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Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle thinking: An application to urban forests

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ABSTRACT

Nature-based solutions (NBS) are gaining relevance as sustainable urban actions because of their potential to provide multiple benefits in the form of ecosystem services (ES), and thus mitigate urban challenges. This paper presents an original semi-dynamic modelling framework that simultaneously considers i) ES supply and demand dynamics, ii) negative environmental impacts, externalities, and financial costs derived from NBS, and iii) life cycle NBS impacts beyond the use phase. Compared to other models, it also aims to be valuable for urban planning actions at site level, i.e., for evaluating the net impacts of specific urban NBS projects. To validate the modelling framework, a proof-of-concept model for urban forests is developed and tested for a case study in Madrid (Spain). The modelling framework is split in two interrelated parts: foreground (dynamic modelling) and background (static modelling). In the foreground, the environmental impacts derived from the use phase of an NBS project are quantified considering its spatio-temporal dynamism, by making use of system dynamics. In the background, the environmental impacts derived from the rest of the life cycle phases of the NBS are quantified making use of steady state life cycle impact assessment. The net economic impact of the NBS project, considering both financial values and externalities, is eventually calculated in the background encompassing all the life cycle phases. Results from the case study illustrate how planning, design, and management decisions over the entire life cycle of an urban forest can influence the net environmental and economic performance of this type of NBS. A discussion is provided to inform on how the modelling framework can help moving beyond the state-of-the-art, and how the derived model can be used for sustainability assessments of urban NBS projects.

1. Introduction

Nature-based solutions (NBS) are being extensively promoted as potentially sustainable and resilient solutions for urban challenges (Cohen-Shacham et al., 2016; Keeler et al., 2019). NBS are defined as solutions supported by nature that contribute to biodiversity conservation and produce environmental, social and/or economic benefits in a cost-effective way (European Commission, 2015). The supply of positive environmental impacts in the form of ecosystem services (ES) is the main way in which NBS can provide benefits and address urban challenges (Eggermont et al., 2015; Potschin et al., 2016). These benefits are also translated into positive social or economic impacts in the form of financial values (i.e., benefits accounted for by the market mechanisms) and/or externalities (i.e., benefits from public goods not accounted for by the market mechanisms). As a result, the suitability of an NBS for a specific urban setting strongly depends on the types and amount of actual ES flows supplied, the existence of cause-effect relationships between these ES and the urban challenges to be addressed, and its overall

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cost-effectiveness (Babí Almenar et al., 2021).

For an accurate quantification of urban NBS impacts, the temporal and spatial dimensions underpinning ES supply–demand dynamics should be represented adequately (Bagstad et al., 2013; Elliot et al., 2019). These dynamics are in part dependent on variations in ecological pressures and ecosystem conditions (Sutherland et al., 2018), which are not usually captured by urban ES models (Ouyang and Luo, 2022). As summarised by Grêt-Regamey et al. (2017), many models proposed in the literature also present (a combination of) the following limitations: i) limited number of ES assessed, ii) lack of monetary valuation, and iii) lack of a characterisation of the outputs uncertainty. Moreover, urban NBS studies do not usually consider negative environmental impacts or disservices derived from NBS (Keeler et al., 2019; Larrey-Lassalle et al., 2022), burdens that sometimes occur off-site and are delayed on time (Pascual et al., 2017). This is also the case for detailed monetary valuations assessing urban NBS cost-effectiveness, which tend to account only for ES values and seldom for negative externalities (i.e., costs not accounted by the market mechanisms) or financial costs derived from NBS.

Urban NBS assessments also tend to overlook environmental and economic impacts occurring outside the "use phase" of the NBS. In other words, impacts generated by life cycle processes occurring upstream (i.e., those relying to the production of plants and other NBS components, and their transportation in situ; hereinafter "NBS implementation phase") or downstream the use phase (i.e., once the entire NBS or some of its plants are removed or die; hereinafter "NBS end-of-life phase"), are usually disregarded (Larrey-Lassalle et al., 2022). Despite studies addressing the abovementioned issues are emerging, (e.g., Chaplin-Kramer et al.(2017), Elliot et al., (2022a), Larrey-Lassalle et al. (2022)), some limitations still occur in current models and studies evaluating (or informing the decision making of) specific urban NBS interventions, and their long term overall cost-effectiveness. For further information, a summary of life-cycle phases, processes and ES, and spatial levels considered in existing urban ES modelling tools is included in the Supplementary Material 1.

To address gaps regarding the integration of financial costs and monetary valuation of ES in NBS assessments, some scholars have considered life cycle thinking methods such as life cycle costing (LCC) (Bianchini and Hewage, 2012; Perini and Rosasco, 2013). LCC account for financial costs and externalities, transforming them into monetary flows over the entire life cycle of a project or product (Swarr et al., 2011). Emergent variants of LCC are becoming aligned with assessments such as cost-benefit analysis (Hoogmartens et al., 2014; Schaubroeck et al., 2019). Accounting for environmental and economic impacts, both positive (beneficial) and negative (detrimental), may allow to understand the net contribution of NBS to urban sustainability and resilience. Other life cycle thinking methods applied to NBS, e.g., life cycle assessment (LCA), can help quantifying their negative environmental impacts along life cycle phases other than the use phase (Larrey-Lassalle et al., 2022). LCA is aligned and consistent with many variants of LCC, such as environmental LCC (Hoogmartens et al., 2014). Additionally, with LCA impact assessments can be performed at midpoint level (Rosenbaum et al., 2018), representing potential negative environmental impacts as responses of direct and indirect environmental stressors (e.g., pollutants emissions), such as global warming or eutrophication (Hauschild et al., 2018). The methodological framework of LCA is standardised according to ISO 14040:2006 and 14044:2006, which makes it suitable for robust assessments of any product system, including NBS (see Hauschild et al. (2018) for further details about LCA, including steps and standards). Many ES classes are measured using physical metrics also used by midpoint LCA indicators, e.g., CO_2, and both refer to environmental effect categories with a similar level of conceptual abstraction, e.g., carbon sequestration vs global warming potential. As a result, LCA and LCC offer suitable methodological background to account for ES, even if little interaction still exists between ES and LCA fields (Vanderwilde and Newell, 2021).

