Trees As Infrastructure
TreesAI

Green Urban Scenarios Framework

Models Specification

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Abstract

This document lays out detailed specification of models, an innovative and practical scenario analysis and impact estimation schemes for green infrastructures. Using the framework, practitioners can design a new urban forest or explore the impact of an existing one. They can investigate each ecosystem service of an urban forest, choosing the level of granularity and complexity on a project-by-project basis.

Keywords: Urban Forest, Nature-based Solutions, Digital Twins, Agent-based Modelling.

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1 Introduction

Trees and other green infrastructure are a critical part of urban infrastructure, alongside bridges, roads and rails. As such, they should enable for investment, profitability and sustainability alike other urban infrastructure does.

This paper provides the technical documentation for the novel Green Urban Scenarios Framework (GUS), which we have developed at TreesAI, to facilitate cities to design, forecast, and monitor green infrastructure portfolios and their long-term impacts under varying weather conditions, maintenance regimes, species compositions, spatial distributions and their exposure to diseases.

Our point of departure is based on the observation that planning, maintaining and estimating the impacts of an urban forest is complex and hence requires a complex systems approach. Figure 1 below summarizes how our approach combines science, practise, and policymaking to make a verifiable difference. It reflects how to make a change in complexity and is inspired by the Cynefin framework (Snowden, 2000), a conceptual framework for decision-making.

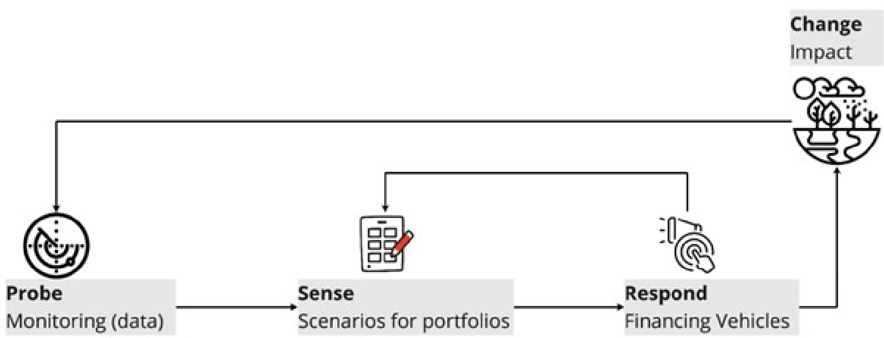

Figure 1: Change model in complexity that combines science, practice and policy.

The very nature of an urban forest as a habitat of trees and other living organisms has four underlying characteristics that mandate a complex system perspective. First, each urban forest is located at a physical location where the soil structure, density of its trees, exposure to the sun, and access to water can vary drastically, comparing one city with another and within the same city. We name this the Specificity factor. Second, each urban forest may have different species composition. Even two trees within the same species often have different shapes and physiology, responding to the same environment differently. Such heterogeneity is an inherent feature of complex systems. Third, a tree is in constant interaction with its environment and other trees. Due to specificity and heterogeneity, its growth process is dynamic depending on its size, age, and its reach to resources such as light, soil, water, or any other factors. The collection of individual tree level interactions leads to the emergence of a forest level growth pattern that might differ from an individual tree. Last, an urban forest is an open system and is exposed to external shocks such as invasive insects, fires, and frequent human interventions. Such externalities are essential and integral to the analysis of complex systems.

Given the level of complexity, we introduce an agent-based scenario analysis framework in which we combine policy intervention, planning, impact forecasting and monitoring. An agent is an abstraction for an autonomous, reactive and proactive information-processing entity. Entities such as trees, bees, birds, or sensors that collect data on soil health could all be construed as autonomous agents. The physical system then can be mimicked digitally by configuring agents and their interactions within the surrounding ecosystem. That enables us to capture the context and conduct very granular computational experiments. In short, such modelling features suggest that agent-related abstractions allow us to model a green infrastructure as a complex system with its components and interactions within a geophysical context.

2 Model

The Green Urban Scenarios framework (GUS) has been developed to facilitate planning and maintenance of urban forests and to estimate their impacts. It consists of a core simulation engine developed following the complex system approach, which is able to simulate the entire ecosystem of trees over N years. It captures the trees' population dynamics, allowing for different case studies and scenario analysis. The framework also incorporates independent modules that use the population data as inputs along with weather data to estimate ecosystem services and benefits. In addition, the framework incorporates a weather data processing module that is used to format local hourly weather data. Figure 2 presents the Trees AI, Green Urban Scenarios (GUS) framework architecture.

The scenario analysis starts from the right-hand side of figure 2, entering the description of a NbS project. The description is given in terms of input parameters to the model describing the size and the characteristics of the population (e.g. number of trees, species, typology, density, etc.), planting/maintaining activities, etc. If the typology already exists, the population is initialized reading the data of the population while using the rest of the input parameters given in NbS design to define the NbS asset proposal along with experiment activities. The initialization description is provided in the following subsection. The initialized tree population, including all parameters along with weather data, is passed to the core simulation engine in $Module$ 1 where the tree population growth and development is simulated over N years. The main component of the simulation engine is a flexible agent-based model that simulates a population of trees at different levels of granularity. If needed, the model can create a digital-twin out of a green urban typology and simulate a spectrum of interactions among the objects (so-called agents) forming that typology. Agents can be trees, humans, invasive species, diseases, etc. All agents are modelled, creating a network among them and taking into account their dynamic interactions also exposed to different weather conditions. Finally, the tree population dynamics emerge out of interactions among agents in the given typology. Another component of the module is a tree growth model developed following the existing literature [...] which will be explained in details in the following sections. The core module provides the synthetic data as output, which are passed to $Module$ 2 along with the hourly weather data from the weather data module to estimate the ecosystem services. Currently, $Module$ 2 includes water retention model whose description is provided in section 3.2 as well as air pollution removal model described in section 3.3. $Module$ 2 calculates ecosystem services and provide data on outcomes to the monitoring activities module, which can be further used to update population data and/or NbS design and to re-simulate the population dynamics and to re-calculate the ecosystem services. Since the nature of the

