Supplementary Material 3 – Additional details on the urban forest model

1. Components and interactions in the modelling framework

The main components of the modelling framework (foreground and background levels) and their relations are summarised in Figure S1 (Babi Almenar et al (in review)). Four modules compose the foreground: Atmosphere, NBS Inputs, NBS cells, and Outputs (including ES). Four parts compose the background: quantification of ES strongly dependent on NBS-landscape interactions (not considered in NBenefit$ yet), the LCA calculation of negative environmental impacts, the monetisation of environmental impacts as externalities, and the quantification of financial costs.

This supplementary material introduces the foreground modules, and later describe them specifically for the urban forest model that is currently integrated in NBenefit$, and was developed and presented in Babi Almenar et al (in review). The logic and calculations developed in the background model are already well described in the paper. For further details, about the modelling framework, the specific urban forest models, or specific equations, please consult Babi Almenar et al (in review).

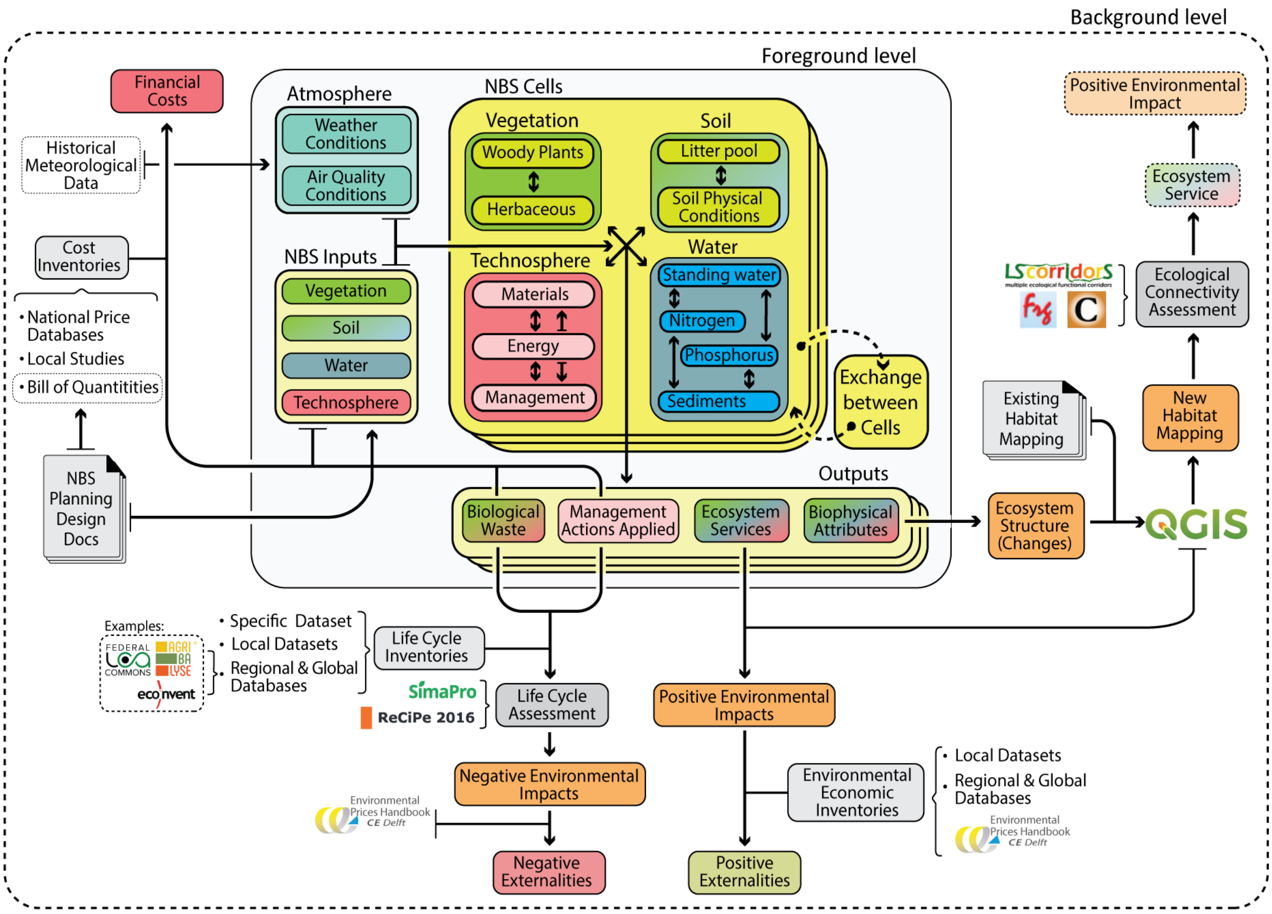

Figure S1. Diagram of the main interactions among the components of the modelling framework (Babi Almenar et al (in review)).

The Atmosphere module is defined as a daily weather generator that estimate weather and air quality variables based on statistical parameters derived from long-term historical weather data. It is formed by the sub-modules *weather conditions* and *air quality conditions*. The values estimated apply equally to all the NBS cells. It is the only module whose outputs (intermediate outputs for NBenefit$) are not calculated per cell but for the entire NBS project.

The NBS inputs module is composed of the sub-modules *vegetation*, *soil*, *water* and *technosphere*. It contains the parametrisation of variables influencing socio-ecological processes in the model, which changes according to the categorical variations in NBS attributes (biotic, abiotic and management)

The NBS cells module is also composed of the sub-modules *vegetation*, *soil*, *water* and *technosphere*. NBS interventions are split in multiple NBS cells of few square metres. The cell is the minimum divisible unit whose attributes and behaviours are spatially homogeneous. The NBS cells module quantifies changes in biophysical attributes, socio-ecological processes, their derived ES flows and biological waste, and applied management actions up to the thematic resolution available.