This paper presents a semi-dynamic modelling framework that combines LCA, LCC and ES to assess the net environmental and economic impacts of NBS at site level. The framework is used to derive a proof-of-concept model applied to urban forests, and it integrates spatio-temporal explicit non-linear modelling (represented by a system dynamics model of NBS), and static modelling applying LCA principles.

2. Methods

This section is organised in three parts: i) conceptualisation of the modelling framework; ii) description of the proof-of-concept model for urban forests; and iii) description of the case study, where the proof-of-concept model is tested. ES classes correspond to the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2018), and the life cycle impact assessment midpoint categories to the ReCiPe 2016 method (Huijbregts et al., 2017). The Environmental Footprint 3.0 (Zampori and Pant, 2019) was also tested as a potentially alternative life cycle impact assessment method (see Supplementary Material 2 for details about the testing results).

2.1. Conceptualisation of the semi-dynamic modelling framework

To capture positive and negative environmental and economic impacts arising at different points in time and space, the modelling framework covers all the life cycle phases of NBS (i.e., implementation phase, use phase, and end-of-life phase), as visualised in Fig. 1. By accounting for financial benefits, financial costs and externalities generated over the entire life cycle of NBS, the framework is aligned with the principles of full environmental LCC and environmental cost-benefit analysis described by Hoogmartens et al. (2014).

The modelling framework only accounts as outputs for the actual ES flows (ES use flows) and their variations over time, as understood in the System of Environmental Economic Accounting – Ecosystem Accounting (United Nations et al., 2021). In short, it quantifies ES supply flows over time and only retains them as output if fulfilling an existing ES demand at the time of supply. For many ES classes, it is assumed that there is always an ES demand. When an ES class has a global character, such as for *CO_2 storage* (*global climate regulation in CICES*), irrespectively of the amount of ES supplied, the demand will never be fully covered in current circumstances. In other cases, the demand may have a local or regional character (e.g., *filtration of air pollutants by plants*). However, due to outputs of other human activities (e.g., air pollutants emission), such demand is expected to be always required in urban areas. Finally, there are cases when ES are demanded by citizens only if specific thresholds are exceeded. The latest is the case of *regulation of temperature & humidity* in the form of cooling, which is relevant only in the hottest periods of the year.

To balance data requirements and computational demand, the framework captures changes in flows of outputs at different spatial, temporal, and thematic resolutions, and it is developed at two levels: foreground (system dynamics model) and background (static or steady state model).

2.1.1. Spatial, temporal and thematic extent and resolution of the foreground and background levels

In the foreground level, the spatial extent is framed at the neighbourhood level. It applies a default spatial resolution of a few meters, splitting each NBS intervention in multiple cells (smallest modelling unit) that can characterise changes in NBS types (e.g., urban forest, green roof) or variations in a specific type, even inside the same NBS project.

In terms of the temporal dimension, the foreground level includes three temporal resolutions (daily, monthly and yearly) and temporal extents of some decades. A daily time-step is used for those ES flows related to socio-ecological processes and pressures with fast variations over time (e.g., plant transpiration, thermal comfort) to capture changes

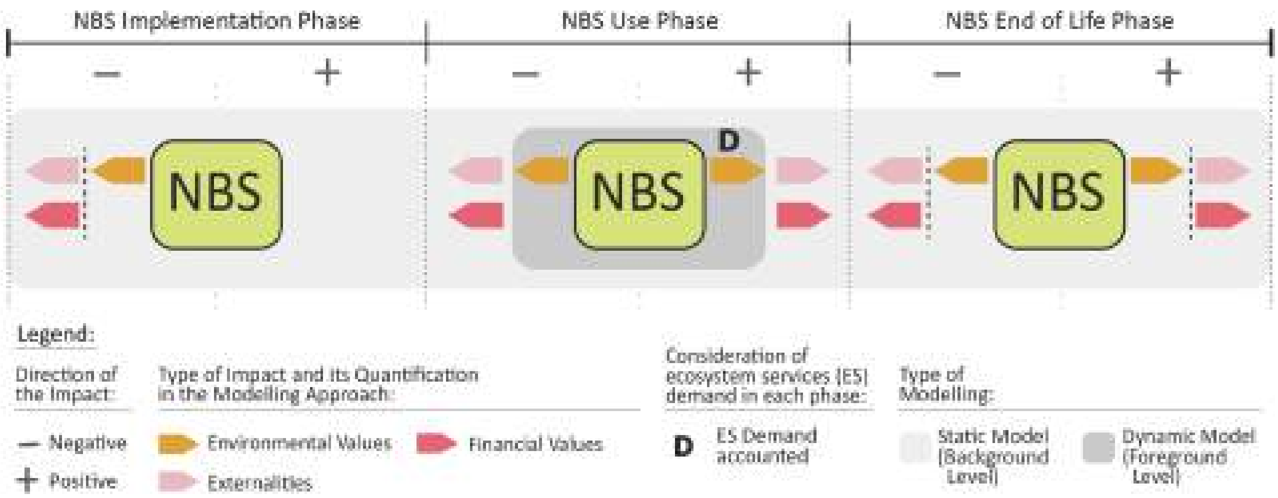


Fig. 1. Conceptualisation of the modelling framework proposed in this paper with respect to environmental and economic impacts, NBS life cycle phases, integration of ES demand, and spatio-temporal dynamism.

in ES supply and benefits (e.g., temperature and humidity regulation) that occur at very short time (Almeida and Sands, 2016). A daily time step is also used to capture variations over time in the application of certain management actions and the estimation of their amount (e.g., volumes of irrigation water). A monthly time-step is used for processes where changes are seasonal or for which assuming a monthly linear behaviour (e.g., shrubs and tree growth) do not lead to meaningful inaccuracies. The yearly time-step is used for aggregating intermediate outputs and when changes in actual ES flows over several years need to be quantified.