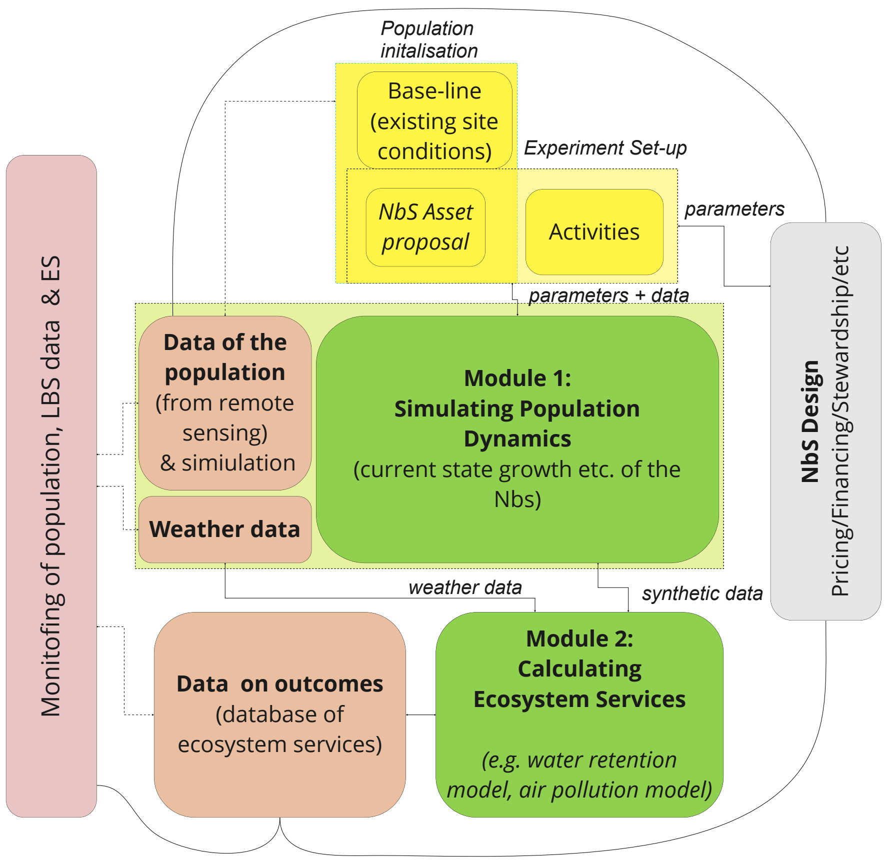

Figure 2: Trees AI, Green Urban Scenarios framework (GUS) architecture diagram.

model is stochastic, the simulation can be performed M times over N years, taking into account different weather conditions and different probabilities of agents' interaction. The results are then aggregated over two dimensions, time and simulation runs, and presented in the coherent way. The entire simulation process can be described in four steps: *(i)* inputs; *(ii)* model dynamics; *(iii)* tree growth process; and *(iv)* outputs. In the following, we describe the simulation process in details.

2.1 Inputs

To make our framework flexible and applicable to any tree typology at any location, we divide the inputs into four different segments: *(i)* site configuration, *(ii)* population configuration, *(iii)* allometric equations, and *(iv)* experiment configuration; where we design an independent (stand alone) database for each segment.

2.1.1 Site configuration

The site configuration is a database with non-exhaustive information about specific sites. For instance, it stores the data about the exact location of the site, its boundaries, the total area of the site, the data about the surface, and any other relevant data that may describe a specific location. The list of variables is expandable therefore, users may use the database to improve the quality of descriptions of the existing sites or enter information about new sites.

2.1.2 Population configuration

The population configuration is a database describing the tree population at a specific location. It can consist of the existing trees at a given location, the planned tree population, or any hypothetical tree population that could be studied at a particular site. The granularity of the data in the database is flexible, meaning that one can describe in detail each tree in the population using a non-exhaustive list of variables such as species, DBH, tree height, canopy height, canopy width, Leaf Area Index (LAI), Bark Area Index (BAI), tree dieback ratio, tree age, canopy overlap, the exact coordinate of each tree in the site, etc. On the other hand, if high granularity is not needed or some data points are missing, one can use less granular data such as more generic species information or, DBH and other tree size measures drawn from a particular distribution. If missing, some of the variables can also be estimated, such as tree height, canopy height, canopy width, Leaf Area Index (LAI), Bark Area Index (BAI), while others such as tree dieback ratio, tree age, canopy overlap, and coordinate can be assumed.

2.1.3 Allometrics

The allometric database consists of allometric equations for specific species at specific locations. Each species at each site is described with allometric equations. If some allometric equations are missing, we have designed a representative or mean allometric for the specific area, taking into account a more generic family of species. In the most generic case, there is one mean allometric for deciduous and one for conifers at specific locations. This database is extended and updated with newly available data.

2.1.4 Experiment configuration

The experiment configuration database describes the experiments to be performed on the particular tree population at the given location. For the time being, there are available experiments related to the different maintaining strategies. One can choose three levels (M_0, M_1, M_2) of tree maintenance which is related to the planting, removal and disposal, and tree replacement. Maintaining level M_0 disregards any of maintaining activities, while the activities increase with maintaining levels M_1 and M_2.

2.2 Model Dynamics

The core model of the GUS framework is an agent-based dynamic-stochastic model. The model uses the inputs to create a digital representation of the green urban ecosystem under the study and using weather data for a specific location it simulates the population growth and development over N years. The digital ecosystem is composed of trees and other participants, so-called "agents", such as people, diseases, invasive species. The results emerge from the agents' interactions given the weather projections for N years.

2.2.1 Initialization

Based on the inputs, the model first initializes the digital ecosystem, creating a digital representation of each tree in the population. Each tree is described by a list of variables (DBH, tree height, canopy height, canopy width, ...) from the population configuration database and each tree is assigned an allometric equation from the allometric database, based on species and location. The digital trees are then distributed on a digital grid.

2.2.2 Spatial Configuration

The model uses a spacial configuration method which, based on the site configuration database, creates a digital site. It allocates each digital tree on a grid, where each tree has its own x and y coordinate. Therefore, each tree has a unique place in the digital site, and it is surrounded with neighbouring trees and other agents. The spatial configuration translates all other site characteristics from the site configuration database into digital space, such as soil type, site size, the distance among trees and, the sun exposure.

2.2.3 Weather Projections

The weather data processing module deals with weather projections. It uses hourly weather data for a specific location as inputs and provides weather predictions for N future years, which are used to simulate tree population growth and to calculate the ecosystem services. Since the tree growth is simulated on a yearly basis, the weather processing module provides only the information about the frost free days to the simulation engine. Note that, many variables such as the sun radiation, amount of rain, etc., are captured as averages by specific allometric equations, while some of them are taken into account at the micro (tree) level as a growth adjustment factors, sun as the sun exposure. The rest of the weather data, such as start and end dates of leaf-on-leaf-off seasons, temperature, atmospheric pressure, relative humidity, wind speed, dew point temperature, the sun radiation, air pollution concentration, mixing height and, atmospheric sounding data (atmospheric profiles for specific locations) are provided on hourly level and used to calculate the ecosystem services described in section 3.

2.2.4 Simulation and data collection

2.3 Materials to be added

The dieback model below is path dependent and depends on (i) the latest condition of the tree, (ii) the age via DBH and (iii) the health of neighboring trees. the new rate is drawn from a uniform distribution between $-1 * healing_rate$ and $risk_rate$.

