Developing an agent-based model for canopy growth simulation and tree-related cooling effect estimation over the canton of Geneva.

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Résumé

En raison des changements climatiques mondiaux de ces dernières décennies, l'apparition d'îlots de chaleur en période caniculaire représente un danger commun à toute ville et métropole, en termes de qualité de vie, de bien-être et de productivité des résidents. Ce phénomène peut également être à l'origine d'une partie des décès prématurés parmi la population urbaine. La plantation d'arbres en milieu urbain permet d'atténuer ce phénomène, grâce à l'ombrage qu'ils apportent, mais aussi grâce au phénomène d'évapotranspiration. La contribution de ces arbres au maintien d'un climat urbain frais et agréable pendant des périodes de fortes chaleurs peut être estimée grâce au taux de canopée. Le canton de Genève souhaite obtenir une évaluation du taux de canopée actuel, ainsi qu'une estimation de l'évolution de ce taux en fonction du temps. Ce rapport présente un modèle permettant d'estimer le taux de canopée d'une région donnée, et de prédire comment ce taux évoluera dans le futur. Ces prédictions pourront être par la suite comparées avec les objectifs fixés par le canton d'ici 2050, afin de fournir une aide à la prise de décision. Le modèle se base sur les géodonnées des arbres présents actuellement sur le territoire, ainsi que sur une formule décrivant l'évolution de l'étendue de la canopée d'un arbre en fonction de son âge (O'Brien et al., 1995, p10), de son espèce et de ses conditions de plantation.

Pour ce projet, le choix s'est porté sur la modélisation basée-agents avec le programme GAMA. Une explication détaillée de cette méthode de modélisation, ainsi qu'une description technique du code source du modèle et des données utilisées sont disponibles dans ce rapport. Diverses simulations ont été conduites avec ce modèle, notamment pour visualiser l'évolution du taux de canopée de trois régions d'intérêt distinctes : la plaine de Plainpalais, le parc des Bastions et le parc des Rois. Les taux de canopée actuels et futurs de ces trois régions sont comparés. Le parc des Bastions possède le plus fort taux de canopée, oscillant entre 45% et 55%. La plaine de Plainpalais possède actuellement un faible taux de canopée, mais celui-ci est en nette tendance à la hausse, dépassant 15% en 2050 et 25% en 2100. La plaine est en effet peuplée à l'heure actuelle de très jeunes arbres, desquels l'on peut attendre une croissance continue dans les années à venir. Le parc des Rois se situe entre ces deux régions, avec un taux de canopée se stabilisant autour de 30%. En faisant varier divers paramètres et règles d'évolution, le modèle peut s'adapter aux besoins et désirs de l'utilisateur, donnant lieu à une exploration personnalisée du système étudié.

1. Introduction

In an urban setting, trees provide shelter from the sun rays in summer and help reduce the effect of heat islands. When the sun rays directly hit the ground, the temperature of that area increases. Moreover, if the ground is composed of dark-colored cement or any other non-permeable coating, the ground will absorb that radiation during the day at a high rate and release it during the night. Heat islands happen when these effects are particularly strong and not regulated. Areas plagued with heat islands will especially be subjected to dangerously high temperatures. Consequences include dips in quality of life for the residents of these areas.

Trees help reduce the local temperatures during the day, thanks to both the shade they provide, and the phenomenon of evapotranspiration. Evapotranspiration combines the evaporation of soil water, and the transpiration from the leaves. In these processes, water is transformed into vapor, which drains local heat and reduces local temperatures. As a result, city parks where large groups of trees with large canopies are planted, become an attractive spot for the population to cool down during tropical summer days.

The canton of Geneva wishes to estimate the current canopy rate, and predict how this quantity will change in the years to come. Canopy rate represents the ratio between the area of land covered by canopy, and the area of land not covered by the canopy.

Current evaluations for canopy growth in Geneva use a ballpark figure of 10 cm per year linear growth. The model that will be described and analyzed in this report, aims to improve this initial estimate. Tree growth is indeed influenced by many parameters, of which a few include the weather, but also the age of the tree, its species, its health condition, its planting conditions and its situation. One of the main goals of our model is to take into account as many of these parameters as possible for canopy growth modelling. On this basis, the model aims to predict the overall canopy extent in 30 years. Alongside canopy growth the model wishes to estimate the overall cooling effect through shade and evapotranspiration. It is then possible to compare these predictions to the goals set by the canton for canopy rate by 2050. Such comparisons can help shed light on whether these goals can be realistically met, or if suitable policies need to be passed.

2. Theoretical concepts

a) Canopy growth modelling

In our model, canopy growth's dependency on the age of the tree is represented by a third order polynomial, based on the work by O'Brien et al., 1995 (p10). Let t be the age of the tree. Its canopy diameter will be modelled using the following formula :

$$D(t) = A_D \cdot t^3 + B_D \cdot t^2 + C_D \cdot t \tag{1}$$

where A_D, B_D and C_D are constants with respect to time. However, these constants depend on a selection of properties specific to the tree they are associated with, namely, the maximum lifetime of the tree t_{max}, and the maximum canopy diameter of the tree, D_{max}, reached at t_{max}.

It is possible to calculate the value of the constants A_D, B_D and C_D in terms of t_{max}, D_{max} and an additional parameter r, thanks to a set of three different equations. The parameter r represents the ratio between the canopy diameter at half-life $t_{max}/2$ and the canopy diameter at maximum lifetime t_{max}. The first equation represents the idea that the tree reaches its maximum canopy diameter at its maximum lifetime, which translates to,

$$D(t_{max}) = D_{max}$$

Another equation can be deduced using the first derivative with respect to time,

$$\dot{D}(t_{max}) = 0$$

Finally, the tree reaches a given canopy diameter at half life,

$$D\left(\frac{t_{max}}{2}\right) = r \cdot D_{max}$$

This yields the following set of three equations,

$$\begin{aligned} A_D \cdot t_{max}^3 + B_D \cdot t_{max}^2 + C_D \cdot t_{max} &= D_{max} \\ 3 \cdot A_D \cdot t_{max}^2 + 2 \cdot B_D \cdot t_{max} + C_D &= 0 \\ \frac{A_D}{8} \cdot t_{max}^3 + \frac{B_D}{4} \cdot t_{max}^2 + \frac{C_D}{2} \cdot t_{max} &= r \cdot D_{max} \end{aligned}$$

Solving for A_D, B_D and C_D will let us express the canopy diameter of a given tree at any point in time, only using its values for maximum canopy diameter, maximum lifetime, and r, by substituting the following formulas into formula (1) :

$$A_D = \frac{8 \cdot r \cdot D_{max} - 6 \cdot D_{max}}{t_{max}^3} \tag{2}$$

$$B_D = \frac{-16 \cdot r \cdot D_{max} + 11 \cdot D_{max}}{t_{max}^2} \tag{3}$$

$$C_D = \frac{8 \cdot r \cdot D_{max} - 4 \cdot D_{max}}{t_{max}} \tag{4}$$

In a similar fashion, the equations for canopy height may follow the same third-order-polynomial dependency in the age of the tree. Let H_{max} be the maximum canopy height of the tree. Canopy height modelling will then be based on the following formulas :

$$H(t) = A_H \cdot t^3 + B_H \cdot t^2 + C_H \cdot t \tag{5}$$

$$A_H = \frac{8 \cdot r \cdot H_{max} - 6 \cdot H_{max}}{t_{max}^3} \tag{6}$$

$$B_H = \frac{-16 \cdot r \cdot H_{max} + 11 \cdot H_{max}}{t_{max}^2} \tag{7}$$

$$C_H = \frac{8 \cdot r \cdot H_{max} - 4 \cdot H_{max}}{t_{max}} \tag{8}$$

For both canopy height and canopy diameter, the actual dynamic values will be artificially lowered to take into account stress perceived by the trees due to their artificial setting. A concrete example of these stress factors would be the lack of space for extending the root system when planted next to a road or a sidewalk. In our modelling, this correction is represented by the growth stress multiplier, abbreviated to GSM :

$$D(t) = GSM \cdot (A_D \cdot t^3 + B_D \cdot t^2 + C_D \cdot t) \tag{9}$$

$$H(t) = GSM \cdot (A_H \cdot t^3 + B_H \cdot t^2 + C_H \cdot t) \tag{10}$$

The shape of the canopy is approximated to a half-ellipsoid of radius $D(t)/2$ and of height $H(t)$ (Thorne et al., 2002, p.2). Canopy area and volume are then given by the following formulas :

$$Area(t) = \pi \cdot \frac{D(t)^2}{4} \tag{11}$$

$$Volume(t) = \frac{2}{3} \cdot Area(t) \cdot H(t) \tag{12}$$

Canopy rate is directly deduced by dividing the total canopy area of the trees enclosed in the region of interest, by the total land area of that region.