The *vegetation* sub-module is formed by the compartments *woody plants* and *herbaceous plants*. This sub-module is where vegetation growth is quantified together with associated changes in biophysical attributes (e.g., root depth, leaf area). These changes influence processes such as rain interception, transpiration, evaporation, air pollution filtration and biological waste generation.

The *soil* sub-module is formed by the compartments *litter pools* and the *soil physical conditions*. The former contains the soil biotic conditions and it is where the litter, humus and microbiota interact. The latter is where physical conditions such as percentage of clay or soil bulk density are defined. The interactions in the soil sub-module influence litter decomposition, soil carbon emission, soil evaporation, water storage, plant transpiration, plant morbidity and actions such as irrigation.

The *water* sub-module is used to represent NBS that form part of aquatic ecosystems (e.g., naturalised ponds, constructed wetlands) and includes the following compartments: *free-standing water*, *nitrogen pool*, *phosphorus pool*, and *sediments* (settling of suspended solid).

The *technosphere* sub-module is composed of the compartments *stocks of materials*, *energy*, and *management actions* used in NBS. In this sense, material, energy and human management actions applied on NBS, which consume material and energy has been represented in this submodule. The management compartment represents human activities applied on NBS over time.

The *Outputs* module stores four type of outputs: biological waste, management actions, ES and biophysical attributes. Quantifying biological waste (i.e., dead wood and leaf litter) permits the calculation of waste disposal and waste treatment in the background level. Only dead organic matter collected (a management action) is counted as biological waste. Collection can variate per each cell, since dead organic matter can be left to decompose, and therefore retained in the *soil* sub-module. Accounting for the management actions allows the quantification of their embedded financial cost, environmental impacts and associated externalities in the background level. ES outputs represent the positive environmental impacts generated by NBS during their use phase, for which quantifications do not strongly depend on landscape characteristics. Quantifying changes in biophysical attributes of NBS permits to capture short and long-term variations in urban ecosystem conditions.

2. Urban forest model: specific foreground model

From the conceptual modelling framework, a specific system dynamics model (foreground level) for urban forest was built (Figure S2). It was developed making use of SIMILE (https://www.simulistics.com/).