2.4 Tree Growth Process

2.4.1 initial state

2.4.2 monitoring weather and growth season

2.4.3 monitoring exposure to light and other resources

2.4.4 dieback

2.4.5 growth

- dbh - height - crown width - crown height

2.4.6 biomass

2.4.7 sequestration

2.4.8 decomposition

2.5 Outputs

2.5.1 Primary variables

2.5.2 Secondary variables

LeafArea etc

3 Ecosystem services - Impact analysis

3.1 Carbon sequestration

The tree growth models are applied to each agent tree, taking into account its relative position in the typology and its exposure to other agents in the model - interactions.

3.2 Water retention

The water retention module uses local hourly weather data and estimates the hourly contribution of an individual tree i to the avoided run-off and storm water retention. i is a tree identifier such that $i \in \{1, 2, 3, ..., N\}$, where, N is the total number of trees in the population. For the sake of readability, we drop index i from the equations in this section. However, the equations will contain the time index t, which identifies hour-day-month-year. The module allows a user to make scenarios with different weather conditions and simulate the impact over n years. For instance, one can simulate the impact of trees in extreme rain events, different temperature scales, etc.

The module is developed following existing literature on hydrology, mainly Shuttleworth, 1993, Hirabayashi, 2013, and Hirabayashi, 2015. Our aim is to trace out the additionality of trees, calculating their net impact. Therefore, we first calculate the total-gross contribution of trees. Then we design a hypothetical scenario without trees to capture a part of the evaporation dynamics that would occur anyway. Subtracting the hypothetical scenario outcomes from trees' gross impact, we obtain their net impact - additionality.

The entire precipitation-interception event can be decoupled into two processes: (1) the process by vegetation interception and evaporation from vegetation; and (2) the process below the vegetation, including evaporation from the ground and run-off or infiltration. For the time being, we will distinguish two land types such as the pervious cover where the infiltration occurs, and the impervious cover where the run-off occurs.

3.2.1 Hourly precipitation-evaporation process for vegetated cover

3.2.1.1 Process by vegetation

As it is described in Hirabayashi, 2013, this process captures the dynamics of precipitation and evaporation from vegetation. It includes three stages, (1) when the precipitation starts and the vegetation still has the capacity to retain water; (2) vegetation drip starts when the vegetation has no capacity to retain water any longer; (3) when the precipitation stops and the evaporation from vegetation continues until the vegetation dries up or new precipitation starts. Therefore, assuming that precipitation starts at time t we calculate the vegetation storage Sv_t[m] at stage 1 such as:

$$Sv_t = Sv_{t-1} + Pv_t - Ev_{t-1}. \tag{1}$$

If $Sv_t < 0$, Sv_t is set to zero, whereas if $Sv_t > Sv_{max}$, Sv_t is set to Sv_{max} and the first stage ends. Sv_{max} is calculated as:

$$Sv_{max} = S_L \cdot PAI, \tag{2}$$

where S_L is a specific leaf storage of water (=0.0002m), see Hirabayashi, 2013, and PAI is Plant Area Index [Leaf Area Index (LAI) + Bark Area Index (BAI)].

Precipitation that is retained by vegetation at time t (Pv_t)[m] is calculated as:

$$Pv_t = P_t - Pd_t, \tag{3}$$

where Pd_t[m] is precipitation drip through the canopy at time t. It is a part of precipitation that will hit the ground, passing through the canopy, despite available vegetation capacity to retain water. It is calculated as:

$$Pd_t = P_t(1 - c), \tag{4}$$

where c is canopy cover friction that depend on PAI:

$$c = 1 - e^{-\kappa PAI}, \tag{5}$$

where κ is an extinction coefficient (=0.7 for trees and 0.3 for shrubs), see Wang et al., 2008. Therefore, the amount of rain hitting the ground during the first stage is equal to Pd_t[m].

Figure 3 illustrates the first stage in the precipitation process by vegetation. The precipitation has filled half of the canopy capacity, while a part of the rain Pd is passing through the canopy. Evaporation from vegetation at time t, $Ev_t[m]$ is calculated as:

$$Ev_t = \left(\frac{Sv_t}{Sv_{max}}\right)^{\frac{2}{3}} \cdot PE_t, \tag{6}$$

where PE_t is potential evaporation $[m]$ at time t calculated using the modified Penman-Monteith equation (Shuttleworth, 1993):

$$PE = \frac{1}{\lambda\rho_w}\left(\frac{\Delta R_n + \frac{D\rho_a c_p}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}\right), \tag{7}$$

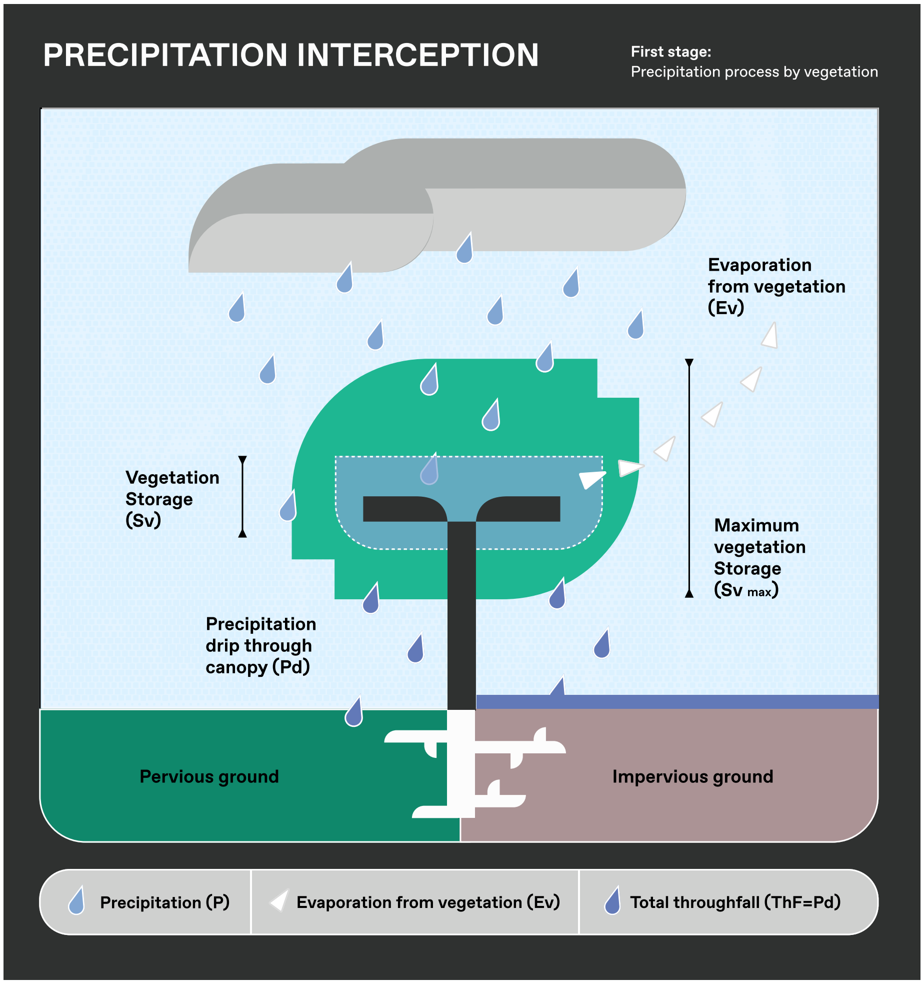

Figure 3: Trees AI, Precipitation interception phase 1.