For visualization purposes, the following graphs lets one appreciate the dependency of canopy diameter on the age of the tree, for different values of r, maximum canopy diameter, and maximum lifetime.

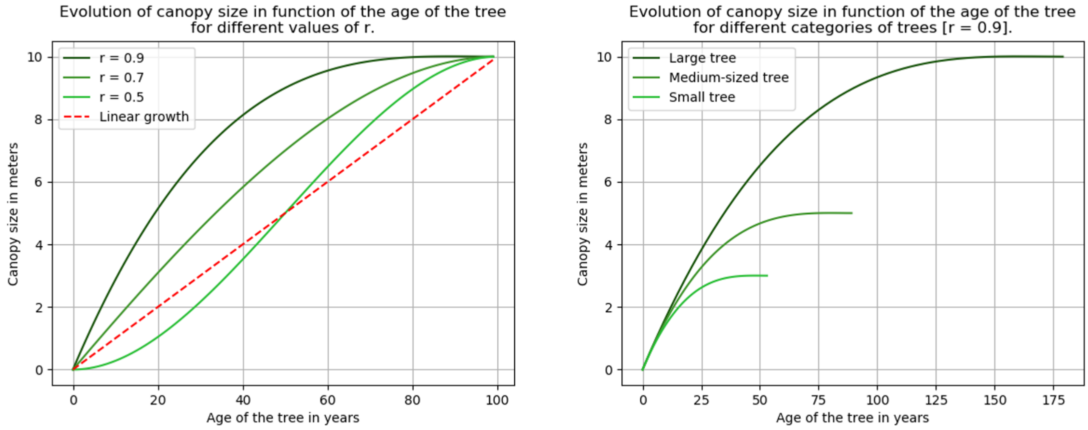

Figure 1: Graphs of the evolution of canopy size in function of time for different values of r (left) and different categories of trees (right).

b) Temperature modelling

Each tree will reduce the local temperatures by a stackable amount, initially equal to 2.5°C, and which can be modified by the user, but may not cause the temperature to drop by a predetermined maximum amount, generally accepted as equal to 7°C. These numbers have been determined based on the works of Rahman et al., 2017, p.11, and the OFEV, 2018, p. 48.

c) Modelling method

For this project, the chosen method is agent-based modelling. Each tree will be represented by a geolocalized agent which is an individual entity with its own memory, perceptions, and behavior. It may also interact with other agents and its environment. Each agent is supplemented with geodata from the SITG, which will be described in chapter 3. With simple rules of evolution at the agent level, one can witness complex behaviors arise at the global scale, which are not only the sum of its parts' individual behaviors. This approach also comes with its fair share of constraints, including but not limited to : the need for large amounts of reliable data, and the need for a deep understanding of the system it wishes to model.

Additionally, each agent of *species* tree (i.e. representing a real-life tree), will be planted on top of a matrix of cells which will record the temperature at that area. This matrix will help compute the overall cooling effect, as well as observe the local decreases in temperatures due to the trees.

GAMA (Taillandier et al., 2019 ; *GAMA platform*, 2021) is a powerful and versatile program enabling the creation of complex agent-based models. GAML, the language used to build such models, is an "agent-oriented language" (*GAML introduction*, 2021) which has similarities with other languages like Java and NetLogo. GAMA enables the creation of species of agents, and introduces a notion of inheritance. Both the world and its simulations, also called experiments, are agents. Each experiment may be defined independently by handpicking any amount of entities from the world itself, which can allow for a deep exploration of the many possibilities a single model has to offer.

In a typical GAMA model, the first steps are dedicated to declaring all relevant variables and actions, then setting up the initial state of the model. Each action can be declared as either a reactive entity (i.e. the actions are performed only when they are specifically called, either by the user or by an entity from the model itself), or a reflex, which executes automatically at each time step, provided the specified conditions are met. After the initialization, the model advances one time step at a time. These time steps are also called "cycles" (or "ticks" in NetLogo) and each cycle corresponds to the execution of all relevant actions and reflexes. As a result, the model proposes a detailed history of the states of the world and its agents at every time step, which can be analyzed on the fly, using the computed values for some key parameters which allow the user to keep an eye on the current state of the world; or saved to a separate file, which the user can then open and study later using data analysis methods.

Following the world initialization, species are then created and defined using the same scheme - declaration of variables, actions and reflexes. It is possible to create sub-species and define the inheritance of some or all of the relevant attributes from the parent species to the children species. Each species may possess a set of predefined skills, for instance the ability to roam about the world. This movement can be random, or tailored to the user's needs. This is particularly useful when modelling mobile entities, such as motorized vehicles in an urban road system.

Grid species may also be defined. A grid of identically-sized cells will then pave the world, and each cell is aware of its neighborhood, as well as the agents that are directly on top of it. Each cell may store some variables, and, similarly to all other types of agents, may instruct any other agent to perform specific actions.

Finally, experiment agents define the output of the model. They may take any set of agents from the model, with their specified variables and actions, and inscribe them into a given context. From there, many useful tools for the visualization of the data on model evolution are available : graphic representations of the world, charts of the values of some key parameters, monitors, to name a few. Experiments are also where the user may directly interact with the model, and in the code for the experiment agent, one can define how the user may interact with the model and what actions they may perform to change the state of the model at any given time. While NetLogo lets the programmer do this work directly on the user interface of the model, GAMA blends this part of model building directly into the source code for the model.

Further documentation on the GAMA program for agent-based model building is available on the GAMA website. A step-by-step learning program can be read on at this address (*Learn GAML step-by-step*, 2021), and the full documentation is available for download at this address (*GAMA downloads*, 2021).

A detailed description of the source code for our model for tree canopy growth will follow in chapter 3.iii.

3. Data and methods

a) Data description

Data is sourced from the *Inventaire Cantonal des Arbres* (ICA) available at the SITG. This inventory strives to record all existing isolated trees on the canton of Geneva. For each tree, a large amount of properties are recorded as attributes in the attribute table. Among these, a select few will be used in our model. The full metadata for the shapefile are available in the appendix.

1. The field "NOM_COMPLET" contains the name of the species of the tree. This field will be used to assign a category (small, medium or large) to each tree. This category will influence the value of the tree's key parameters for canopy growth modelling.

2. The fields "HAUTEUR_TRONC" and "HAUTEUR_TOTALE" will be used to calculate the height of the canopy, as recorded in the shapefile.

3. The field "DIAMETRE_COURONNE" contains the diameter of the canopy, as recorded in the shapefile.

4. The field "DATE_PLANTATION" contains the plantation date of the tree.

5. Finally, the field "DATE_OBSERVATION" contains the observation date of the tree. By combined this field with the previous field, the time the tree has spent in the soil can be deduced. Its age is given by adding this quantity to its age at plantation date.

We will discuss how this data will be arranged in the following section.

b) Methods

i. Data treatment and formatting

First, each species of tree is slotted into one of the three categories : small, medium or large. Using a python script (*appendCategoriesToAttributeTable.py*) with the *arcpy* module, the attribute table of the ICA shapefile is accessed and a new attribute named "Category" is created. Each tree is given a category based on its species.