The temporal extent (lifetime) spans several decades because it aims to cover the entire NBS use phase. Where urban NBS are implemented to remain over several human generations, the temporal extent should cover up to when major modifications are expected or the social actors bearing their costs and benefits change. Previous studies have considered 50 years as the default NBS use phase (Broun et al., 2014; Ottelé et al., 2011; Perini and Rosasco, 2013). Framing the lifetime (NBS use phase) as explained above ensures that the overall contribution of NBS to sustainability and resilience is considered inside a temporal extent equivalent to an adult generation.

To adequately simulate variations in the flows of ES, materials, energy and management actions of different NBS projects, the foreground level includes several attributes, among which abiotic, biotic and NBS management parameters. Those represent the thematic extent of the modelling framework, which also provides detailed variations in each of those attributes as discrete classes (e.g., vegetation species, tree size at planting, soil texture). The latter represent the thematic resolution of the model per input attribute. Differentiating input attributes at a fine thematic resolution permits discerning variations over time in flows even when assessing alternatives of the same urban NBS Type (e.g., urban forest) for which there are only slight variations in a few input attributes (e.g., age at which trees were planted, percentage of a certain tree species planted).

Unlike the foreground level, the background level assumes a static condition (i.e., time is not an independent variable) and relies on LCA, ecological connectivity modelling and economic valuation methods to calculate final environmental and economic outputs. It uses a lower thematic resolution for land components, defined as land cover/use classes. Moreover, the calculation of outputs for the implementation and end-of-life phases are not spatially explicit. These simplifications in the background level were deemed necessary due to limitations in input data requirements and otherwise excessive computational power, which among others aspects hamper applying a fully dynamic LCA approach as outlined in state-of-the-art studies on dynamic LCA (Sohn et al., 2020). The use of a static condition and the non-spatialisation of some phases permits the use of a broad set of databases and inventories, which is a common practice in LCA.

2.1.2. Main components of the conceptual modelling framework and their interactions

The main components and interactions among the foreground and background level are visualised in Fig. 2.

The foreground level is composed of four modules: Atmosphere, NBS Inputs, NBS cells, and Outputs. Flows of ES, materials, energy, and management actions associated with an NBS over time are modelled concurrently through the interaction of the above modules and their sub-modules. In this sense, the foreground model represents an integrated model where ES are neither quantified from models applied independently, nor estimated independently from other flows (e.g., management actions). In other words, changes in ES and other flows over time are modelled together. This means that intermediate variables (i.e., attributes or ecosystem processes), and their values per time step, influencing the supply of different ES classes as well as other flows are shared. This also means that the foreground model includes feedback loops between components of each module or sub-module influencing different flows.

The background level is composed of four parts: i) the quantification of ES strongly dependent on NBS-landscape interactions, ii) the LCA calculation of negative environmental impacts, iii) the monetisation of environmental impacts as externalities, and iv) the quantification of financial costs.

The following paragraphs provide further details about the components of the foreground and background levels and briefly anticipate the interactions occurring between modules in the foreground level. Detailed explanations are provided in the Supplementary Materials 3 and 4.

The Atmosphere module is defined as a generator of daily values of weather and air quality variables, based on statistical parameters derived from long-term data. The sub-module *weather conditions* characterises the daily temperature (average, maximum, minimum and dew), vapour pressure deficit, precipitation, average wind speed, atmospheric pressure, cloud fraction and solar radiation. The sub-module *air quality conditions* characterises the daily average ambient levels (i.e., atmospheric concentration) of air pollutants (i.e., CO, SO_2, NO_2, O_3 and PM_{10}) commonly used in the definition of well-known air quality index such as AQI, CAQI or EAQI (further details on air quality indexes in Tan et al., 2021). The estimated values apply equally to all the cells of a specific NBS project, being the only module where values per time step