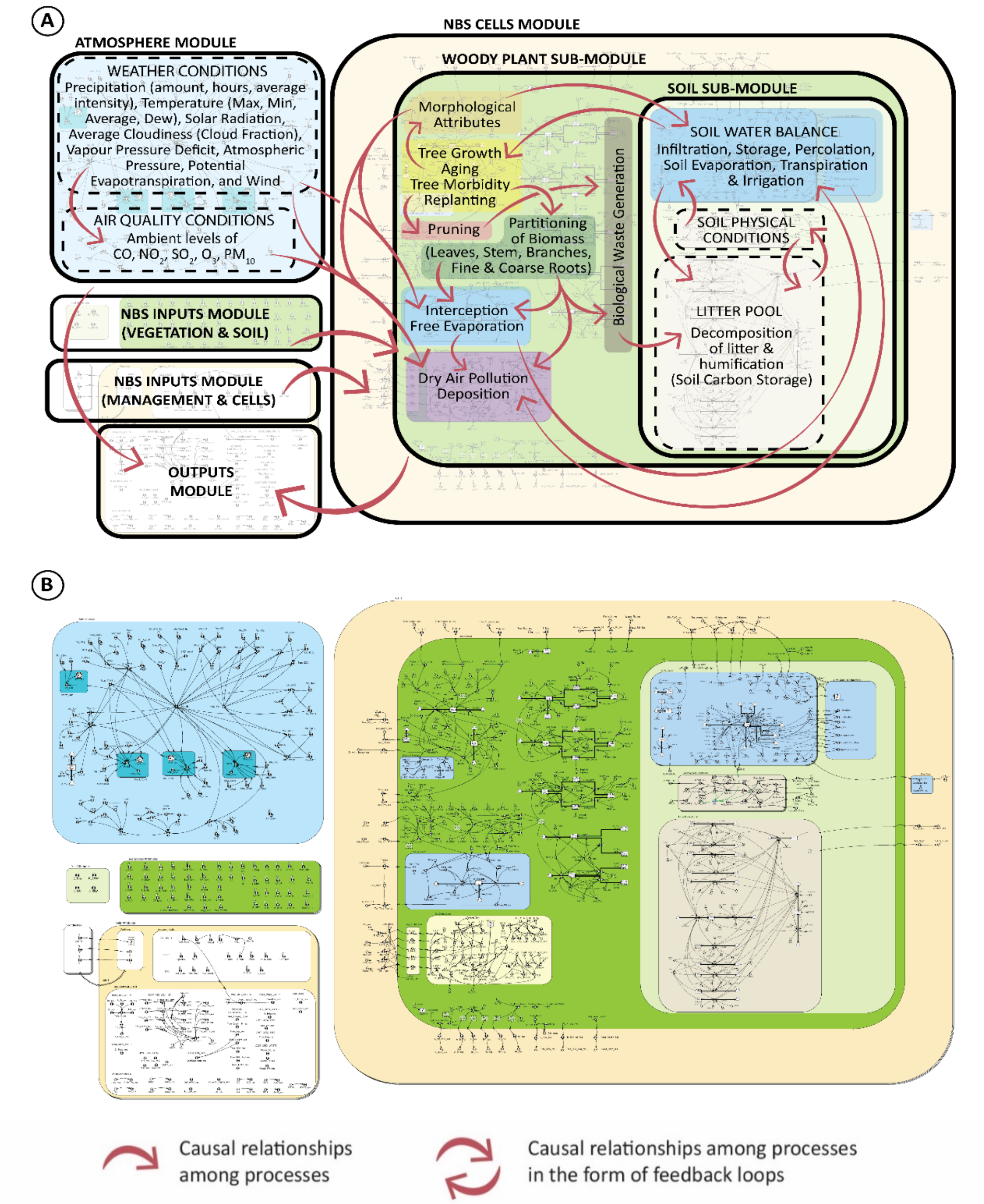

Figure S2. (**A**) Schematic representation of the urban forest model; (**B**) Visual declarative representation of the urban forest model in SIMILE (Babi Almenar et al (in review)).

The urban forest model uses a temporal extent of 50 years and daily, monthly and yearly temporal resolutions. The NBS cells are defined at a spatial resolution of 10m x 10m and assuming a maximum of four trees per cell. Urban forests usually have a low tree density, hence a maximum tree density of 25 m^2 per tree is assumed realistic. Categorical attributes (e.g., tree species, soil texture) inside a cell should be homogeneous, since it is the minimum modelling unit. In terms of the thematic extent and resolution, as already illustrated in the paper, categorical variations are included for the following attributes (Figure S3): climate, tree species, soil texture, soil cover, paving, irrigation, pruning, and intensity of biological waste removal. Their specific combination define an urban forest archetype. Since categorical attributes inside a cell need to be homogeneous, they can only contain one archetype.