One of the chosen regions of interest is the Plaine de Plainpalais. Its extent is defined and corresponds to an area of 112'514 m^2. The modified ICA layer is clipped to match the predefined extent. This work also has to be done for each additional region one wishes to model. This will be illustrated by performing a simulation run on the Parc des Rois and the Parc des Bastions, in additional to our main region of interest, the Plaine de Plainpalais.

For calibration, a CSV file is generated from the clipped layer by selecting the category, trunk height, total height, crown diameter, plantation date and observation date fields for each tree. This is done automatically thanks to another python script with the *arcpy* module (*selectCalibrationTrees.py*).

ii. Calibration

The goal of the calibration is to define the initial value of a given number of key parameters, that are mandatory for canopy growth modelling. These key parameters are :

- The maximum canopy diameter of the tree, D_{max}
- The maximum canopy height of the tree, H_{max}.
- The maximum lifetime of the tree, t_{max}.
- The ratio between the canopy size at half life, and the maximum canopy size, r.
- The age at plantation date, APD.
- The growth stress multiplier, GSM.

There exists one set of these parameters for each category of trees. Each one of these parameters is different from one set to the other.

The python script *CalibrateModel.py* uses the calibration data from the output of the *selectCalibrationTrees.py* script. For each category, the value for each of the six key parameters is allowed to vary within a given range, depending on the category of the tree. For instance, for Large Trees, the value for the maximum canopy diameter of the tree may boast a wider range than for Small Trees.

All combinations of the values for these parameters are then tested. The canopy diameter and height are computed using equations (9) and (10) for each combination of parameters, and then compared with the actual recorded values in the ICA. A ranking of each combination is established by comparing the percentage error of the computed values with respect to the recorded values. The top 20 combinations are sent to a CSV file, which can then act as a useful tool for the user to determine the optimal values for these key parameters.

Once calibration runs have been concluded, it is mandatory to edit the file *allCalibrationParameters.csv* located in the *includes* folder of the GAMA model to incorporate the values of the key parameters obtained through calibration.

iii. Detailed description of the GAMA code

The GAMA source code starts by initializing all the required variables at the global level. Total canopy area is given by the sum of the areas of each tree's individual canopy. Each tree's canopy area is given by applying formula (11). Canopy rate is then calculated by dividing this quantity by the total area of the chosen region of interest.

The path of the root folder containing all the necessary files for the model is specified. Changing the root path from one folder to another lets one perform the modelling on different regions of interest.

All relevant files are imported into the model : the shapefile containing all the data for the trees, the basemap, and other files used when calibrating the model. The key parameters obtained from the calibration step are also imported.

The envelope of the world is defined to match the shape of our region of interest.

The model then enters the step of initialization at the global level. Trees of the generic species are created from the shapefile, and they inherit some of the attributes contained in the shapefile, namely the plantation date, their category (small, medium or large), their recorded canopy diameter and height (deduced by their recorded tree height and trunk height). Based on their plantation date, the trees are asked to evaluate their age. If their plantation date exists and is posterior to 1980, they are signaled as capable of being modelled, otherwise, they are not.

These generic trees are then tasked to create a species-specific tree based on their category. These new trees inherit all of the attributes of their generic parent. If no category is detected, a medium tree is created. The generic trees are not needed anymore after this step, so they disappear.

The final step of the initialization will ask all trees marked for modelling to compute their age, as well as their canopy diameter, in order to provide an accurate initial state representation to the user. All trees that are not marked for modelling will instead set the canopy diameter and height to the values recorded in the shapefile, while computing their canopy area and volume at the same time. If this data is missing, then the tree will select all the other trees within a circle of 50m radius and set its canopy height and diameter to the mean value of these quantities among all selected trees. If it can't find neighboring trees, then the tree will set its canopy diameter and height to an arbitrarily low value (respectively 2m and 3m).

Actions at the global level are then defined, namely those responsible for highlighting the last location the user clicked on the map, the buttons the user may press to plant trees manually, the button used to update the key parameters the model works with, if they have been changed by the user.

Automatic behaviors called *reflexes* are also defined here. Reflexes are actions that will be executed at every time step automatically. Reflexes at the global level include the random spawn of new trees based on a given probability, as well as updating the temperature of each cell. Each cell is first asked to reset its temperature to its exposed value, then, each tree in a given vicinity of the cell (150% of the tree's canopy diameter) will decrease the temperature of that cell, based on the value of the temperature decrease per tree, the impacted cell's distance to the trunk of the tree, and σ, the strength of the latter's effect on temperature decrease. However, it cannot influence the temperature to drop below 7.0 degrees under the exposed temperature.

The final reflex will save a pair of variables at every time step to a CSV file. These variables are the current year being modelled, and the computed overall canopy rate. These saved data can be later analyzed and plotted using data analysis tools.

After fully initializing the global species with its variables, actions and behaviors, the model transitions to the initialization of the generic species *Trees*, by first declaring all relevant variables. These variables will be specific to the species *Trees*, and can only be accessed in a *Trees*-agent context.

The first reflex of this species is the most important one : it calls the action *computeAllModelledValues* at every cycle, but only for the trees marked for modelling.

The action *computeAllModelledValues* represents the heart of the model. First, if the user wants the trees to die, then their age is incremented at every time step and their age may exceed their max lifetime, causing them to die during the second reflex of species *Trees*. If the user does not want the trees to die, their age is incremented only if their age is strictly inferior to their maximum lifetime. As a result, they will never exceed their max lifetime, they will never die, and their canopy will not evolve anymore. During the second part of this action, all equations from (1) to (12) of chapter 2. are used to calculate the canopy height, diameter, area and volume for each modelled tree.

The second reflex of this species simply cuts down the tree when it exceeds its maximum lifetime, or, if enabled, when it reaches the age of premature death defined by the user. The original tree spawns a medium or large 10-year-old tree at the same location, which inherits the growth stress multiplier. It is also marked for modelling.

Finally, the aspect of the tree is defined : the trees will be represented by a small dot of radius 10cm for their trunk, and another, larger circle, of which color will depend on the category of the tree, and diameter will correspond to the canopy diameter of the tree.

Following the generic species *Trees* definition, three subspecies are declared, one for each category. These subspecies are children of the *Trees* generic species, and inherit all parameters, actions, reflexes and aspects as a result. For each subspecies, an action is defined in order to automatically store all relevant category-specific parameters more easily. These parameters include : maximum canopy height and diameter, maximum lifetime, the ratio r, the age at plantation date, the growth stress multiplier, and the canopy color. All of these parameters are different for each category of tree.

The last species to be declared is a grid of cells that occupies the whole virtual world. Each cell has its own temperature variable, and color value. The color of the cells will depend on their temperature : from red (high temperature) to green (low temperature). This species does not have any action of its own, it is instead called by other species that will then change the value of the cells themselves.

The main logic behind the model is now fully defined. However, it is mandatory to declare the outputs and inputs of the model, as well as define the user's interaction with the model. First, key parameters such as maximum canopy diameter and height, maximum lifetime, the r ratio, the age at plantation date, the growth stress multiplier, for each category of trees, some parameters relative to temperature, tree spawn rate, and other parameters, are declared as dynamic parameters, which means they can be modified anytime by the user. They are initialized using the values obtained through calibration.

All the buttons are also initialized and assigned to their corresponding action defined in the global context. They may be pressed anytime by the user when they wish to execute the corresponding action.

Then, the output is defined. This output is composed of a view of the region of interest with the modelled trees, a view of the temperature map, and some useful charts and monitors. On the first view, all species are loaded onto the map, and their evolution can be visualized in real time. On the second view, only the temperature grid is loaded onto the map, so that the temperature can be represented clearly using the color code defined for this grid species. Finally, the third view records the values of canopy rate and average temperature for each time step and plots these values with respect to time.

