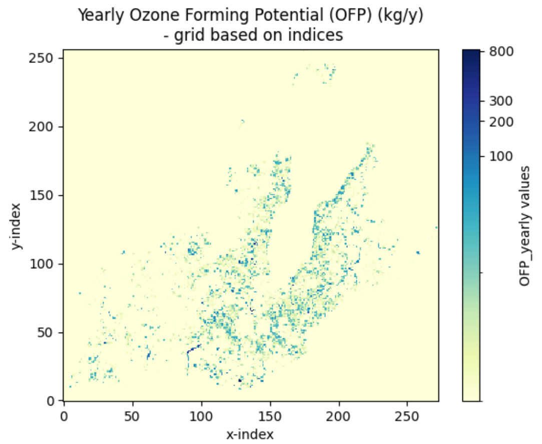

Figure 2: OFP for 120000 trees

Removed mass of O_3:
Trees have the capacity to absorb a certain amount of O_3 that enters the plant through its stomata. In figure 3, one can see that the maximum amount of O_3 that can be absorbed by the trees of one grid cell is around 8.18 kg/y. Most values range between 0 and 2 kg/y. Over the whole canton, 2952 kg/y of O_3 can be absorbed. These values are around 25 times smaller than for OFP. This means that the trees in Geneva have the potential to contribute to the formation of a higher quantity of ozone than the amount they absorb.

Net O_3 uptake:
The net O_3 uptake considers the real amount of ozone absorbed by the trees if one takes account of the fact that they contribute to O_3 formation. This means we take the difference between the mass of O_3 removed by the trees and the OFP. We can see on the graph in figure 4 that the results are negative, which leads to the conclusion that the trees can form more O_3 than they absorb.
In figure 4, less negative values are depicted in white and more negative values are in red. The most negative value found for a grid cell is -827 kg/y. Most of the net O_3 uptake lies between 0 and -100 kg/y. The total net ozone uptake is -68342 kg/y, which means that a total of 68342 kg/y of ozone could be emitted by the trees.

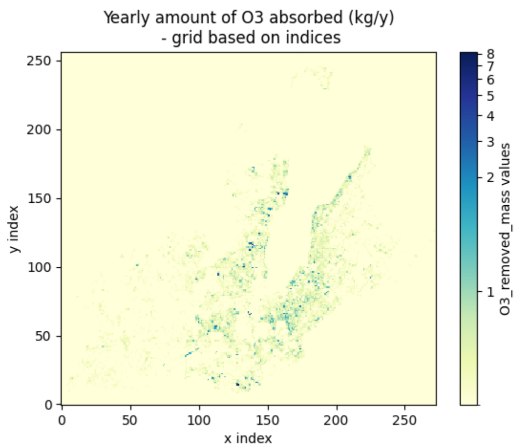

Figure 3: Removed mass of O_3 for 120000 trees

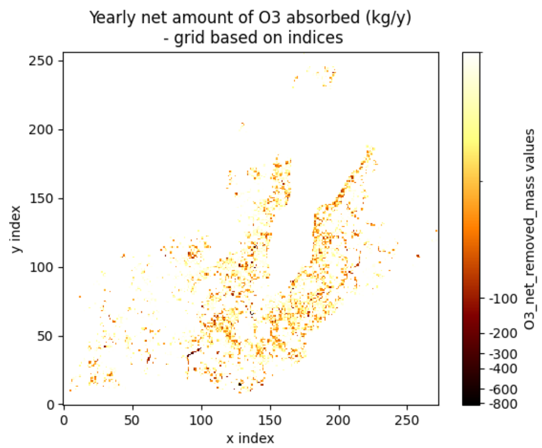

Figure 4: Net O_3 uptake for 120000 trees

Even though these results may seem surprising and counterintuitive, they are not senseless and approximately correspond to those found by Kofel, Donato, et al.. The higher ozone concentration and the lower PM_{10} concentration in 2023, compared to 2019, result in increased total deposition of O_3 and decreased deposition of PM_{10}. Nonetheless, our calculations show a continuation of the trend found by Kofel, Donato, et al. : Trees emit ozone and absorb PM_{10} but they don't necessary enhance air overall quality.