where R_n is the net radiation (available energy) $[MJ\ m^{-2}]$. λ is latent heat of vaporization $[MJ\ kg^{-1}]$ given as:

$$\lambda = 2.501 - 0.002361T, \tag{8}$$

where T is temperature $[^{\circ}C]$. ρ_w denotes density of water $[kg\ m^{-3}]$, and it is estimated as:

$$\rho_w = 999.88 + 0.018T - 0.0051T^2. \tag{9}$$

Dividing R_n by $\lambda\rho_w$ one can obtain an equivalent debt of evaporated water in [m].

D is vapour pressure deficit ($=e_s - e$)[kPa], where e_s is saturated vapour pressure $[kPa]$ given as:

$$e_s = 0.6108exp\left(\frac{17.27T}{237.3 + T}\right), \tag{10}$$

and e is vapour pressure $[kPa]$ given as:

$$e = 0.6108exp\left(\frac{17.27DT}{237.3 + DT}\right), \tag{11}$$

where DT is dew point temperature $[°C]$. If $e_s - e < 0$, D is set to zero.

Δ is a slope of vapour pressure temperature curve $[kPa\,°C^{-1}]$ given as:

$$\Delta = \frac{4098e_s}{(237.3 + T)^2}. \tag{12}$$

ρ_a is the density of air $[kg\,m^{-3}]$ calculated as:

$$\rho_a = 3.486 \cdot \frac{P}{275 + T}, \tag{13}$$

where P is measured surface pressure [kPa].

c_p is specific heat of moist air (=1.013)$[kJ\,kg^{-1}\,°C^{-1}]$.

r_a is aerodynamic resistance $[m\,s^{-1}]$ given as:

$$r_a = \frac{4.72 \cdot \ln\left(\frac{Z_t}{Z_{ov} d_t}\right)}{1 + 0.536U_t}, \tag{14}$$

where Z_t is the wind estimate height for trees (tree height) [m]. Z_{ov} is mass transfer coefficient (=0.0123[m]). d_t is roughness height for trees (=0.95[m]). U_t is estimated wind speed at the tree top $[m\,s^{-1}]$ given as:

$$U_t = U \frac{\ln\left(\frac{Z_t}{d_w}\right)}{\ln\left(\frac{Z_u}{d_w}\right)}, \tag{15}$$

where U is measured wind speed $[m\ s^{-1}]$, Z_u is wind measurement height (=10[m]), and d_w is roughness height for water (=0.00137[m]).

γ is a psychometric constant $[kPa\,°C^{-1}]$ given as:

$$\gamma = \frac{c_p P}{\epsilon\lambda} \cdot 10^{-3}, \tag{16}$$

where ϵ is the ratio of the molecular weight of water vapour to that for try air (=0.622).

r_s is stomatal resistance $[m\ s^{-1}]$ calculated as:

$$r_s = \frac{200}{PAI}. \tag{17}$$

Figure 4 demonstrates the second stage in the precipitation process by vegetation when the vegetation storage reach its maximum $Sv = Sv_{max}$. Precipitation that used to be retained by vegetation Pv now becomes vegetation drip Vd and together with the precipitation drip through the canopy Pd sums up to total throughfall ThF, thus $ThF = P$, while evaporation continues throughout this stage. Sv is calculated using equation 1 resulting in $Sv = Sv_{max}$, while Pv, Pd, and Ev are calculated using equations 3, 4, and 6 respectively.

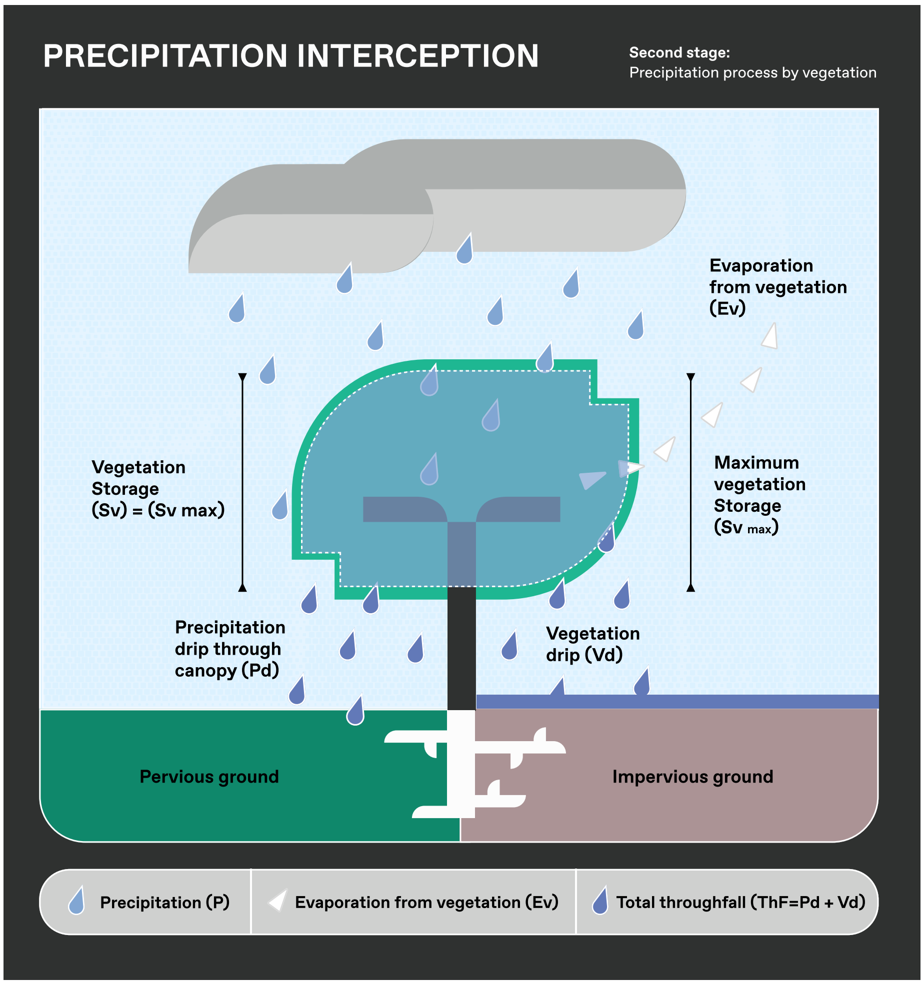

Figure 4: Trees AI, Precipitation interception phase 2.