In parallel to these representations, some useful monitors are available to the user at any point in time. These monitors depict the evolution of some key variables, such as total canopy area, canopy rate, average temperature, and the amount of trees of each category.

iv. Validation

We use LIDAR datasets for canopy extent in 2017 and 2019 and calculate canopy rate on these datasets. These values will help us determine if our model is close enough to reality or if adjustments need to be made.

Currently, attempts at validation were not successful, because the datasets for calibration (ICA from the SITG) and the data for validation (LIDAR) were largely contradicting each other, in terms of canopy extent. Further attempts at validation will have to first address these problems and make sure the data used for both processes are trustworthy.

Upon further investigation of the ICA dataset, the following problem was found : the data for canopy extent may not have been updated at each subsequent observation date. For instance, a tree with a registered 3m canopy diameter in 2010, may have had part of its attributes reassessed in 2020, but its canopy diameter may have been excluded from this reassessment. The tree will then have its observation date updated to 2020, while still keeping a 3m canopy diameter from 2010.

This is a possible explanation for the discrepancy between the two datasets, however we do not know exactly why it exists. The LIDAR datasets only represent data from a single year, so it has a higher chance of being more reliable than the ICA dataset. As a result, further attempts at validation should first blend the ICA and LIDAR datasets for calibration, and then take advantage of another dataset for validation. This dataset can be obtained by performing a new program of canopy diameter measurements from the ground, for instance.

v. Output formatting

Some data from the GAMA simulations are automatically saved to a CSV file for later use. These saved data include the value of canopy rate for the region of interest for every cycle of the simulations. Since each cycle represents one year, it is then possible to use a python script (*drawOutputCharts.py*) to plot the evolution of canopy rate through time.

4. Results and discussion

a) Plaine de Plainpalais

i. Simulation 1

On the Plaine de Plainpalais, the first simulation was run with the following parameters (see Table 1) for maximum canopy diameter and height, maximum lifetime, r ratio, age at plantation date (APD) and growth stress multiplier (GSM). The values of these parameters for Medium and Large Trees were determined with the help of a preliminary calibration run using only the trees from the ICA layer that had a complete dataset.

Category	**Max canopy diameter**	**Max canopy height**	**Max lifetime**	r	**APD**	**GSM**
Small	5 m	5 m	50 yrs	0.8	11 yrs	0.75
Medium	15 m	10 m	120 yrs	0.84	10 yrs	0.75
Large	18 m	13 m	150 yrs	0.8	12 yrs	0.75

Table 1: Detailed values for all key parameters used for Simulation 1. APD stands for Age at Plantation Date, GSM stands for Growth Stress Multiplier. r is the ratio between the canopy size of the tree at half life, and the maximum canopy size.

No additional trees were planted, and the trees were not allowed to age past their maximum lifetime and die. When they would reach their maximum lifetime, they would be frozen in time and their canopy would not grow anymore.

Based on these assumptions, the following results for canopy rate over the canton of Geneva were produced. In 2021, the canopy rate was estimated to 7.36%. It would reach 15.62% in 2050 and 26.80% in 2100. Figures 2, 3 and 6 display the evolution of the main view of the model, the heatmap and the charts at these three different points in time.

The simulated values of canopy rate for 2017 and 2019 were also compared with the values of canopy rate from the LIDAR datasets for these two specific years. Table 2 presents the results of these comparisons.

	2017	**2019**
Simulation	6.08%	6.49%
LIDAR dataset	9.3%	9.0%
From LIDAR To Simulation	-34.6%	-27.9%
From Simulation To LIDAR	+53.0%	+38.7%

Table 2: Canopy rates obtained from the simulation and the LIDAR datasets for 2017 and 2019. The last two rows contain information about the relative differences between the simulated results and the LIDAR datasets.

Since our model was calibrated with data in contradiction with the LIDAR datasets, it is important to remember that our model might produce results with a large error margin. In particular, all simulations may under-estimate the true potential canopy rate of the area by an unknown amount, roughly 40 to 50%.

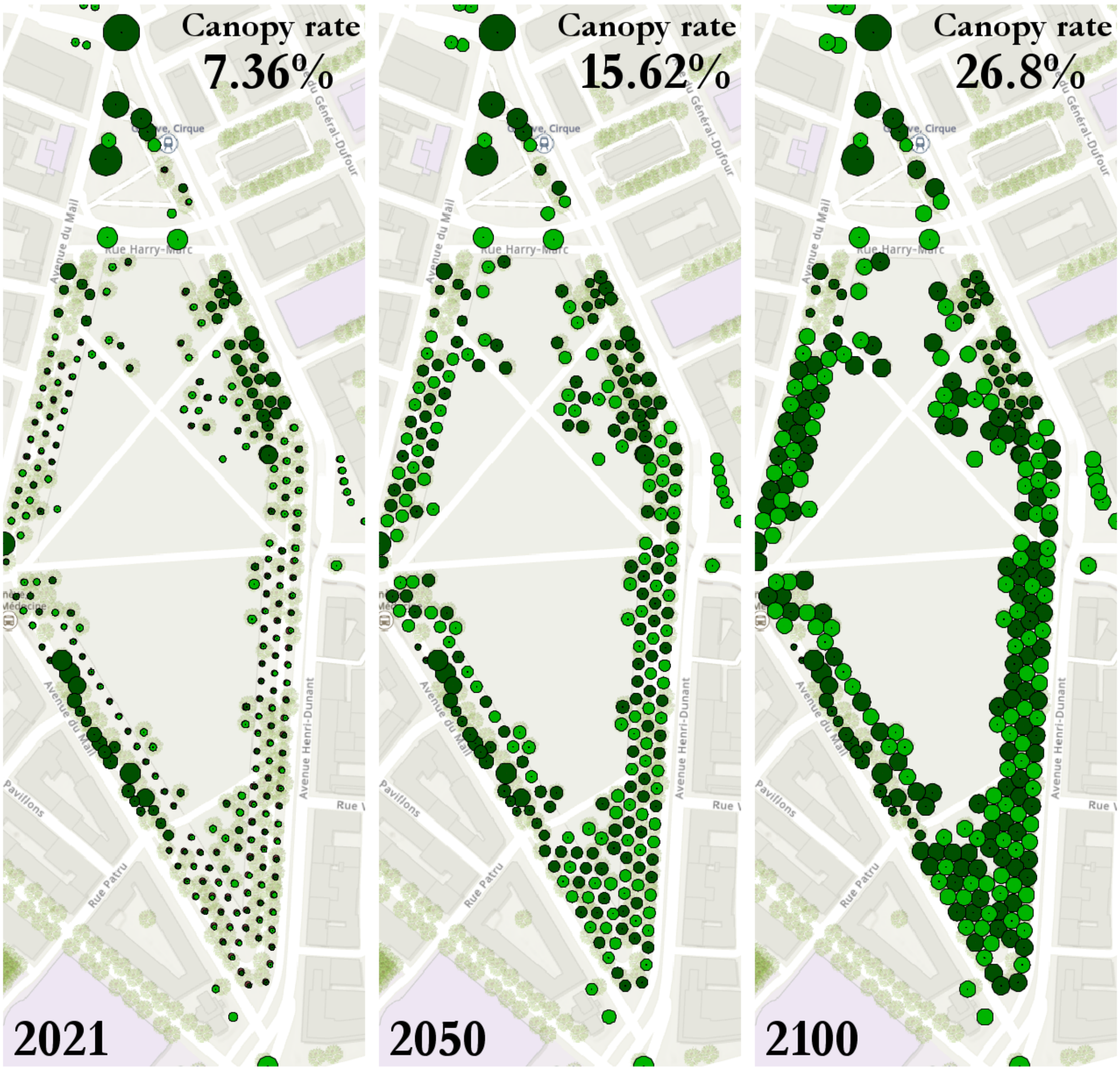

Figure 2: Evolution of the simulated canopy extent over the plaine de Plainpalais from 2021 (left) to 2100 (right), under the assumptions of Simulation 1.