5 Reflection

Due to computation time, we limited the analysis to 120000 trees. Even though this impedes direct comparison with Kofel, Donato, et al., the results and spatial maps are of the same order of magnitude.. This means that the code seems to be well working. The ratio between OFP to O_3 removal should be more or less independent of the amount of trees taken into account. Kofel, Donato, et al. found OFP to be approximately 10 times higher than the O_3 removal, while we observed a ratio of 25. The reasons will be discussed in the following paragraph.

5.1 Reflection on Approximations

First, we will discuss how our approximations differ from those done by Kofel, Donato, et al., such as the calculation of the missing crown diameter. The model used will be discussed in the next subchapter.
Our approach of filling in missing measurements, such as crown heights and diameters, with averages from the tree dataset clearly influences our results, as it depends on the number of trees used for computation. Kofel, Donato, et al.'s method of using an average per genus has less impact on the results. However, even more nuanced possibilities, such as applying a two-dimensional random normal distribution of heights and diameters based on genus and environmental factors could be applied. Another option to improve would be the implementation of a latin hypercurbe sampling method to generate a near random sample of values. Lastly, using average values per genus for variables such as shading coefficient or EF can be misleading since there are differences from species to species [7]. A weighted mean or a median value could be more precise. Another issue is that we limited the data to optimize program runtime, as explained and discussed in more depth in the corresponding README.md file.

5.2 Reflection on Model used

It is also interesting to discuss the limitations of the model used. The values of emission and deposition are calculated under ideal conditions, an issue already discussed in Kofel, Donato, et al.. In the computation for this model, a static, well-dispersed concentration over the area was assumed, which is far from reality. Air pollutants are influenced by wind speed, aerosols and much more, while e.g. the OFP of a tree also depends on environmental factors, such as temperature or NO_X concentrations [5]. These factors were ignored for simplicity. Also, this model accounts only for the influence of a tree in its vicinity, ignoring e.g. the half-life of pollutants. Nevertheless, the model allows to perceive a trend in the role of trees in specific areas and can guide the strategic planting of well-suited tree species to enhance air quality. It helps monitoring how the OFP can develop within the city and which species would be well suited for improving air quality. For that, OFP of species used in urban areas should to be analyzed, e.g. as done in [2].

6 Conclusion and Outlook

6.1 Conclusion

Even though they depict a positive impact on PM_{10}, urban trees in Geneva have a negative impact on ozone concentration under the assumption that all of the predicted ozone by the OFP is actually produced.
Tree species with a high deposition potential for PM_{10} and O_3 are often planted in urban areas to enhance air quality. Unfortunately, those tree species also often depict a high OFP reducing their net uptake and potentially emitting more than they absorb [5]. Due to the relationship between OFP and environmental stress, such as higher temperatures, a decrease in OFP cannot be expected in the future. Therefore, tree species used in urban areas need to be chosen wisely and environmental stress should be considered when planning urban tree planting and wherever possible, reduced [3].
This project may therefore help planning urban tree distribution and choice of tree species to enhance air quality in the future.

6.2 Outlook

Enhancements regarding the implementation as code are mentioned in the README.md file. For missing measured values, approaches like a Latin hypercurbe or a two-dimensional normal distribution, considering species and environmental conditions, could be implemented. For missing scientific data, such as emission factors, we propose the usage of a weighted average to account for different species within the same genus. This project can directly be used for other cities in Switzerland, e.g. Zurich, that offer a register of their isolated trees. Only the function for reading in the data needs to be changed and eventually a coordinate transformation to LV95 should be implemented. Regarding the model used, it would be very interesting to couple it with a model estimating the distribution of ozone and PM_{10} within a city. A model proposed by Liu, Y. et al. [8] could be used. These proposed refinements could further advance urban planning in addressing air pollution through urban trees. But as already mentioned by Kofel, Donato, et al.. trees alone cannot be the solution to air pollution. The problem needs to be tackled at the source of emission.