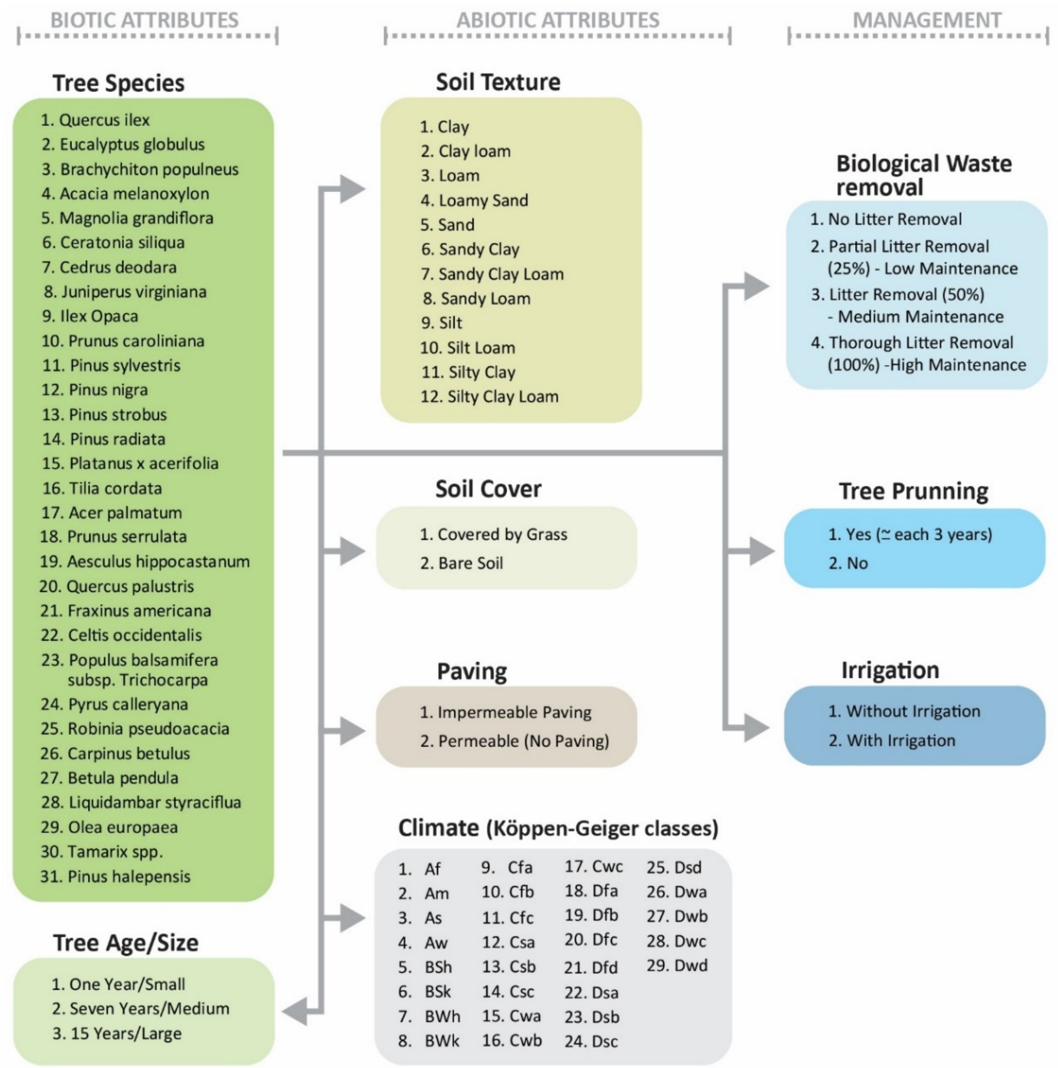

Figure S3. Thematic resolution of biotic, abiotic and management attributes of the urban forest model.

2.1. Description of the main structure of the system dynamics model and the modelled processes

As described in Section 1, the system dynamics model is composed of four modules: Atmosphere, NBS Inputs, NBS cells, and Outputs. They interact with each other to generate the outputs.