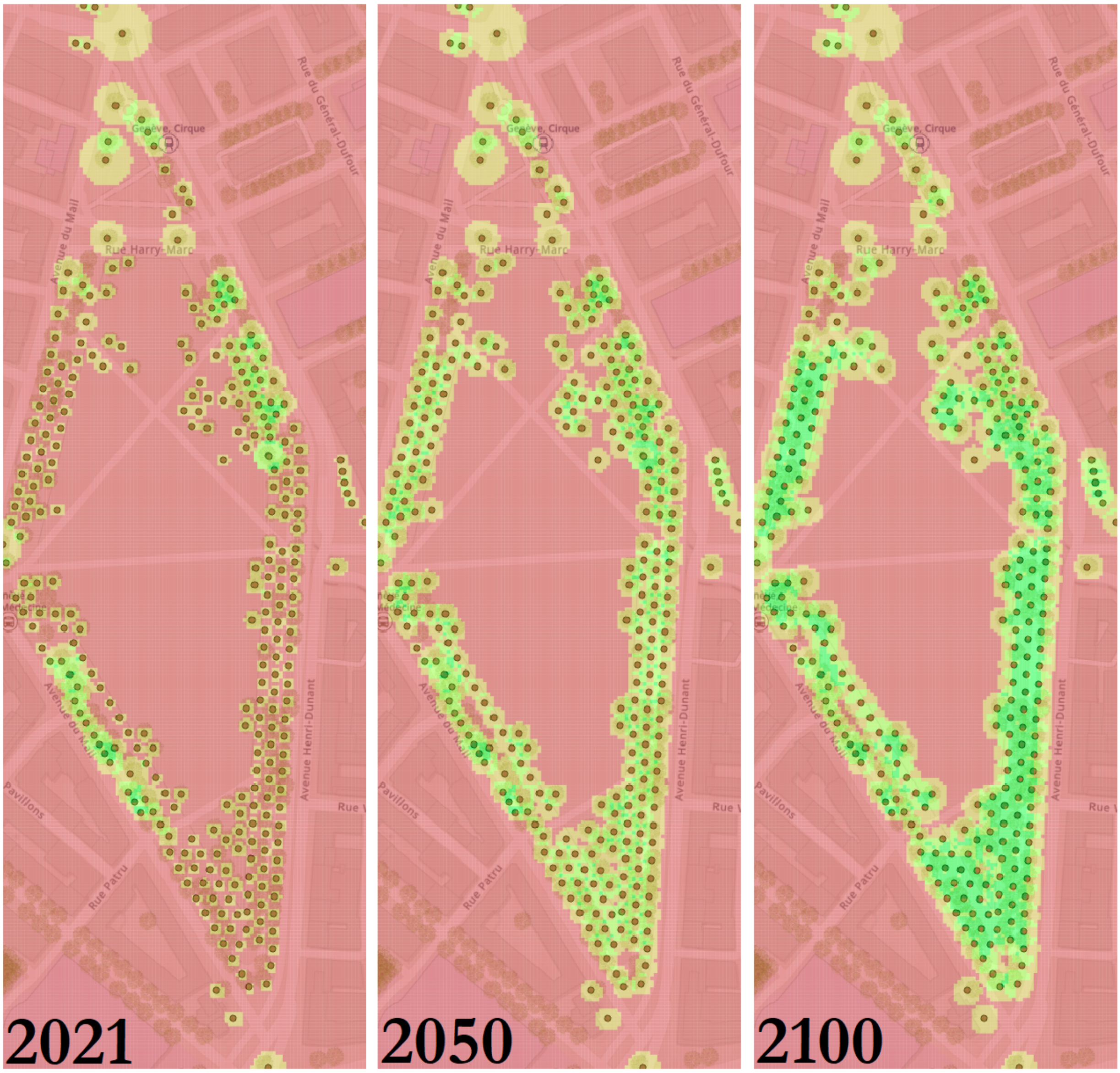

Figure 3: Map of the simulated temperature decrease over the plaine de Plainpalais from 2021 (left) to 2100 (right), under the assumptions of Simulation 1.

ii. Simulation 2

The second simulation modifies the lifetimes of the trees by a large amount. All of the other parameters are the same as Simulation 1, however, the trees are abruptly cut down when they reach 50 years of age. This simulation aims to explore what would happen if the planted trees suddenly had a much shorter lifespan than predicted due to diseases, bad planting conditions or other stressful external conditions, while retaining their maximum lifetime, that would correspond to growth in perfect conditions. Please refer to Table 1 for maximum canopy diameter and height, maximum lifetime, r ratio, age at plantation date (APD) and growth stress multiplier (GSM).

This time the trees were allowed to age past their predefined lifespan (here, 50 years) and die. However, they keep the same maximum lifetime in perfect conditions as during Simulation 1. When they would reach their predefined lifespan, they would be cut down and replaced by a young 10-year old tree. Naturally this would be accompanied with a sharp decrease of the local canopy extent, which is what we intend to see during the simulation.

Figures 4, 5 and 6 display the evolution of the main view of the model, the heatmap and the charts at these three different points in time.