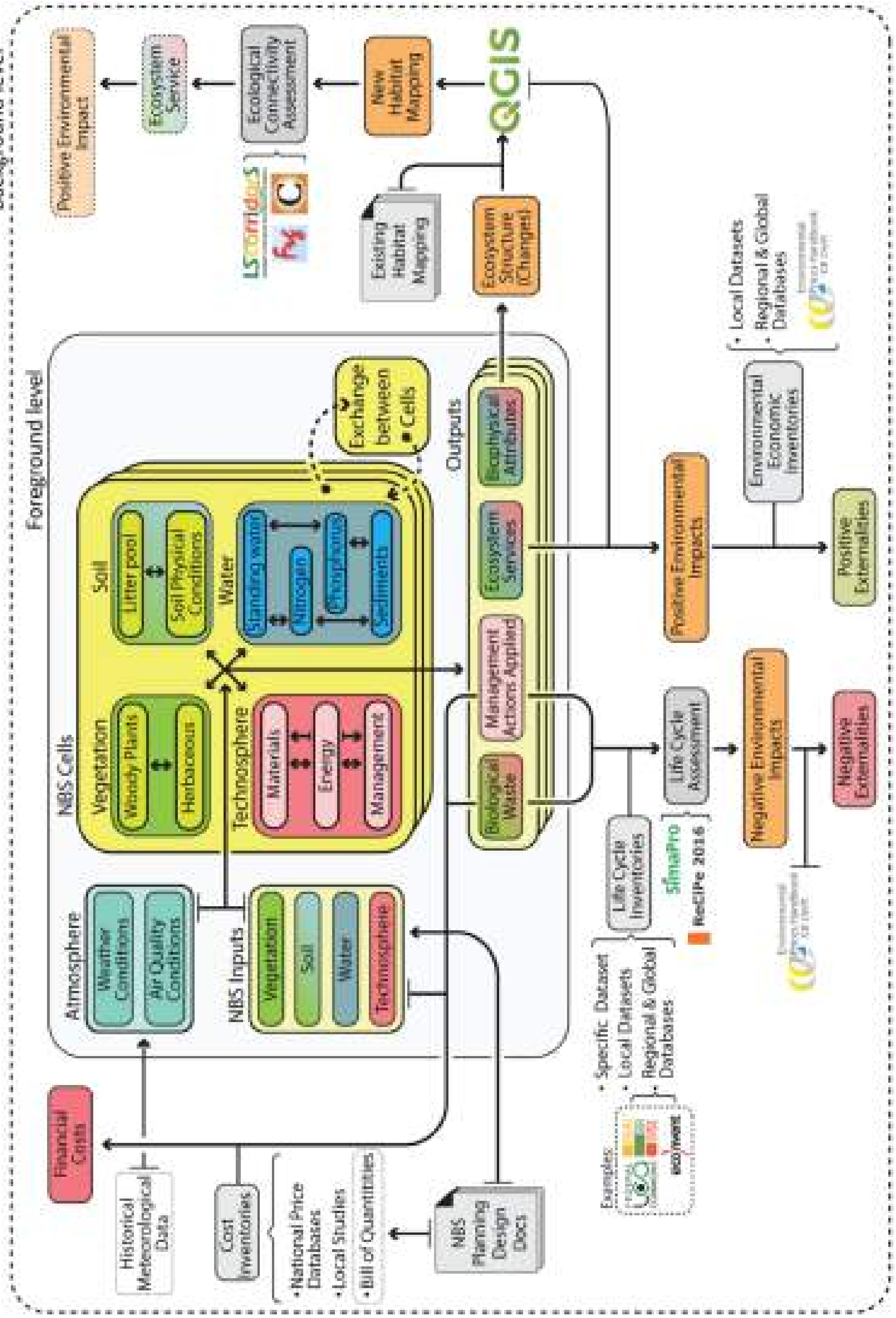


Fig. 2. Outline of the main interactions among the components of the modelling framework. For simplicity, NBS cells are represented as individual entities even if this might not always be the case.

are not calculated cell by cell.

The NBS inputs module is composed of the sub-modules *vegetation*, *soil*, *water* and *technosphere* (Fig. 2). It contains the parametrisation of variables influencing socio-ecological processes in the model, which changes according to the NBS attributes (biotic, abiotic and management). The NBS attributes proposed in the project, or most similar substitutes, are identified per NBS cell based on the NBS planning and design documentation. Only attributes (e.g., plant species, soil types, management actions) already parametrised can be assessed for specific urban NBS interventions. Thus, it is necessary to represent an extensive library of categorical variations in NBS attributes to adequately assess complex urban NBS interventions.

The NBS cells module is also composed of the sub-modules *vegetation*, *soil*, *water* and *technosphere* (Fig. 2). NBS interventions are split in multiple NBS cells of a few square metres. The NBS cells module quantifies changes over time in biophysical attributes, socio-ecological processes, their derived ES flows and biological waste, and applied management actions.

The *vegetation* sub-module is formed by the compartments *woody plants* and *herbaceous plants*. They are treated separately because they differ in terms of growth behaviour and socio-ecological processes. These compartments' presence depends on the NBS type (e.g., woody plants may not be found in green roofs or green walls). This sub-module is where vegetation growth is quantified together with associated changes in biophysical attributes (e.g., root depth, leaf area). The variation in those attributes (and their rate of variation) over time depends on interactions with variables of other modules. For example, precipitation influences soil water balance, which influences tree growth, and therefore, tree biomass and leaf area. Similarly, changes in the values of biophysical attributes such as leaf area influence processes such as rain interception, transpiration, evaporation, air pollution filtration and biological waste generation, which occur in other sub-modules and influence the generation of multiple output flows over time.

The *soil* sub-module is formed by the compartments *litter pools* and the *soil physical conditions*. The former contains the soil biotic conditions and models the interactions between the litter, humus and microbiota. The latter defines soil physical conditions such as percentage of clay or soil bulk density. The interactions in the soil sub-module influence litter decomposition, soil carbon emission, soil evaporation, and water storage. They also influence the processes occurring in other sub-modules, such as plant transpiration and plant morbidity, and management actions, such as irrigation, which eventually lead to changes in outputs over time.

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 free-standing water defines a simple water balance model of the NBS. The nitrogen pool is the compartment that calculates mineralisation/nitrification, denitrification, and volatilisation processes. The phosphorus compartment and the sediment compartment model the interactions influencing the removal of phosphorus through settling.

The *technosphere* (well-established concept in LCA) is composed of the compartments *stocks of materials*, *energy*, and *management actions* used in a specific NBS intervention. Such *technosphere* submodule accounts for the use of materials and energy from the natural system or generated in earlier production processes associated with an NBS project. The consumption of materials and energy are relevant sources of impacts in hybrid NBS such as green roofs or green walls, but also in NBS such as urban forests. In these cases, actions of irrigation, pruning, replanting, and removal of biowaste (e.g., leaf litter) over time underpin an environmental pressure (e.g., through the use of fuels and the release of emissions) that generates negative environmental impacts and financial costs. The management compartment represents human activities applied over time on *vegetation*, *soil*, and *water* sub-modules in a specific NBS intervention. They influence the values of biophysical attributes in those sub-modules, which influence in turn the output flows. For example, actions such as pruning will change i) the amount of branch biomass, which will influence the carbon storage of the NBS, and ii) the leaf area, which will influence processes such as evapotranspiration and interception, and the ES flows depending on them. In this sense, management actions represent non-physical attributes, and might help to inform on the effects (e.g., changes in ES flows) of applying NBS Type 1, i.e., better management, or NBS Type 2, i.e., partial restoration/reclamation, on existing ecosystems and NBS Type 3, i.e., complete ecosystem reclamation or novel ecosystems (Babí Almenar et al., 2021).