For the first time in the second stage, where $Sv_{t-1} < Sv_{max}$ vegetation drip Vd[m] is calculated as:

$$Vd_t = Pv_t - (Sv_{max} - Sv_{t-1}) - Ev_t. \tag{18}$$

After that Vd is calculated such as:

$$Vd_t = Pv_t - Ev_t. \tag{19}$$

Therefore, the total amount of precipitation reaching the ground in the second stage at time t is given as $ThF_t = Vd_t + Pd_t$.

Figure 5 shows the third stage, when the precipitation stops and the evaporation from vegetation continues, which is calculated using equation 6.

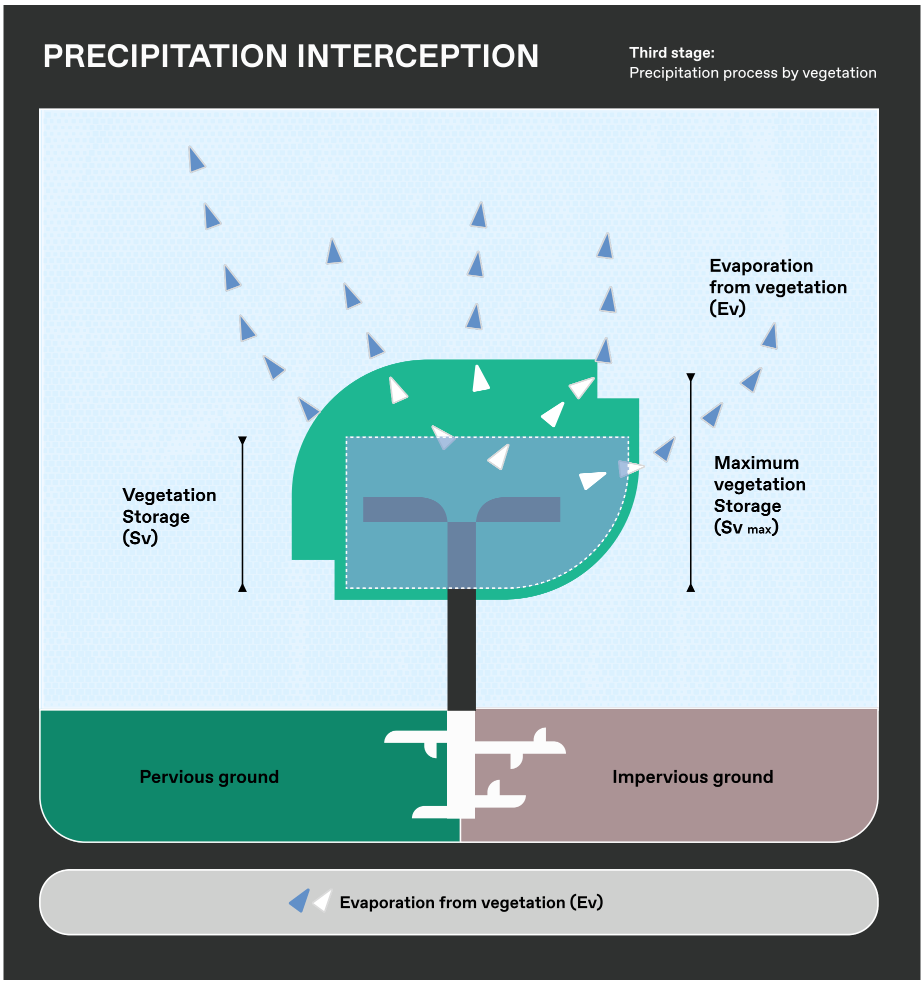

Figure 5: Trees AI, Precipitation interception phase 3.

3.2.1.2 Process by impervious cover under the canopy

Total precipitation reaching the ground ThF_t is a sum of precipitation drip through the canopy Pd and vegetation drip Vd after the vegetation storage reach its maximum capacity. Given this amount, we will apply here the same three stages as in the previous section. **Figure 6** illustrates the first stage of the process.

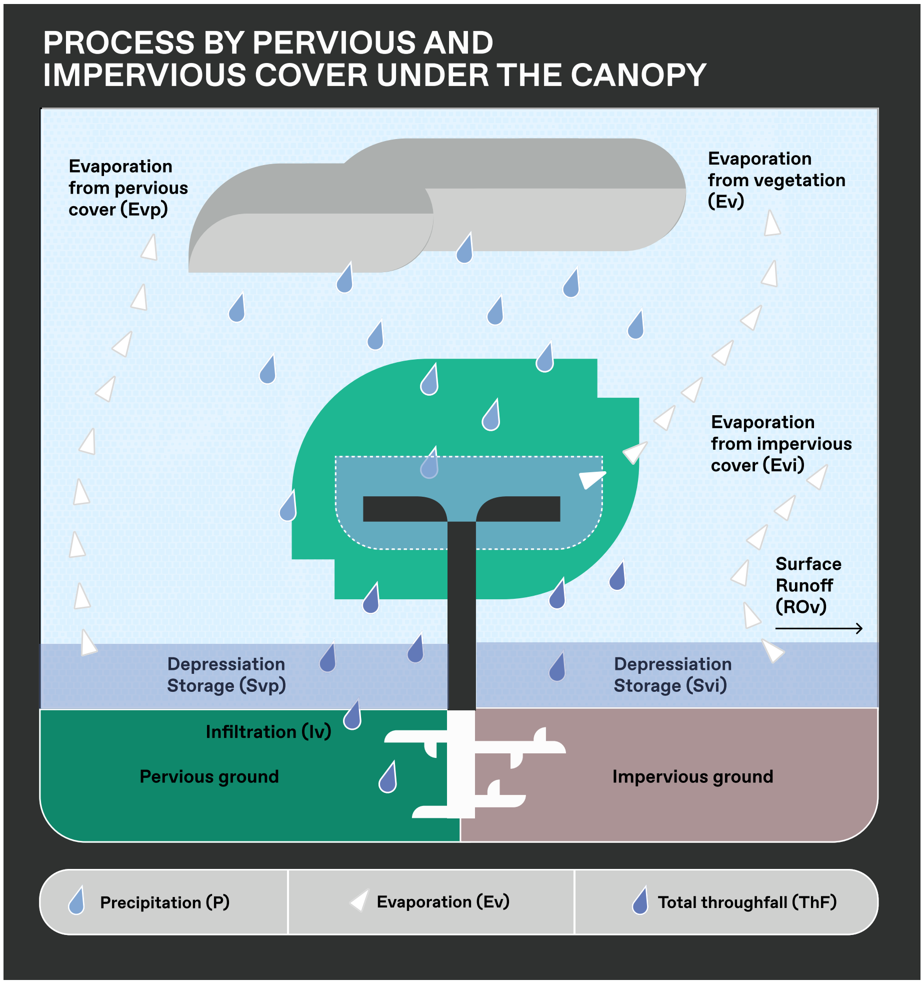

Figure 6: Trees AI, impervious/pervious covers under the canopy.