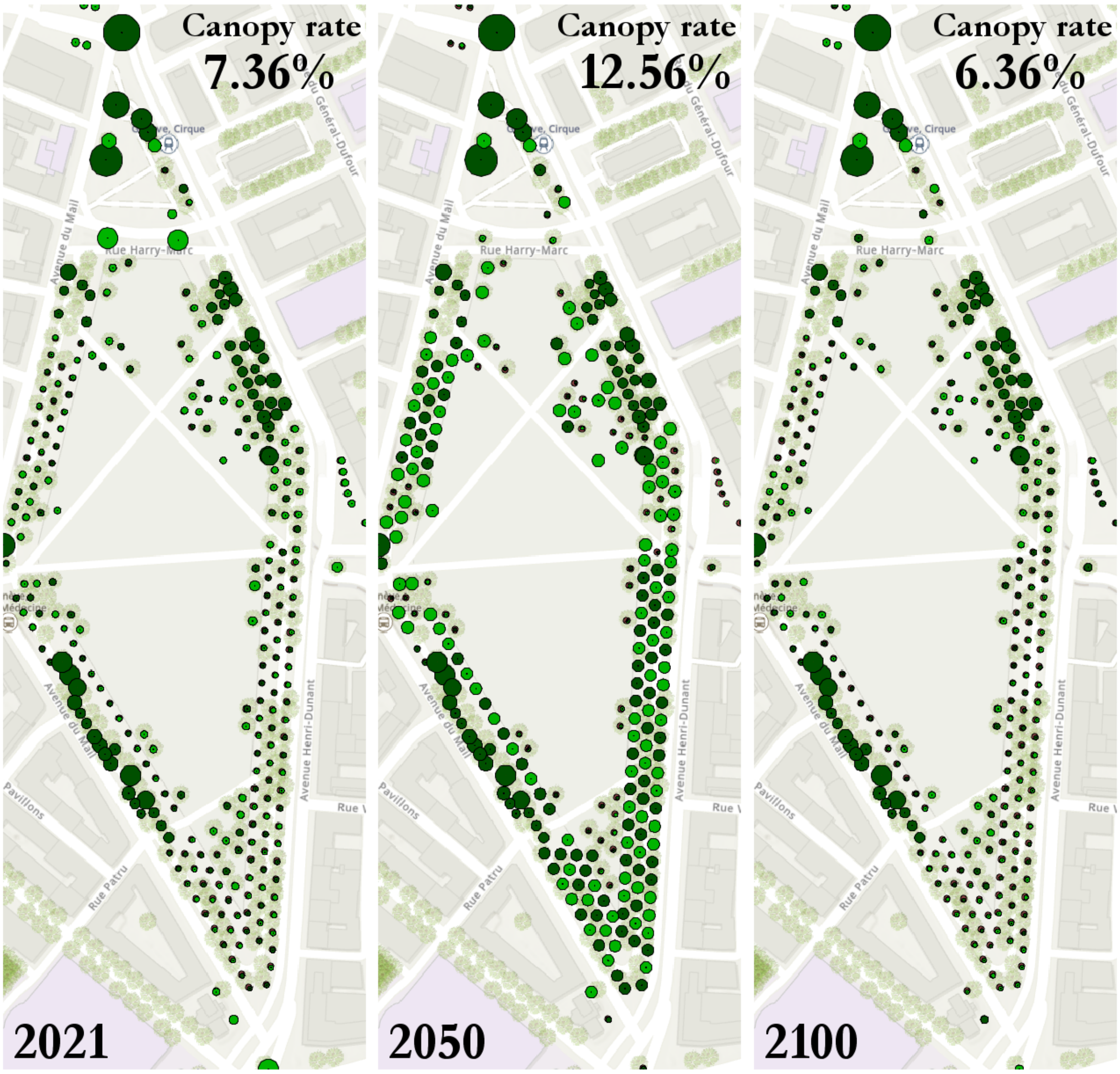

Figure 4: Evolution of the simulated canopy extent over the plaine de Plainpalais from 2021 (left) to 2100 (right), under the assumptions of Simulation 2.

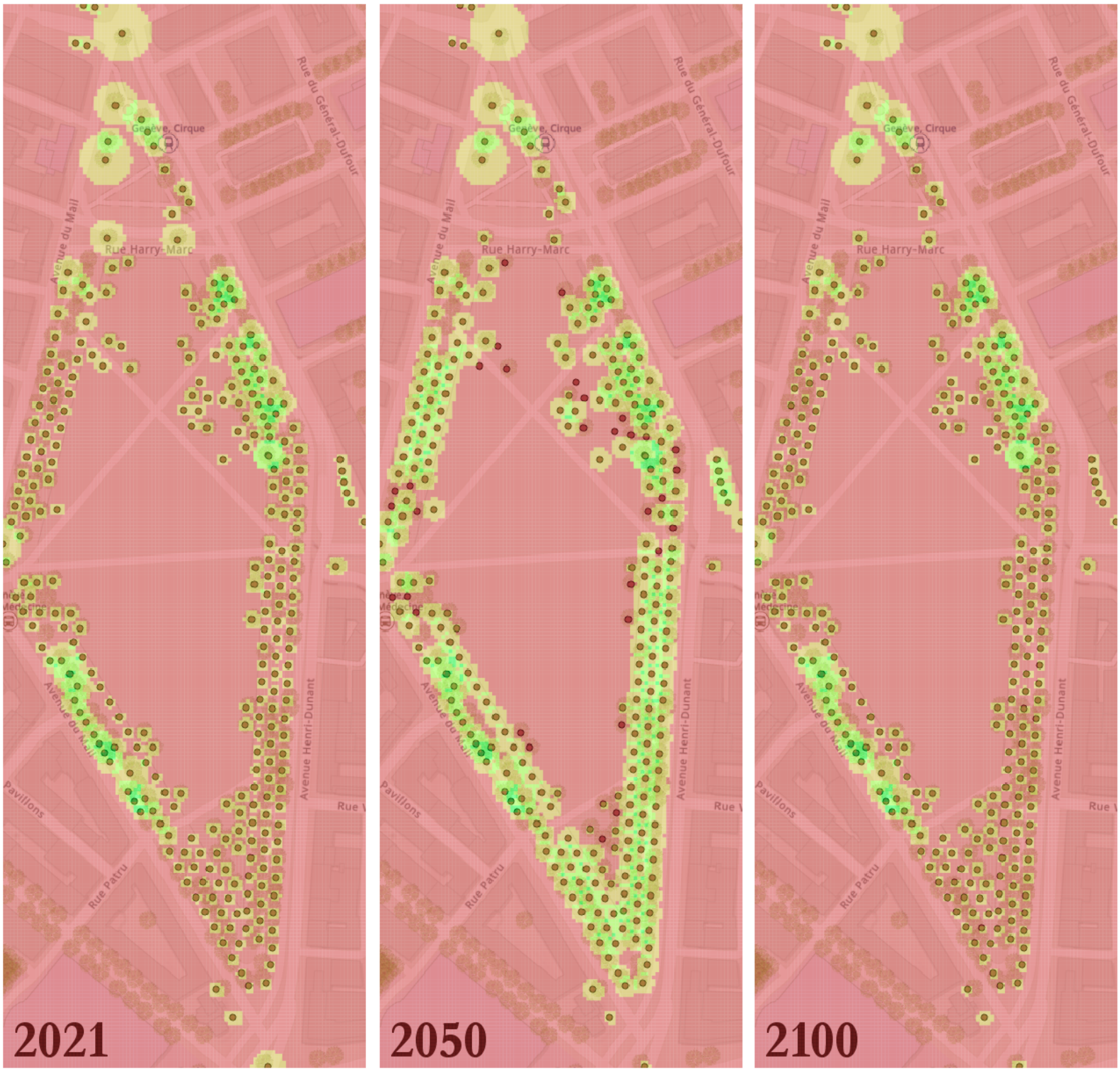

Figure 5: Map of the simulated temperature decrease over the plaine de Plainpalais from 2021 (left) to 2100 (right), under the assumptions of Simulation 2.

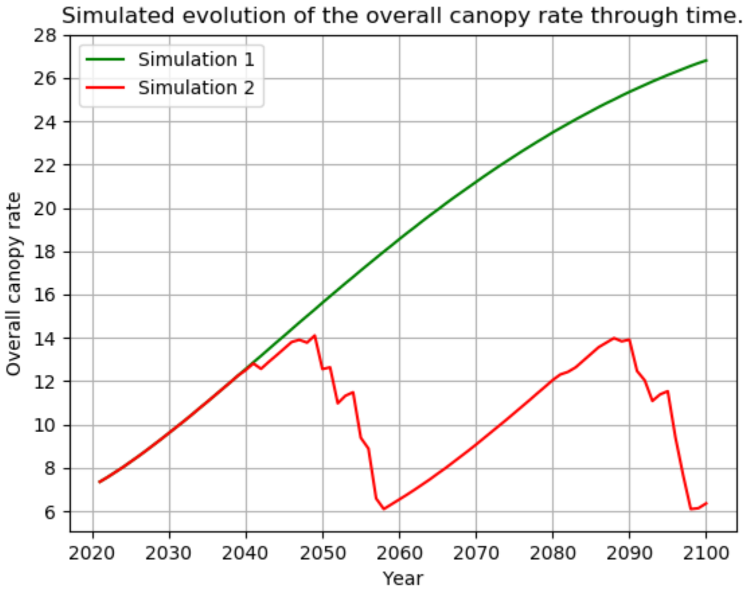

Figure 6: Evolution of the simulated canopy rate over the plaine de Plainpalais from 2021 to 2100, under the assumptions of Simulation 1 (in green) and Simulation 2 (in red).

This time the canopy rate evolution is trickier to describe. Instead of a steady increase as seen during Simulation 1, there are cycles of a period of canopy rate increase followed by a sharp decrease, which corresponds to the moment when most trees are cut down and replaced once they reach their maximum lifetime.

iii. *Simulation 3*

During Simulation 3, additional trees are planted on our chosen region of interest. These trees correspond to a reorganization of the Avenue du Mail, situated next to the plaine de Plainpalais. The goal of this project is to increase the canopy rate of the area. We can use our model to try to quantify what will be the impact on the canopy rate of the area, by comparing the results from this Simulation, and Simulation 1.

These trees are planted in 2022, and are considered to be medium-sized trees (see Table 1 for properties of these new trees). These trees are colored in red for visualization purposes (see figures 7 and 8).