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7 Annex

Figure 5: Map of Geneva [14]

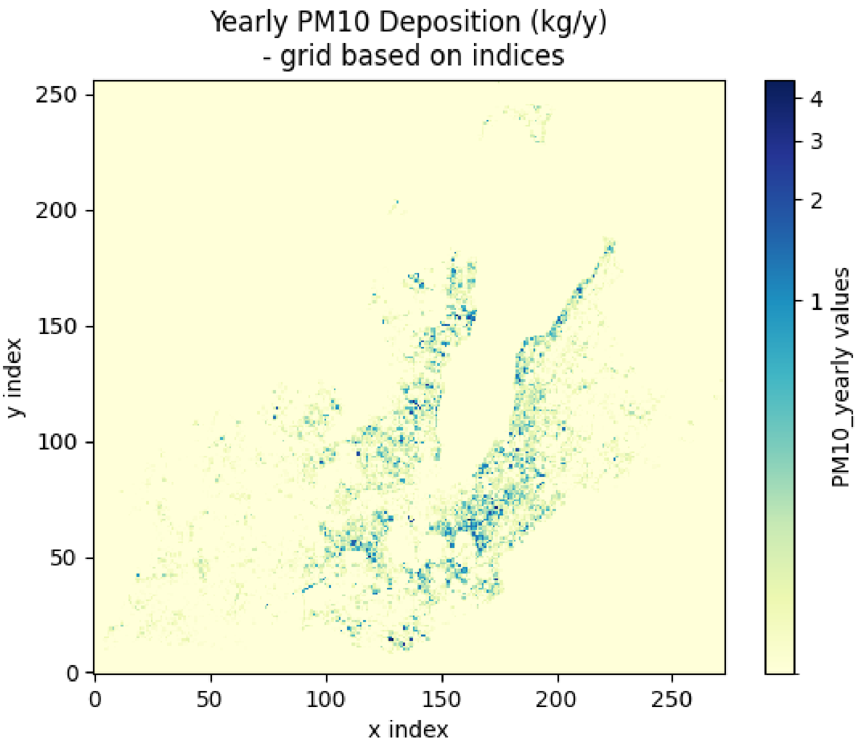

Figure 6: Removal of PM_{10} for 120000 trees