1.1. Atmosphere module

The atmosphere module is a stochastic weather generator that simulates daily weather and air quality variables that are required for the socio-ecological processes modelled in the NBS cell module. This module requires daily historical data as inputs to compute the parameters defining the statistical distribution of the atmospheric variables (list of variables included in Weather Conditions in Figure S3). These parameters are then used by the daily weather generator. They could be adjusted to represent variations result of climate change scenarios or other type of scenario (e.g. progressive changes in vehicles engines leading to reduction on ambient levels of specific air pollutants). In terms of the historical baseline, to ensure an adequate accuracy, the historical data should be obtained from close monitoring stations or as a substitute from remote sensing data with enough spatial and temporal resolution. The generation of daily values representative of the local conditions are preferred to a direct use of historical data because i) the behaviour of the NBS is not compared always against the same values; ii) temporal extents can be adjusted more freely; and iii) modifications in statistical parameters used as inputs could permit a representation of future transitions in local weather and/or air quality conditions.

The simulation of precipitation, wind, and atmospheric pressure considers variations in the statistical distribution of variables at monthly level to acknowledge the seasonal changes over the year. Previous studies showed that air temperature and solar radiation of wet and dry days in the same month require many times an independent parametrisation of the statistical distribution (A D Nicks & Harp, 1980; Richardson, 1981). Consequently, besides monthly variations, the simulation of air temperature and solar radiation also considers variations in the statistical distribution of variables between rainy and non-rainy days inside each month. The occurrence and amount of precipitation and average wind speed is modelled according to the CLIGEN model of the USDA developed by Nicks (1975). The duration of the daily storm event is modelled according to the CLIGEN model, the documentation of the EPIC model (Sharpley & Williams, 1990) and Lobo et al. (2015). Air temperature (max, min, average and dew) and average solar radiation are modelled following the equations defined by Nicks (1975) and Nicks and Harp (1980). Average cloud fraction is modelled based on the adaptation of the Angstrom-Prescott model defined by Luo, Hamilton and Han (2010). Potential evapotranspiration is modelled according to the Hargreaves method, (Hargreaves & Samani, 1985), since it only requires air temperature as input data. Modelling evapotranspiration according to the Penman-Monteith equation is usually preferred. However, it requires a parametrisation of an excessive number of variables, including woody plant attributes, that was not possible to characterise for a long temporal extension. Vapour pressure deficit is modelled using the method described in the FAO guidelines (Allen et al., 1998).

The modelling of air pollutant ambient level is also generated with stochastic simulation following the same logic than for weather variables. Several authors have illustrated that independently of the specific urban context and the average temporal resolution used common air pollutants such as CO, SO, O_3, NO_2 and PM_{10} follow log normal frequency distributions (Larsen, 1971; Bencala and Seinfeld, 1976). Additionally, many scholars have shown that pollutant species variate over the year having periods of higher concentration in certain seasons (Fernández Jiménez et al., 2003; Kassomenos et al., 2014; Salvador et al., 2011). For example, SO_2, CO and NOx are higher in winter and O_3 is higher in summer. PM_{10} usually is higher in winter, but also during days of high atmospheric pressure. Instead, $PM_{2.5}$ tend to be higher in summer. In general, pollutants' concentration is influenced by mixing depth (influenced by air temperature) and wind speed. Moreover, some air pollutants, especially PM_{10} and $PM_{2.5}$ are lower during rainy days. Based on the above evidence, air pollutants are simulated stochastically according to a log-normal distribution differentiating variations in statistical distribution by month and by rainy or non-rainy day.

1.2. Woody plant module

The woody plant module simulates the following processes:

i) tree growth;
ii) the partition of the tree biomass in different compartments (stem, branches, foliage, coarse roots, and fine roots);
iii) changes in biophysical attributes (crown diameter, crown height, tree height, root area and root depth);
iv) tree evaporation;
v) the interception of rainfall by canopy;
vi) air pollutants removal (CO, SO_2, NO_2, O_3 and PM_{10});
vii) tree morbidity; and

viii) biological waste generation by each tree compartment naturally or as a result of management actions.