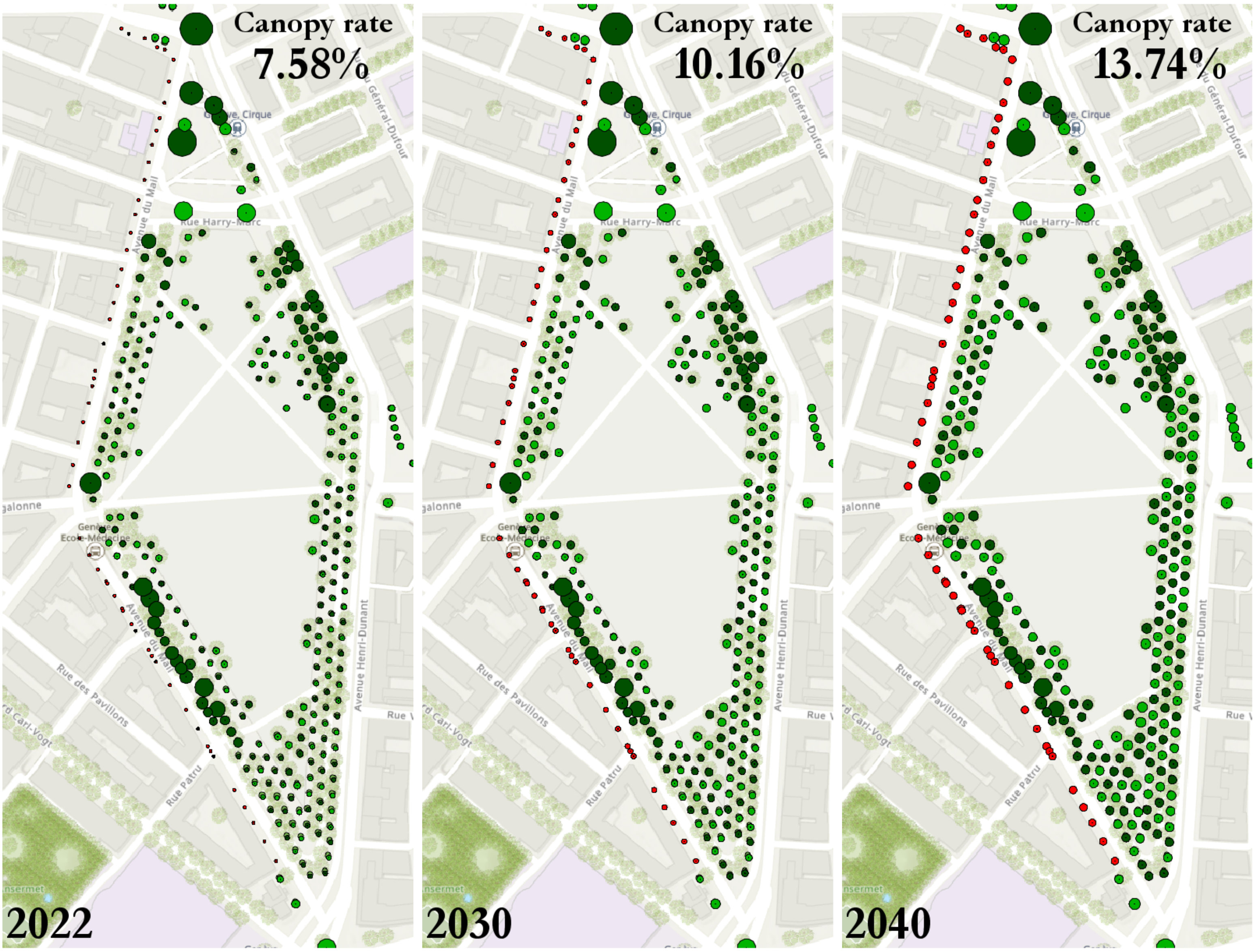

Figure 7: Evolution of the simulated canopy extent over the plaine de Plainpalais from 2022 (left) to 2040 (right), under the assumptions of Simulation 3.

Figure 8: Evolution of the simulated canopy extent over the plaine de Plainpalais from 2050 (left) to 2100 (right), under the assumptions of Simulation 3.

Figure 9 displays the evolution of the canopy rate through time on a graph, taking into account the newly trees planted from Simulation 3, and compares it to the situation without any newly planted trees from Simulation 1. The new trees are expected to account for an increase in canopy rate by 1.88 point in 2050 (12% increase in canopy extent), and 4.44 points in 2100 (16.6% increase in canopy extent). While the effect of these new trees might not be felt immediately, as their canopy grows, local cooling effect and shade provided should drastically increase over time.

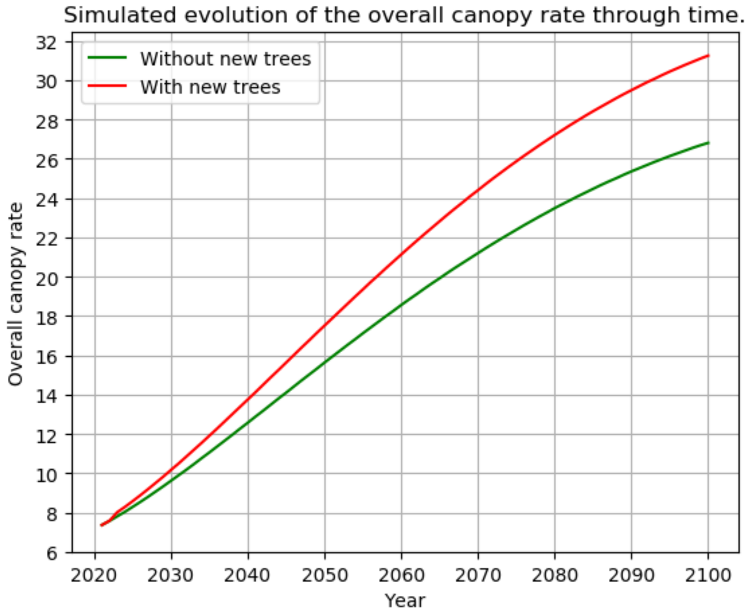

Figure 9: Evolution of the simulated canopy rate over the plaine de Plainpalais from 2021 to 2100, under the assumptions of Simulation 1 (in green) and Simulation 3 (in red).

These three simulations demonstrate the flexibility of agent-based models. Rules of evolution may be bent at the will of the user, as seen in Simulation 2. The user may also directly interact with the agents themselves, this was illustrated in our case by the planting of new trees at chosen locations during the year 2022 (Simulation 3). The model then resumed by taking into account these new trees into the simulation.

b) Other regions of interest

The previous experiments were repeated for two additional regions of interest, situated in the vicinity of the plaine de Plainpalais : the parc des Bastions, and the parc des Rois. The simulations were ran with the parameters from Table 3 and 4 respectively, for maximum canopy diameter and height, maximum lifetime, r ratio, age at plantation date (APD) and growth stress multiplier (GSM). The values of these parameters for Small, Medium and Large Trees were determined with the help of a preliminary calibration run using only the trees from the ICA layer that had a complete dataset.

Category	Max canopy diameter	Max canopy height	Max lifetime	r	APD	GSM
Small	5 m	5 m	30 yrs	0.8	4 yrs	0.7
Medium	11 m	10 m	40 yrs	0.8	2 yrs	0.8
Large	15 m	13 m	70 yrs	0.82	6 yrs	0.75

Table 3: Detailed values for all key parameters used for simulation over the parc des Bastions. APD stands for Age at Plantation Date, GSM stands for Growth Stress Multiplier. r is the ratio between the canopy size of the tree at half life, and the maximum canopy size.

Category	Max canopy diameter	Max canopy height	Max lifetime	r	APD	GSM
Small	7 m	5 m	30 yrs	0.8	8 yrs	0.65
Medium	12 m	10 m	40 yrs	0.8	4 yrs	0.75
Large	8 m	13 m	70 yrs	0.9	10 yrs	0.75

Table 4: Detailed values for all key parameters used for simulation over the parc des Rois. APD stands for Age at Plantation Date, GSM stands for Growth Stress Multiplier. r is the ratio between the canopy size of the tree at half life, and the maximum canopy size.