The *Outputs* module stores four type of outputs: biological waste, management actions, ES, and biophysical attributes. As introduced in previous paragraphs, these outputs change dynamically as a result of the interaction over time among attributes and processes occurring in different sub-modules. Quantifying biological waste (e.g., dead wood and leaf litter) generated over time permits to calculate afterwards the waste disposal and waste treatment in the background level. Only dead organic matter collected in situ is counted as biological waste. As a management action, collection can be defined for each cell and, when it is not activated in the model, dead organic matter is left to decompose and retained in the *soil* sub-module. As an output, management actions account for changes in the amount of each of them over time. They are related to supply chain processes that in some cases go beyond the use phase. A disaggregated quantification of the total embedded financial cost, environmental impacts, and associated externalities derived from these actions is calculated 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. Biophysical attributes and changes in ecosystem condition are used in the background level as inputs for finalising the quantification of ES dependent on the interaction between the NBS and its surrounding landscape.

In the background level, only two ES classes are quantified: i) *maintaining nursery populations and habitats*, ii) *characteristics of living systems that enable activities promoting health*. In plain terms, the latter refers to physical recreational activities that occur inside the NBS such as running or walking.

The provision of these two ES classes depends on the type of NBS. For example, green roofs or green walls might provide a limited contribution to maintaining habitats and populations compared to other NBS (Mayrand and Clergeau, 2018). For *maintaining nursery populations and habitats*, changes in biophysical attributes estimated in the foreground level can be used to inform when mature habitat patches in the area of NBS intervention are generated or have disappeared. In the background level, combined ecological connectivity assessments, such as the one proposed in Babí Almenar et al. (2019), could use data on habitat patches in the surrounding landscape to assess whether changes in the NBS intervention (or several) have an effect on ecological connectivity. For *characteristics of living systems that enable activities promoting health,* changes in some of the biophysical attributes (e.g., tree height) quantified in the foreground inform attractiveness over time of the NBS to visitors, which influence the citizens' willingness to walk (in time) to get to the NBS intervention (Filyushkina et al., 2017). By default, the minimum value and maximum value of willingness to walk to green open spaces, grassland-like (i.e., with no woody plants) and mature wooded areas respectively, are the ones estimated by Ta et al (2020) for Paris through a discrete choice experiment. The willingness to walk change over time in relation to changes in specific NBS attributes. In the case of NBS that include woody plants, the main attribute is the average tree height (up to 5 m), which is used as a proxy of maturity. When available, local choice experiments should be run to identify the relevant attributes and estimate their impact on NBS attractiveness. Based on the computed willingness to walk, a network analysis of the landscape, such as those done in functional ecological connectivity analysis, is performed in the background to identify the potential area of population serviced by the NBS intervention. By default, only walking is considered in the modelling framework as a type of mobility, but other means of transportation (e.g., bikes, public transport, cars) could also be incorporated. Further details for this ES class can be found in the descriptions of Supplementary Materials 3 and 4 for the proof-of-concept model.

For the estimation of environmental impacts via LCA, the NBS area and its lifetime is used as the default functional unit, as in previous LCA studies of green roofs and urban forests (Mcpherson et al., 2015; Vacek et al., 2017). Such a simple and straightforward functional unit can suit a large number of NBS types, and permit the association of all the environmental impacts derived from an NBS to an areal unit. In addition, the technosphere processes employed in input and intermediate output management actions (over all the life cycle phases) are documented and quantified making use of life cycle inventories. The bill of quantities of NBS projects are used to partially describe processes related to NBS inputs, such as transport of plants. In most cases, documentation for the life cycle inventories need to be completed with scientific literature and reference life cycle inventory databases. Once the life cycle inventories are completed, the environmental impacts are calculated as LCA midpoint impact categories (Hauschild et al., 2018). These impacts are typically detrimental (negative), except in cases of reutilisation of materials or outputs generated from waste treatment (both occur at the end-of-life phase), which are used as inputs for new technosphere processes.

Positive and negative environmental impacts are monetised in the form of externalities by making use of value transfer approaches. By default, negative environmental impacts and few positive environmental impacts (ES) are monetised based on the environmental prices defined by De Bruyn et al (2018) for the European Union. Several externalities derived from actual ES flows are also computed using the value transfer method based on a review of primary studies collected by Petucco et al (2018). When available, monetary values for environmental impact categories can be obtained from local or regional studies or databases to make it more locally relevant and accurate. In fact, in the case study, the monetisation of few environmental impact categories is based on data from local and regional reports (see Supplementary Material 5 for further details).

Monetary values are always adjusted to a common base (e.g., Euro 2018 for EU-28), when they come from different base years. Those transferred from non-local studies are also corrected for inflation (using the GDP deflector data provided by the World Bank), purchasing power parity (using the PPP exchange rates computed by the World Bank), and, when necessary, by the average income (based on the GDP per capita data in 2010 USD from the World Bank database) to adjust the willingness to pay for an ES to the local economic conditions. When the last adjustment is needed, a unitary income elasticity of Willingness-To-Pay (WTP) is used (Tyllianakis and Skuras 2016). By default, prices and costs are assumed as constant over time, which may not be the case in reality. However, the development of dynamic price models was out of the scope of the current modelling framework and its derived urban forest model.

All externalities are multiplied by a discounting factor, which however is set by default equal to one, meaning discounting is not applied. This decision follows the indications of the Dutch Discount Rate Working Group, as described in De Bruyn et al. (2018). This working group does not recommend discounting the price of externalities generated by future environmental impacts that end damaging human health. It also follows the principles of environmental LCC (Rödger et al., 2018), which do not allow discounting because of intergenerational equity considerations. Nonetheless, if discounting has to be applied, it suffices to set a positive discount rate. Moreover, given the semi-dynamic nature of this modelling framework, it is rather easy to apply a declining discount rate by providing the desired discount rate trajectory.

Financial costs are quantified based on the quantities of inputs and intermediate outputs of the foreground level, which are converted into monetary units making use of available national price databases or market prices from local studies. Some financial costs might be extracted from the planning and design documentation (e.g., draft bill of quantities) of the NBS project being evaluated. For those financial costs, it is not necessary the use of price databases because the value is already known. As for the externalities, the financial costs and benefits are multiplied by the chosen discount factor.