The impervious cover depression storage Svi_t [m] at time t is calculated as:

$$Svi_t = Svi_{t-1} + ThF_t - Evi_{t-1}. \tag{20}$$

If $Svi_t < 0$, Svi_t is set to zero, whereas if $Svi_t <= Si_{max}$, Svi_t is set to Si_{max} and the first stage ends. Si_{max} is constant (=0.0015m).

Evaporation from the impervious cover Evi_t[m] at time t is calculated as:

$$Evi_t = \left(\frac{Svi_t}{Si_{max}}\right) \cdot PEg_t, \tag{21}$$

where PEg_t is the potential evaporation at time t from the impervious cover, calculated using equation 7.

Runoff over the impervious cover ROv_t[m] at time t is calculated as:

$$ROv_t = ThF_t - (Si_{max} - Svi_{t-1}) - Evi_t. \tag{22}$$

At the second stage, impervious cover depression storage Svi_t at time t is calculated using equation 20 having $Svi_t = Si_{max}$. Evaporation Evi_t is computed using equation 21, while runoff ROv_t at time t is calculated as:

$$ROv_t = ThF_t - Evi_t. \tag{23}$$

At the third stage, evaporation Evi_t is calculated using equation 21.

3.2.1.3 Process by pervious cover under the canopy

The same three stages as in the previous sections are applied to calculate the precipitation-evaporation process over the pervious cover under canopy. **Figure 5** illustrates the first stage of the process. The pervious cover depression storage Svp_t [m] at time t is calculated as:

$$Svp_t = Svp_{t-1} + ThF_t - Evp_{t-1}. \tag{24}$$

If $Svp_t < 0$, Svp_t is set to zero, otherwise if $Svp_t <= Sp_{max}$, Svp_t is set to Sp_{max} and the first stage ends. Sp_{max} is constant (=0.001m).

Evaporation from the pervious cover Evp_t[m] at time t is calculated as:

$$Evp_t = \left(\frac{Svp_t}{Sp_{max}}\right) \cdot PEg_t, \tag{25}$$

where PEg_t is the potential evaporation at time t from the pervious cover, calculated using equation 7.

Infiltration over the pervious cover Iv_t[m] at time t is calculated as:

$$Iv_t = ThF_t - (Sp_{max} - Svp_{t-1}) - Evp_t. \tag{26}$$

At the second stage, pervious cover depression storage Svp_t at time t is calculated using equation 24 having $Svp_t = Sp_{max}$. Evaporation Evp_t is computed using equation 25, while infiltration Iv_t at time t is calculated as:

$$Iv_t = ThF_t - Evp_t. \tag{27}$$

At the third stage, evaporation Evp_t is calculated using equation 25.

3.2.1.4 Transpiration by vegetation

Transpiration is the release of water in the form of water vapour from plants. The process is composed of two stages: (1) evaporation of water from cell walls, and (2) diffusion out of the leaf, mainly through stomata (Kramer, 1983 and

Hirabayashi, 2015). Hourly transpiration flux $TF[g\,m^{-2}hr^{-1}]$ is calculated (following Kramer, 1983) as:

$$TF = \frac{C_{leaf} - C_{air}}{\frac{1}{g_s} + r_a} \cdot \frac{3600}{LAI}, \tag{28}$$

where g_s is stomatal conductance $[s\,m^{-1}]$ and $\frac{1}{g_s}$ is equivalent to stomatal resistance $r_s[m\,s^{-1}]$ given in equation 17. r_a is aerodynamic resistance given in equation 14. C_{leaf} and C_{air} are water vapour concentration at the evaporating surfaces within the leaf and water vapour concentration in the air $[g\,m^{-3}]$ respectively. They are calculated following (Monteith and Unsworth, 1990) as:

$$C_{leaf} = \frac{M_w e_s}{RT} = \frac{2165 e_s}{T}, \tag{29}$$

$$C_{air} = \frac{M_w e}{RT} = \frac{2165 e}{T}, \tag{30}$$

where M_w is the molecular weight of water $(= 18[g\,mol^{-1}] = 18000[g\,kmol^{-1}])$. R is universal gas constant $(= 8.314[J\,mol^{-1}\,K^{-1}] = 8.314[kPa\,m^{-3}\,kmol^{-1}\,K^{-1}])$. e_s and e are saturated vapour pressure and vapour pressure given in equations 10 and 11 respectively. T is temperature$[K]$.

The hourly transpiration flux mass per unit canopy cover, $TF[g\,m^{-2}\,hr^{-1}]$ is converted to depth $[m\,hr^{-1}]$ by multiplying 10^{-6} (1 g of water flux $m^{-2} = 10^{-6}\,ton\,m^{-2} = 10^{-6}\,m^3\,m^{-2} = 10^{-6}\,m$). It is then adjusted based on hourly potential evapotranspiration $PET[m\,hr^{-1}]$ from plants and inside the soil. We first calculate the average ratio between TF and PET using only observations when PET is larger than TF during the leaf-on season, such as:

$$\bar{R} = \frac{\sum_t (TF_t/PET_t)}{n}. \tag{31}$$

Then, when $TF > PET$ along the year or during the leaf-off season, TF is adjusted as:

$$TF = \bar{R} \cdot PET, \tag{32}$$

where PET is calculated as the sum of water released from plants (transpiration) and inside the soil (evaporation) that would take place if a sufficient water source were available. To estimate the hourly potential evapotranspiration, we employ equation 7 using the aerodynamic resistance $r_a = \frac{208}{U_t}$.

3.2.2 Hourly precipitation-evaporation process for the ground cover - hypothetical case

3.2.2.1 Process by impervious cover - hypothetical case

In the hypothetical case without any vegetation, the same process as in section 3.2.1.2 can be applied, except that now all precipitation P_t[m] at time t reaches the ground. **Figure 7** illustrates the precipitation-interception process by impervious cover.