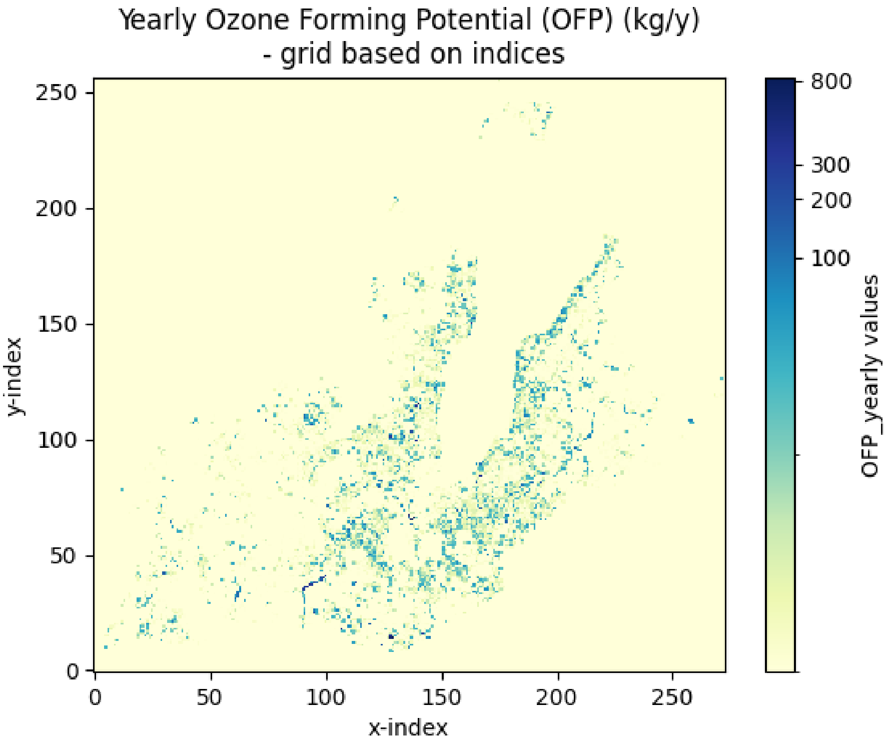

Figure 7: *OFP* for 120000 trees

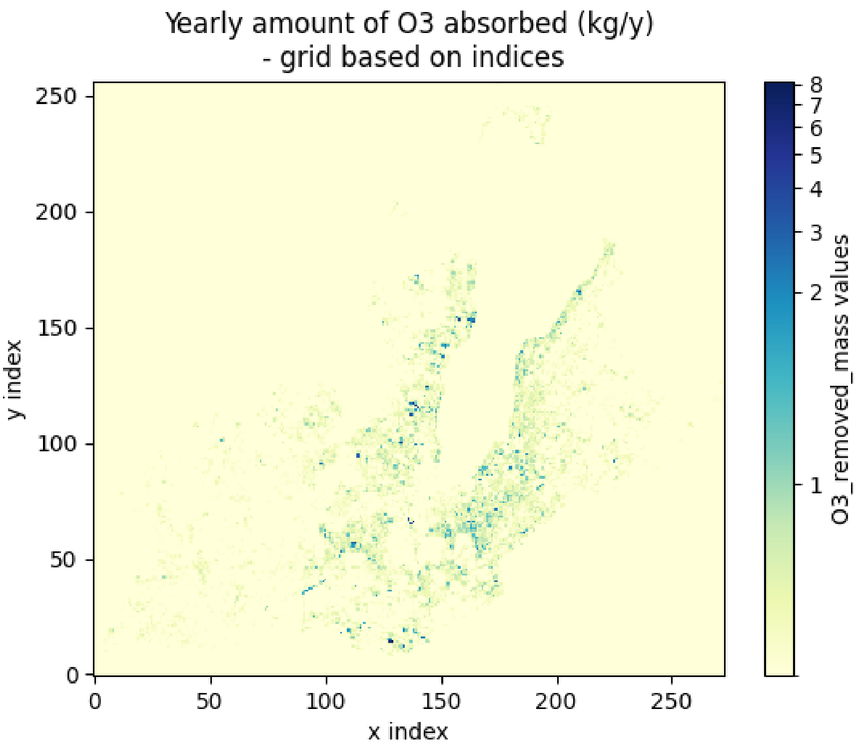

Figure 8: Removed mass of O_3 for 120000 trees

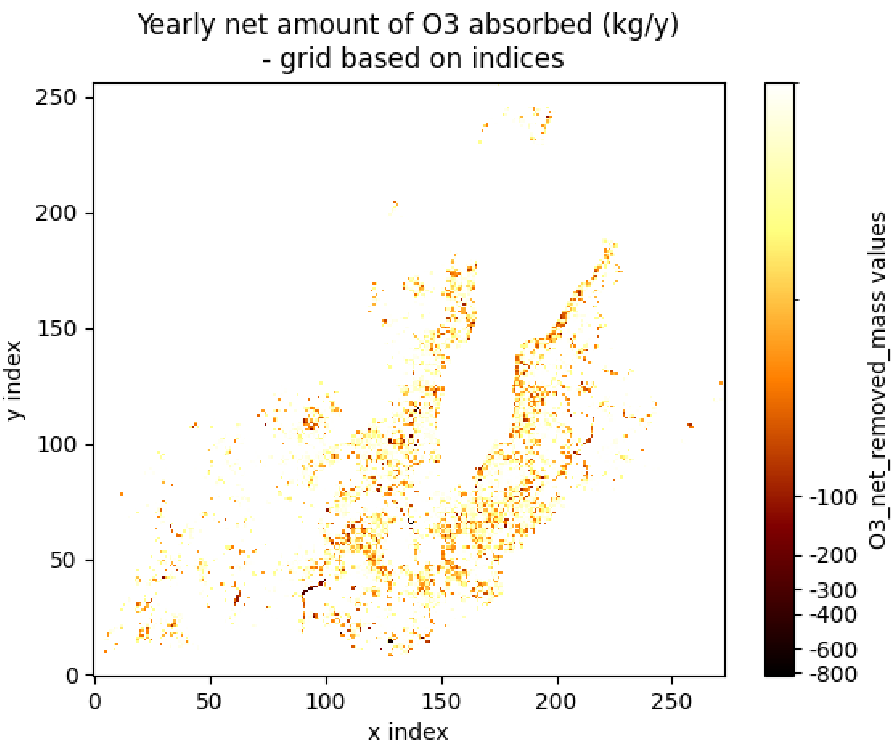