2.2. *A Proof-of-concept model for urban forest*

From the conceptual modelling framework, a system dynamics

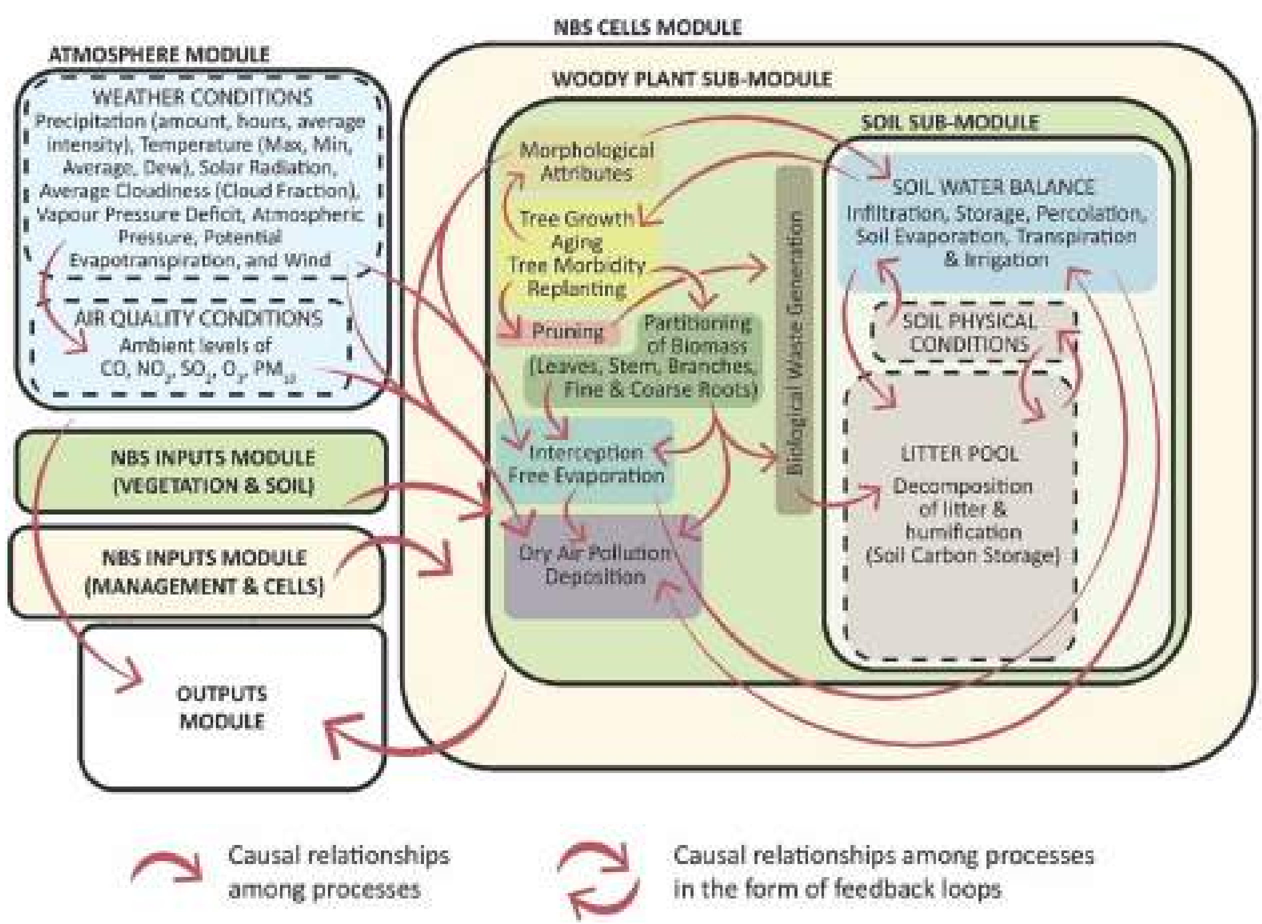


Fig. 3. Schematic representation of the urban forest model. The visual declarative representation of the urban forest model generated in the software SIMILE can be seen with the script of equations in the Supplementary Material 3.

model (the foreground level) specific for urban forest was built (Fig. 3). It was developed making use of SIMILE (https://www.simulistics.com/), a software for visual declarative modelling useful to build spatially-explicit and time-dependent system dynamics models.

The urban forest model uses the default temporal extent of 50 years and daily, monthly, and yearly temporal resolutions. The NBS cells are defined at a default spatial resolution of 10 m × 10 m 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 was considered realistic. For example, in the 26 green open spaces sampled by Cariñanos et al. (2017) as representative of Spanish green open spaces, none of them overcomes a tree density of 25 m^2/tree. In addition, the average crown width for many adult tree species in urban areas is between 5 and 10 m (see crown width of common urban tree species in Chanes and Castano (1969)). Thematic input 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 illustrated in Fig. 4, categorical variations in inputs are included for the following attributes: climate, tree species, soil texture, soil cover, paving, irrigation, pruning, and intensity of biological waste removal.

Fig. 5 summarises the specific outputs calculated in the urban forest model, the indicators used to represent them, and the connections among management actions, environmental impacts, externalities, and life cycle phases. It also indicates which ES and LCA categories are equivalent, i.e., a unique final net environmental impact can be obtained in biophysical units. For further details, Supplementary Material 3 and 4 include the list of equations, a detailed representation of the urban forest model and the explanation of its modules, which adjusts and expands the description provided in this section.

2.3. Application of the urban forest model to a case study

The model was applied to the urban forest of La Mancha, in the south-eastern sector of the Phase I of Valdebebas Park (Fig. 6). This open space is part of a new urban development close to Barajas airport (Madrid, Spain). The Phase I is the only one fully developed for which the Council of Madrid shared the NBS planning and design documentation. Valdebebas Park covers an area of around 140 ha, of which 17.33 ha correspond to La Mancha. Supplementary Material 5 contains the default values used for monetising externalities as well as values of some of them extracted from local and regional studies and reports specific for the case study. Supplementary Material 6 describes technical details about the preparation of the input data for the case study. Supplementary Material 7 includes the details about its life cycle inventory.