First, the module calculates the increase of the diameter at breast height (Dbh) per monthly time step making use of available allometric equations for trees species in urban areas. Most of the allometric equations Age-Dbh parametrised in the library of the NBS inputs module have been obtained from the Urban Tree Database (McPherson et al., 2016). Growth-reducing factors are applied to the standard radial growth rate to mimic the effect of drought (based on tree drought tolerance index of Ninements and Valladares (2006)) or paved conditions.

Once the Dbh by timestep is obtained, the model uses it as intermediate input to calculate the dry biomass stocks of each compartment (i.e. stem, branches, roots, foliage biomass and leaf area) based by default on the allometric equations of Forrester et al. (2017) and McPherson, van Doorn and Peper (2016), unless local allometric equations are not available. The modelling of biomass growth is needed to compute tree carbon storage and biological waste generation. Biophysical attributes such as tree height, crown radius and crown height are also modelled mainly through allometric equations from the Urban Tree Database. Crown radius will permit the calculation of the canopy area per cell, needed to obtain leaf area index (LAI). The tree root area is modelled by assuming it equivalent to the root protection area as defined by the British Standards 5837:2012 (British Standards, 2012). Tree root area and root depth, based on (Soares & Almeida, 2001) defines how much of the water available in soil is directly available to trees.

Leaf area per time step is used to calculate LAI per canopy area, which together with the ratio of cell covered by the tree canopy is used to model daily canopy interception and free tree evaporation. To use LAI per canopy area instead of LAI per cell area allows modelling more accurately socio-ecological processes controlled by thresholds when trees are very small and when their crowns are very large and overpass the area of the cells. LAI and the soil water balance are used to estimate daily tree transpiration and soil evaporation based on SWAT model equations (Neitsch et al., 2011). LAI together with tree height, tree transpiration, and most of the variables of the atmosphere module are used to calculate dry deposition of the different pollutants based on i-Tree ECO equations adjusted to daily time steps instead of hourly time steps (Hirabayashi, 2013, 2016).

All the ES flows are constrained by tree mortality, which is simulated through stochastic equations to account for the variation of this ecological process. It would be difficult to treat mortality as a deterministic process, especially since the causes of death, their importance, and interrelation are still not fully understood. The default death probability included in the model relies on the tree death statistics of Nowak, Kuroda and Crane (2004) for Baltimore[1], which are related to the different Dbh (age) of trees. Additionally, probability of death increases beyond the default probability depending on three stressors (i.e. drought, waterlogging, and paved conditions). These stressors are among the most relevant for growth and death for which roughly quantitative characterisations are discussed in the scientific literature (Chen et al., 2017; Ko et al., 2015b, 2015a; Koeser et al., 2014; Nowak et al., 2004; Roman et al., 2014; Roman & Scatena, 2011). Moreover, the stochastic equation always includes a residual probability of death even if none stressors occur, to account for unobserved and exogenous stressors (e.g. pests) influencing death. The use of stochastic equations for the assessment of NBS requires to replicate simulations several times to ensure that the mean and standard deviation of each output are representative of the range of potential values.

Plant litter generation is calculated making use of the biomass per compartment, which permits differentiation of the type of waste. Stem residues are only produced once a tree dies. Branch residues comprise dead branches, pruned branches, or all the branches if a tree dies. Leaf litter is calculated making use of leaf turnover rates characterised for evergreen broadleaves, deciduous broadleaves, and coniferous in BIOME-BGC model (White et al., 2000). In the case of tree death, all the foliage becomes plant litter. Roots are split in fine roots and coarse roots following White et al. (2000). Fine roots turnover is modelled as in BIOME-BGC and coarse roots turnover only occurs if tree dies. Plant litter produced in the roots compartment serve as input in the organic matter decomposition process simulated in the soil module and cannot be accounted as biological waste removed from site by management actions. All residues are split into a decomposable fraction (more easily degradable) and a resistant fraction, according to the parametrisation described in Shirato and Yokozawa (2006). If residues are not collected as biological waste, they become inputs of the soil module to calculate soil carbon storage.