Figure 9: Net O_3 uptake for 120000 trees

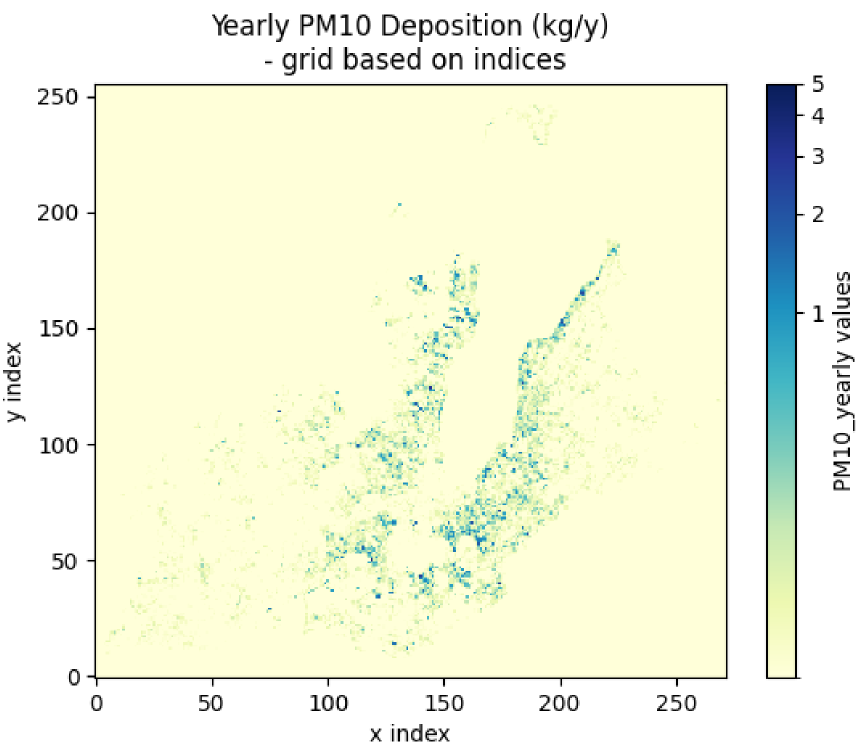

Figure 10: Removal of PM_{10} for 60000 trees

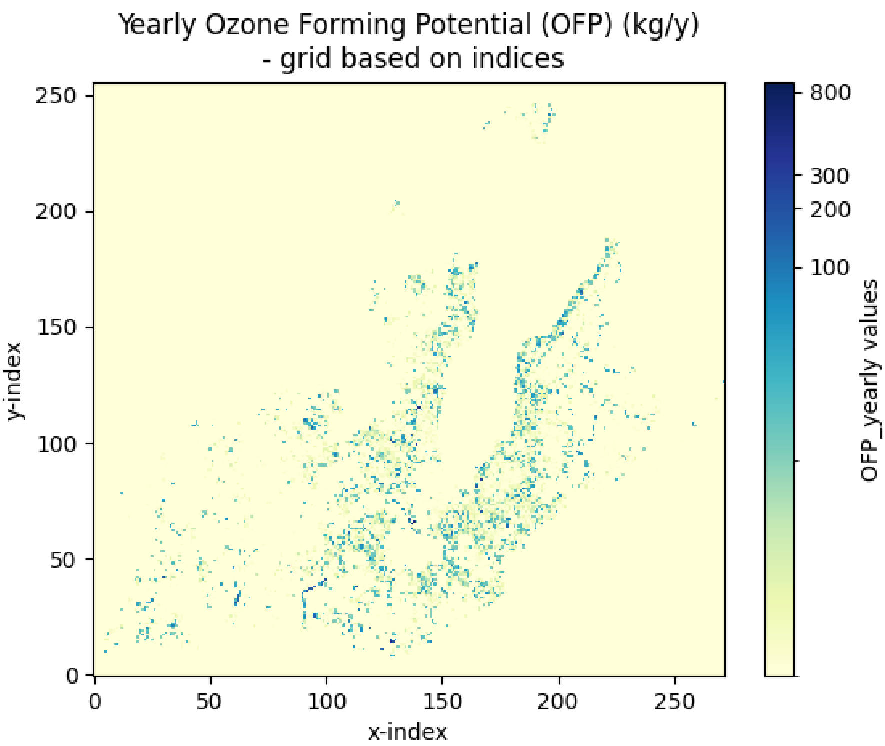