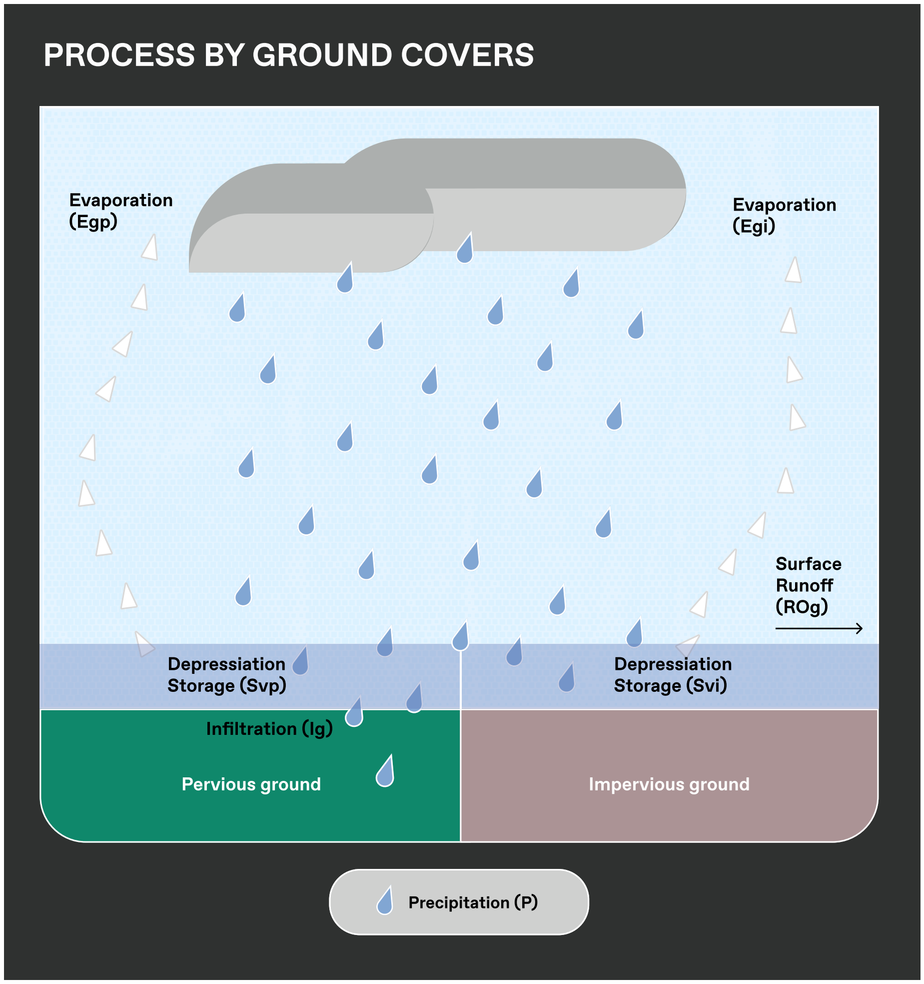

Figure 7: Trees AI, ground covers - hypothetical case.

The impervious cover depression storage Sgi_t [m] at time t is calculated as:

$$Sgi_t = Sgi_{t-1} + P_t - Egi_{t-1}. \tag{33}$$

If $Sgi_t < 0$, Sgi_t is set to zero, whereas if $Sgi_t <= Si_{max}$, Sgi_t is set to Si_{max} and the first stage ends. Si_{max} is constant (=0.0015m).

Evaporation from the impervious cover Egi_t[m] at time t is calculated as:

$$Egi_t = \left(\frac{Sgi_t}{Si_{max}}\right) \cdot PEg_t, \tag{34}$$

where PEg_t is the potential evaporation at time t from the impervious cover, calculated using equation 7.

Runoff over the impervious cover ROg_t[m] at time t is calculated as:

$$ROg_t = P_t - (Si_{max} - Sgi_{t-1}) - Egi_t. \tag{35}$$

At the second stage, impervious cover depression storage Sgi_t at time t is calculated using equation 33 having $Sgi_t = Si_{max}$. Evaporation Egi_t is computed using equation 34, while runoff ROg_t at time t is calculated as:

$$ROg_t = P_t - Egi_t, \tag{36}$$

At the third stage, evaporation Egi_t is calculated using equation 34.

3.2.2.2 Process by pervious cover - hypothetical case

Without vegetation, the same process as in section 3.2.1.3 can be applied, except that all precipitation P_t[m] at time t reaches the ground. **Figure 7** illustrates the precipitation-interception process by pervious cover. The pervious cover depression storage Sgp_t [m] at time t is calculated as:

$$Sgp_t = Sgp_{t-1} + P_t - Egp_{t-1}. \tag{37}$$

If $Sgp_t < 0$, Sgp_t is set to zero, whereas if $Sgp_t <= Sp_{max}$, Sgp_t is set to Sp_{max} and the first stage ends. Sp_{max} is constant (=0.001m).

Evaporation from the pervious cover Egp_t[m] at time t is calculated as:

$$Egp_t = \left(\frac{Sgp_t}{Sp_{max}}\right) \cdot PEg_t, \tag{38}$$

where PEg_t is the potential evaporation at time t from the impervious cover, calculated using equation 7.

Infiltration over the pervious cover Ig_t[m] at time t is calculated as:

$$Ig_t = P_t - (Sp_{max} - Sgp_{t-1}) - Egp_t. \tag{39}$$

At the second stage, pervious cover depression storage Sgp_t at time t is calculated using equation 37 having $Sgp_t = Sp_{max}$. Evaporation Egp_t is computed using equation 38, while infiltration Ig_t at time t is calculated as:

$$Ig_t = P_t - Egp_t, \tag{40}$$

At the third stage, evaporation Egp_t is calculated using equation 38.

3.2.3 Annual interception by trees

So far, we have calculated hourly interception for each individual tree and ground cover over n years, where index t identifies hour-day-month-year.

In the following, we will calculate annual outcomes, aggregating the variables on the yearly level. For instance, *annual evaporation from vegetation* is calculated as:

$$Ev_y = \sum_{month}\sum_{day}\sum_{hour} Ev_{h,d,m,y}, \tag{41}$$

where we replace index t with index y to identify annual outcomes. The same annual aggregation is applied to other variables as well.

3.2.4 Aggregate interception by trees

The interception by trees as well as by ground cover is defined in terms of the debth $[m]$ or in thousands of litters per square meter $[m] = [m^3/m^2] = [1000l/m^2]$. To calculate the aggregate benefits of a particular project, we will first calculate the total contribution of individual trees, multiplying the benefits $[m]$ by the under canopy area $[m^2]$, and then aggregate over all trees. Thus, the aggregate benefits will be converted to volumes $[m^3]$. Our main variables of interest will be: (1) *canopy interception loss*, which is identical to *evaporation from vegetation* Ev; (2) *storm water retention* SWR; (3) *improvement in storm water retention* SWR^{net}; and (4) *avoided runoff* RO^{net}.

Annual canopy interception loss per tree $Ev^{total}_{i,y}[m^3]$ is calculated as:

$$Ev^{total}_{i,y} = Ev_{i,y} \cdot UCA_{i,y}, \tag{42}$$

where $Ev_{i,y}$ is the annual evaporation from vegetation $[m]$ for the tree i in year y, and $UCA_{i,y}$ is the under canopy area $[m^2]$ of the tree i in year y.