1.3. Soil module

The soil module simulates the following processes, which are needed to estimate the soil water balance:

i) litter decomposition and organic carbon retained in the soil;

[1] The parametrisation of the stochastic equation could be adjusted according to local statistics of tree death if those are available.

ii) infiltration of throughfall (i.e. net rainfall after interception) and associated overflow;

iii) percolation;

iv) soil water movement due to water pressure gradients;

v) soil evaporation;

vi) tree transpiration; and

vii) irrigation.

The soil module assumes a maximum root depth of two meters, and it is split by default in eight horizons of 25 cm depth. Litter decomposition and additional organic carbon retention is only modelled in the topsoil horizon. The soil is split in horizons to permit a more accurate modelling of the available water for plants over their growth. The depth of each horizon and its specific soil physical conditions can be adjusted on a case by case basis.

The maximum root depth is defined based on the work of Crow (2005). He indicates that usually tree roots, especially in artificialized environments, do not penetrate a depth greater than 2 meters. The ones that go more in-depth tend to correspond with species (e.g. *Quercus robur*) that maintain the growth of their tap root (i.e. primary vertical root) at adulthood. Crow (2005) also illustrates that in general 80-90% of the roots tend to be within the 60 cm of soil, and that a 90-99% stay in the first meter of soil. Day et al. (2010) also describes that in most cases roots are mostly concentrated in the upper 30cm of soil, since they tend to exploit more the upper horizons of soil. Despite it is a generalisation, for the purpose of this proof of concept model two meters of maximum root depth is assumed adequate for all tree species.

The soil physical conditions are defined making use of the equation of Saxton and Rawls (2006), which model the relationship between soil texture (including organic matter), field capacity, wilting point, water content at saturation and saturated hydraulic conductivity. Default values for bulk density are defined per soil texture class making use of the values proposed by USDA for optimal growth of plants (USDA, 2020). Consequently, soil compaction is disregarded as a stressor in the model even if it widely occurs in urban green open spaces.

Organic carbon retention is modelled at monthly time steps. Four compartments are used (decomposable plant material, resistant plant material, humus, and microbial biomass), with equations adapted from the RothC model for agricultural soils (Coleman & Jenkinson, 2014). The decomposable plant material and resistant plant material obtained from the tree model, once converted into carbon, and the initial amount of humus and microbial biomass per cell are used as inputs for the soil module to calculate organic carbon retention. Each fraction of the plant residues decay becoming carbon microbiota, carbon humus, and emitting atmospheric carbon. In all the compartments litter decomposition decay is influenced by the amount of organic matter, the conversion proportions between compartments, the intrinsic decomposition rate constants of each compartment, and the rate modifying factors for temperature, soil moisture and soil cover as established in the original RothC model. The total organic matter present in the model in each time step is calculated as the sum of the organic matter in all the compartments. For changes in the soil physical conditions (soil texture) over time, only the proportion of humified organic carbon is considered and up to a maximum value of an 8 %, because higher values in agricultural or urban soils are very unlikely.

The infiltration of throughfall is modelled at daily time steps considering the soil texture of each soil horizon, which influences water content at saturation (and consequently maximum water storage). Infiltration is based on a pre-calculated infiltration table at hourly level developed outside the model making use of the Green-Ampt method as described in SWMM (Rossman & Huber, 2016). This approach for estimating infiltration is used because it is simple enough, and already widely used in practice since it represents well enough real infiltration rates (Kale & Sahoo, 2011). Its use in the model at daily time steps required to know the values of storm duration, and associated average intensity of daily precipitation, which are calculated in the atmosphere module. The precalculated table is obtained for all the possible changes in the soil of the percentage of sand, clay and silt on a 5% interval. Percolation only occurs when field capacity is overpassed, and it is modelled according to SWAT (Neitsch et al., 2011). Additionally, soil water upward and downward movement to equilibrate water pressure gradients between adjacent horizons are modelled making use of the Darcy's equation as described in the work of Soares and Almeida (2001). The soil water balance is completed with the modelling of tree transpiration and soil evaporation described in the woody plant module. When irrigation is activated as a management action, it only occurs when the available soil water is below a 20% of its potential capacity and it is equivalent to the transpiration demanded by the tree.

As visually illustrated in Figure S3, the four modules and compartments described above interact with each other for the simulation of processes and generation of outputs.

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