No additional trees were planted, however the trees were allowed to age until their maximum lifetime, at which point they would be cut down and replaced by a 10-year-old young tree. The following table (Table 5) presents the canopy rates estimated by the model for our three regions of interest, at three different points in time.

Region of interest	2021	2050	2100
Plainpalais	7.36%	15.62%	26.8%
Bastions	44.77%	52.09%	48.59%
Parc des Rois	28.67%	30.29%	29.47%

Table 5: Estimated canopy rates for three regions of interest in 2021, 2050 and 2100.

Figure 10 depicts the evolution of canopy rate through time for the parc des Bastions and the parc des Rois, whereas Figure 11 stacks all three plots of canopy rate in function of time for our three regions of interest, onto a single graph.

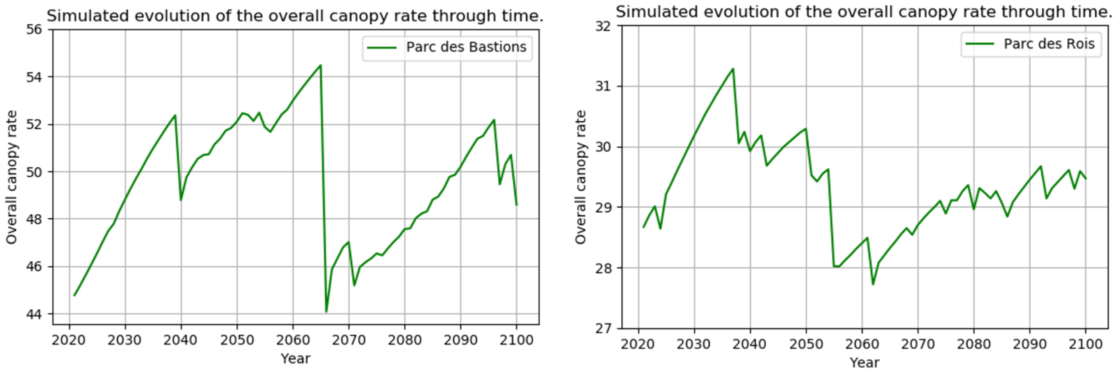

Figure 10: Evolution of the simulated canopy rate over the parc des Bastions and parc des Rois from 2021 to 2100.

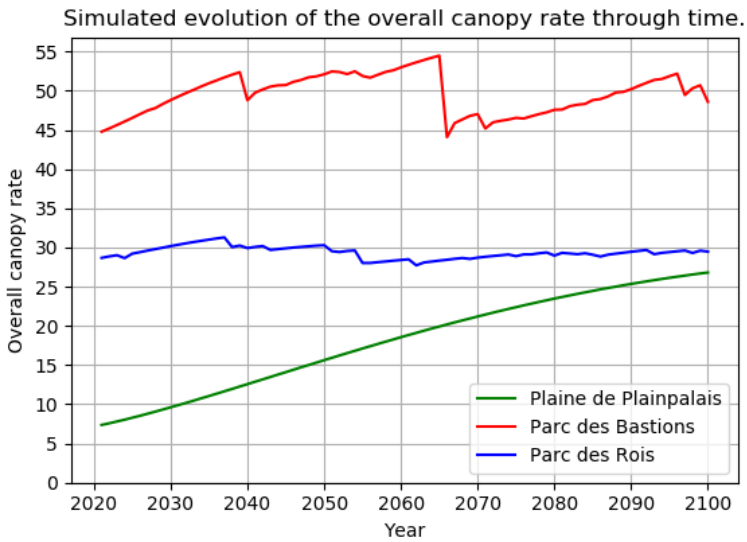

Figure 11: Evolution of the simulated canopy rate over the parc des Bastions, the parc des Rois and the plaine de Plainpalais, from 2021 to 2100.

A glance at Figure 11 indicates that the overall canopy rate of the parc des Bastions is much higher than the canopy rates for the parc des Rois and the plaine de Plainpalais. Plaine de Plainpalais' canopy rate starts off at a relatively low value, but is expected to surpass 15% by 2050 and 25% by 2100, effectively approaching the rate for the parc des Rois. This is mainly due to the fact that the plaine is composed of newly planted trees, which do not yet boast a very large canopy, but are expected to grow during the years to come, providing the neighborhood with the benefits of a large canopy cover.

5. Conclusion and Outlook

In summary, a model for canopy rate over the canton of Geneva has been developed, featuring a dynamic evolution of canopy size in function of age and species (grouped into categories), thanks to a third order polynomial dependency of canopy size in function of the age of the tree, thus improving the initial estimate of a 10 cm per year linear growth for all trees.

For the plaine de Plainpalais, results indicate that if trees are allowed to stay in place for their entire duration, the canopy rate of the area will steadily increase to reach over 15% in 2050 and over 25% in 2100. However, if for some reason, they need to be cut down prematurely, dips in canopy rate are to be expected, which won't be immediately compensated even when planting new trees. When taking account the projected planting of new trees in 2022, associated with a reorganization of the adjacent avenue du Mail, the total canopy extent was increased by 12% in 2050 and 16.5% in 2100, resulting in a increase in canopy rate of 1.88 points and 4.44 points, respectively. Other regions of interest can be modelled provided the geodata for the regions are available. The parc des Bastions and the parc des Rois were taken as illustrations of this possibility.

When comparing with a 30% canopy rate objective for the canton of Geneva by 2050, our results indicate that the goal is already met for the parc des Rois, and largely overtaken for the parc des Bastions. However, the current canopy rate for the plaine de Plainpalais is currently quite poor (7.36% from our simulation for the year 2021, 9% from the 2019 LIDAR data), and, based on our predictions, the objective will not be met by 2050 for the plaine de Plainpalais, with a projected 15.6% canopy rate. However, it is important to stress that the predictions obtained from the model may be underestimating the true potential canopy rates of the areas by an uncertain amount, that might lie in the 40 to 50% range.

The model lets the user experiment with many parameters and actions, in order to visualize the repercussions some changes may have on the system. For instance, the values of the key parameters may be changed at any time, some of rules of evolution for the trees may be modified (most notably the timing at which they are cut down), and new trees may be planted at any given location.

A rough estimation of the trees' cooling effect was given, although the model for temperature lacks precision, as well as calibration and validation steps. Moreover, the validation of the model in general was not made possible, because of highly conflicting calibration and validation data.

Further work needs to be done on this model in these two domains. A better estimation of the cooling effect by the trees needs to be crafted, and sets of data need to be found in order to put this estimation to the test and confirm it is indeed sound. Additionally, for canopy rate, the reliability of the data used for the calibration and validation steps needs to be reassessed, only then may a proper validation take place.

When continuing the work done during this project, the author highly recommends extracting the canopy area of each tree from the LIDAR data for calibration and coupling it with the ICA dataset for all other parameters such as the age of the tree and its category, thus discarding the data for canopy diameter from the ICA dataset. This step will cement the calibration process and drastically reduce the error margin currently exhibited by the model. However, an additional dataset will be required for validation purposes. This dataset may be obtained by launching a new series of canopy extent measurements from the ground, for instance.

A suitable over-arching goal for the project would be to extend the simulation to the whole canton of Geneva. To achieve this goal, a large amount of computational resources will be needed. Improving the accessibility of the model is also an important consideration. Some prospects include : streamlining the process between geodata acquisition, data treatment and formatting and integration into the model, as well as transforming the whole process into a single executable program, in order to enhance user quality of life and ease of use.

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All related links used in this report are :
GAML introduction, https://gama-platform.org/wiki/Introduction
Learn GAML step by step, https://gama-platform.org/wiki/LearnGAMLStepByStep
Downloads, https://gama-platform.org/download
For all GAML and GAMA links : last visited 2021.

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