Six scenarios were considered, and their cumulative long-term net environmental and economic (financial and externalities) values assessed over 50 years (Fig. 7a). Besides the six scenarios, the individual environmental performance of the urban forest cell types (i.e., specific combination of tree species, tree age at planting, and soil texture) that compose the open space of La Mancha was also assessed (Fig. 7b). Those cell types were compared against (hypothetical) alternatives growing on paved ground (Fig. 7b).

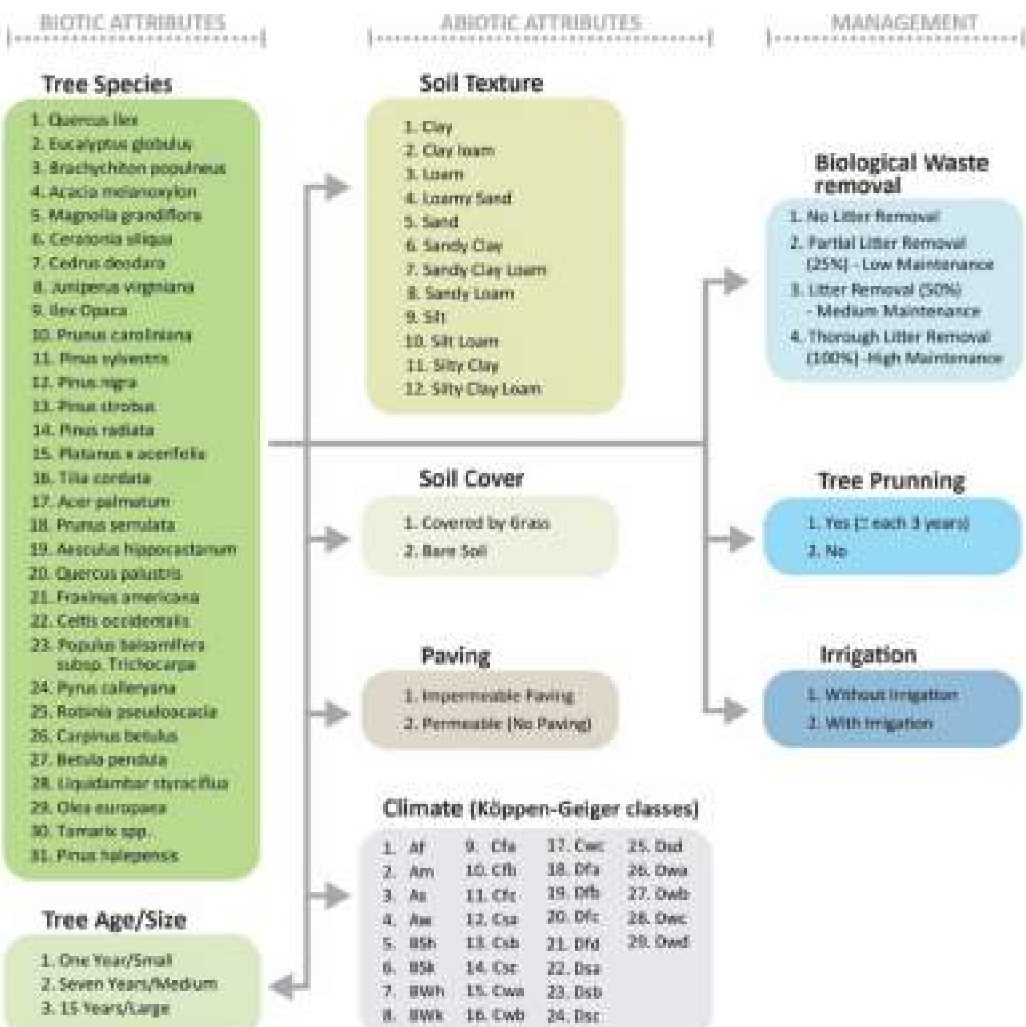
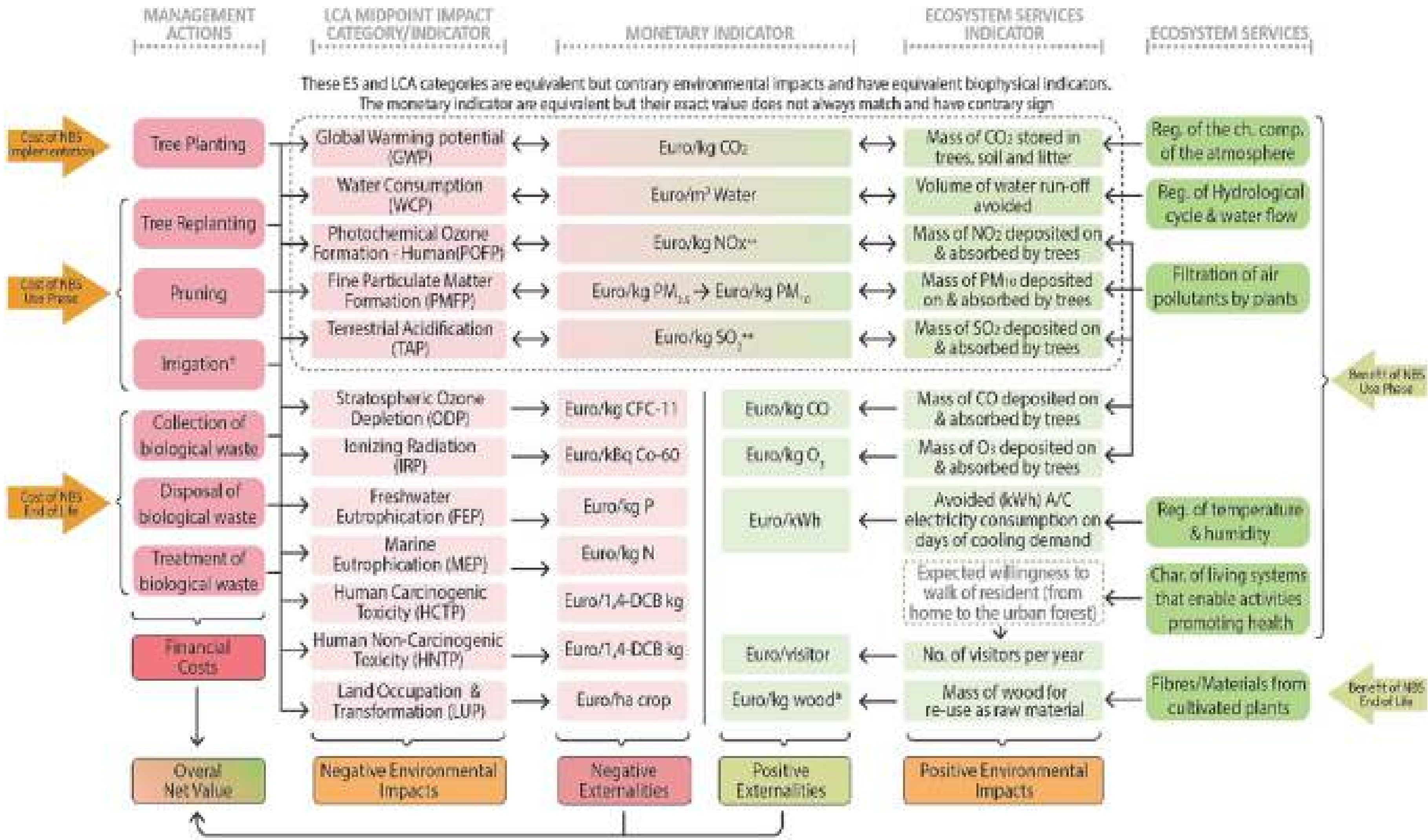