Figure 11: *OFP* for 60000 trees

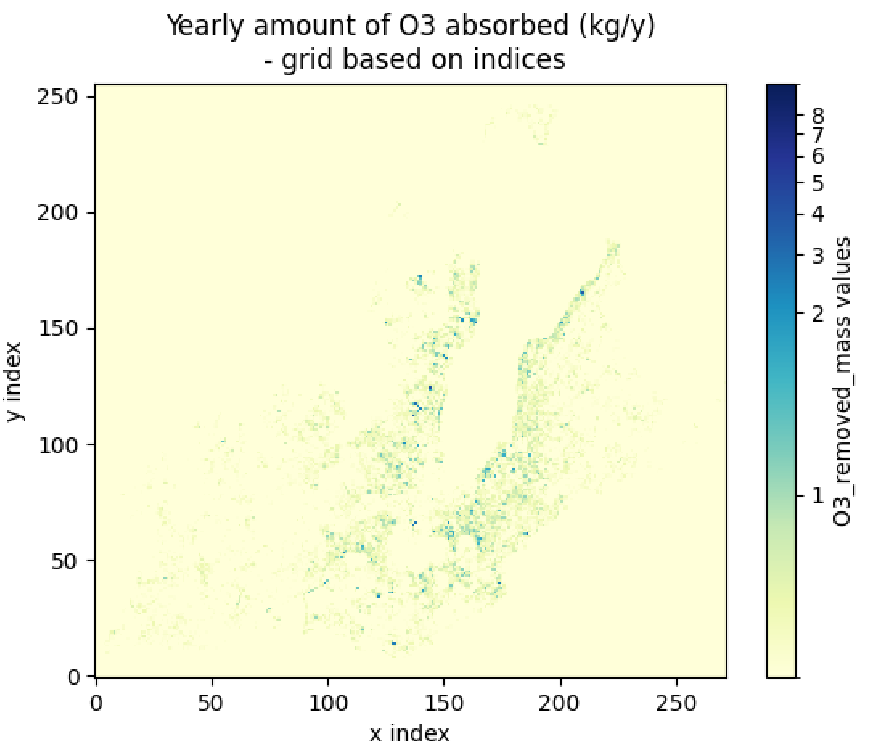

Figure 12: Removed mass of O_3 for 60000 trees

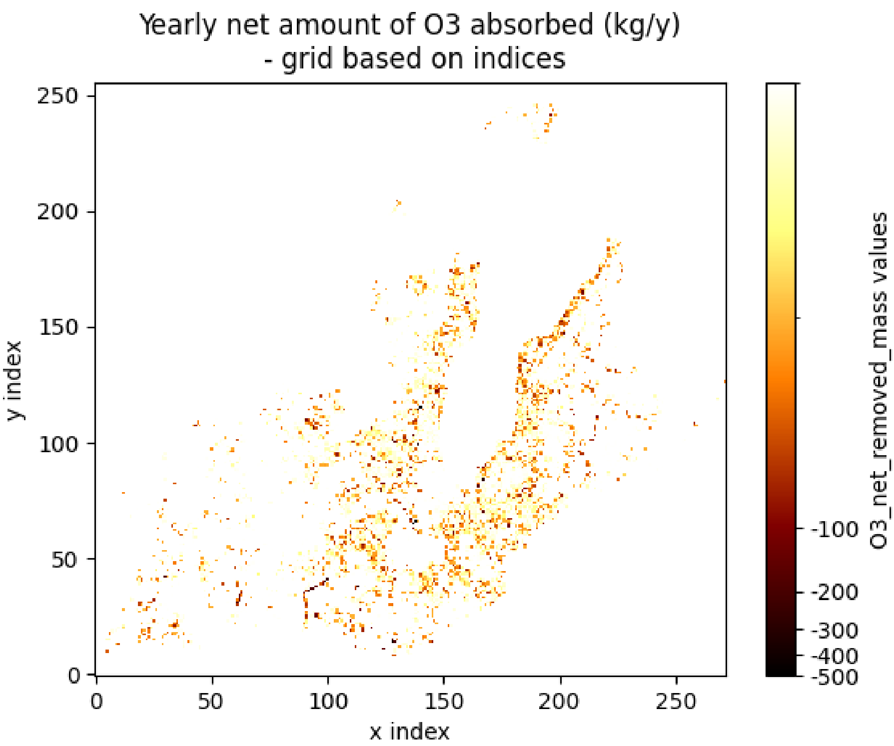

Figure 13: Net O_3 uptake for 60000 trees