Annual storm water retention per tree $SWR^{total}_{i,y}[m^3]$ is given as:

$$SWR^{total}_{i,y} = (Ev_{i,y} + TF_{i,y} + Evi_{i,y} \cdot ICS_{i,y} + Evp_{i,y} \cdot PCS_{i,y}) \cdot UCA_{i,y}, \tag{43}$$

where $Ev_{i,y}$ is the annual evaporation from vegetation $[m]$ for the tree i in year y, $TF_{i,y}$ is the annual transpiration $[m]$ for the tree i in year y, $Evi_{i,y}$ is the annual evaporation from the impervious cover under vegetation $[m]$ for the tree i in year y, $ICS_{i,y}$ is the impervious cover share [%] below the tree i in year y, $Evp_{i,y}$ is the annual evaporation from the pervious cover under vegetation $[m]$ for the tree i in year y, $PCS_{i,y}$ is the pervious cover share [%] below the tree i in year y, and $UCA_{i,y}$ is the under canopy area $[m^2]$ of the tree i in year y.

To calculate the annual improvement in storm water retention (additionality) of each tree, we first calculate the hypothetical annual storm water retention for the area below each tree $SWR^{total}_{hyp(i),y}[m^3]$, assuming that the trees were not there:

$$SWR^{total}_{hyp(i),y} = (Egi_y \cdot ICS_{i,y} + Egp_y \cdot PCS_{i,y}) \cdot UCA_{i,y}, \tag{44}$$

where $Egi_y[m]$ is the evaporation from the ground impervious cover in a year y, and $Egp_y[m]$ is the evaporation from the ground pervious cover in a year y. Thus, the annual improvement in storm water retention $SWR^{net}_{i,y}[m^3]$ per tree is calculated as:

$$SWR^{net}_{i,y} = SWR^{total}_{i,y} - SWR^{total}_{hyp(i),y}. \tag{45}$$

To calculate avoided runoff for each tree $RO^{net}_{i,y}[m^3]$ we calculate runoff per tree $RO^{total}_{i,y}[m^3]$ and runoff for the hypothetical case $RO^{total}_{hyp(i),y}[m^3]$ such as:

$$RO^{total}_{i,y} = ROv_{i,y} \cdot UCA_{i,y} \cdot ICS_{i,y}, \tag{46}$$

where $ROv_{i,y}[m]$ is runoff below the tree i in a year y. And,

$$RO^{total}_{hyp(i),y} = ROg_y \cdot UCA_{i,y} \cdot ICS_{i,y}, \tag{47}$$

where $ROg_y[m]$ is runoff for the hypothetical - ground cover case in a year y. Therefore, annual avoided runoff per tree is calculated as:

$$RO_{i,y}^{net} = RO_{hyp(i),y}^{total} - RO_{i,y}^{total}. \tag{48}$$

Once we have calculated the variables of interest for each tree, we can perform further aggregation per species, per genera, for the entire site, etc. Here we will present an example where we aggregate the outcomes for the entire project. Thus, the annual canopy interception loss for all trees is calculated as:

$$Ev_y^{total} = \sum_i Ev_{i,y}^{total}, \tag{49}$$

annual storm water retention for all trees is given as:

$$SWR_y^{total} = \sum_i SWR_{i,y}^{total}, \tag{50}$$

annual improvement in storm water retention for all trees is calculated as:

$$SWR_y^{net} = \sum_i SWR_{i,y}^{net}, \tag{51}$$

and annual avoided runoff for all tree is given as:

$$RO_y^{net} = \sum_i RO_{i,y}^{net}. \tag{52}$$

3.3 Air pollution removal

The air pollution removal module uses location specific weather data and air pollutant measurements along with urban forest information to estimates the improvement in air quality in a specific location. The dry deposition of air pollution is estimated for particular matter less than 10 (PM10) following mainly Hirabayashi et al., 2015.

The module consists of several functions that enable us to estimate the improvement in air quality. Each function is described in the following.

3.3.1 Air pollutant flux calculation for PM10

The pollutant flux $F[g\ m^{-2}\ h^{-1}]$ for PM10 is given as a product of deposition velocity $Vd[m\ s^{-1}]$ and the air pollutant concentration $C[g\ m^{-3}]$:

$$F = V_d \cdot C \cdot 3600 \tag{53}$$

$$F_{min} = V_{d,min} \cdot C \cdot 3600 \tag{54}$$

$$F_{max} = V_{d,max} \cdot C \cdot 3600, \tag{55}$$

Where $V_{d,min}$ and $V_{d,min}$ are minimum and maximum deposition velocity, while F_{min} and F_{max} are minimum and maximum pollutant flux.

3.3.2 Deposition velocity calculation for PM10

As in Hirabayashi et al., 2015, deposition velocity for PM10 is calculated following minimum, maximum and average values provided by Lovett, 1994:

$$V_d = V_{d,PM10,avg} \cdot \frac{BAI + LAI}{BAI + LAI_{PM10}}, \tag{56}$$

$$V_{d,max} = V_{d,PM10,max} \cdot \frac{BAI + LAI}{BAI + LAI_{PM10}}, \tag{57}$$

$$V_{d,min} = V_{d,PM10,min} \cdot \frac{BAI + LAI}{BAI + LAI_{PM10}}, \tag{58}$$

where $V_{d,PM10,avg}$ is the average deposition velocity for $PM10$ ($= 0.0064[m\ s^{-1}]$); $V_{d,PM10,max}$ is the maximum deposition velocity for $PM10$ ($= 0.01[m\ s^{-1}]$); while $V_{d,PM10,min}$ is the minimum deposition velocity for $PM10$ ($= 0.0025[m\ s^{-1}]$). LAI_{PM10} is Leaf Area Index for particle deposition ($= 6$) and BAI and LAI are Bark Area Index and Leaf Area Index respectively.

3.3.3 Air quality improvement calculation for $PM10$

The hourly air quality improvement per unit tree cover $I_{unit}(\%)$ is calculated as:

$$I_{unit} = \frac{F}{F + M_{total}} \cdot 100, \tag{59}$$

where F is pollutant flux $[g\ m^{-2}\ h^{-1}]$. M_{total} is total air pollutant mass per unit tree cover $[g\ m^{-2}\ h^{-1}]$, which is calculated as:

$$M_{total} = H \cdot C, \tag{60}$$

where H is urban mixing height $[m]$, and C is air pollutant concentration $[g\ m^{-3}\ h^{-1}]$.

Hourly air quality improvement, for total tree cover area, $I_{total}[\%]$ is given as:

$$I_{total} = \frac{F \cdot \frac{T_c}{100}}{F \cdot \frac{T_c}{100} + M_{total}} \cdot 100, \tag{61}$$

where T_c is total tree cover in [%] in the area.

3.3.4 Air pollutant ($PM10$) concentration change

The module calculates the change in air pollutant concentration as:

$$\Delta C = \frac{C}{1 - \frac{I_{total}}{100}} - C \tag{62}$$

where ΔC is the air pollutant concentration change $[\mu g\ m^{-3}]$ for $PM10$, and C is the air pollutant concentration $[\mu g\ m^{-3}]$ for $PM10$.

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