Fig. 4. Thematic resolution of biotic, abiotic and management attributes of the urban forest model.



Note:

* For irrigation only the impact of water use is considered, excluding the one of building the infrastructure. As a result water use only affects the LCA mid-point category water consumption . Moreover, the economic value of irrigation is only considered as part of financial costs. Regional public water authorities in EU (this is the case of river basin authorities in Spain) usually internalise part of the environmental impacts of water consumption when they establish the price of water. Therefore, using the price of water as financial cost and adding a monetisation of the environmental impact would have generated double counting.

** The monetary value Euro/kg NOx and Euro/kg SO_2 for the negative environmental impact category correspond to the monetary value given to the midpoint category in De Bruyn et al. (2018). In the case of ES, the monetary value correspond to the value given to the chemical substance in De Bruyn et al. (2018). Negative environmental impacts in terms of NOx and SO_2 contribute to more categories than POFP and TAP, being the impact of the emission of these substances already included in other categories. In the case of positive environmental impacts from deposition and absorption of this substances we need to account for its overall value since we do not have equivalents for the rest of of LCA categories for which they avoid/mitigate the impact.

Fig. 5. Ecosystem services and management actions considered in the urban forest model, their interrelation and their conversion to negative and positive environmental impacts, financial costs and positive and negative externalities. Each cost (output), except irrigation, contributes to all the environmental impacts represented by the LCA midpoint impact categories included.

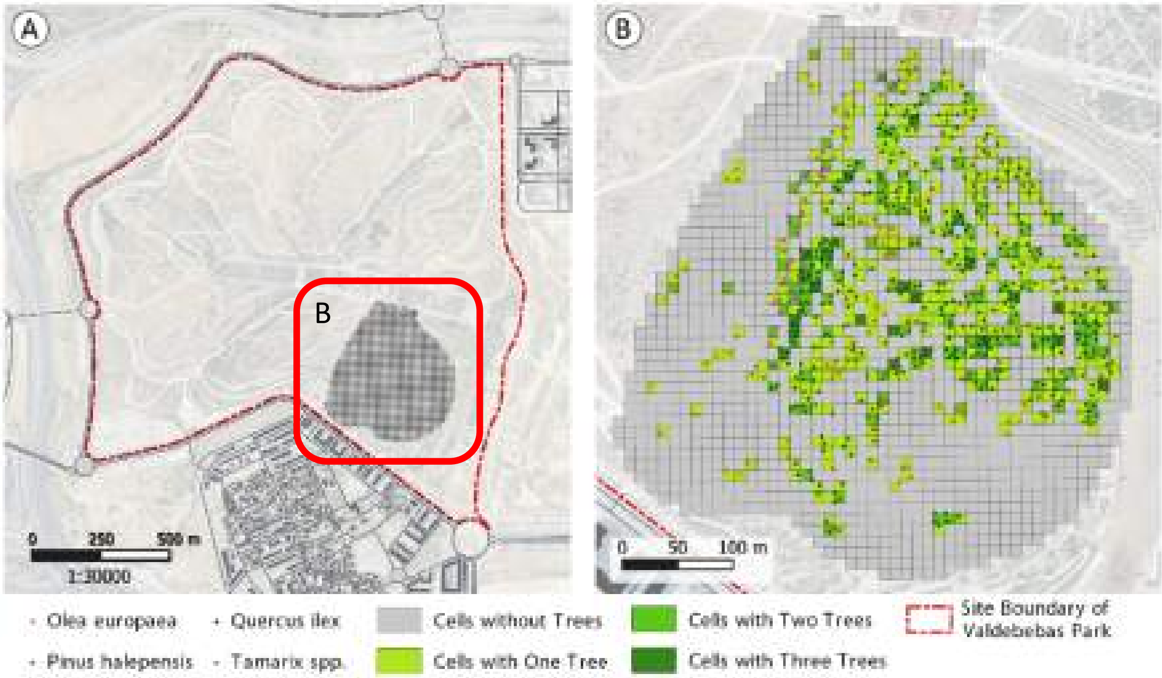


Fig. 6. A) Site boundary of Phase I Valdebebas Park with the zone La Mancha mapped; B) Zoom on La Mancha showing cells that include trees and determine the distribution of tree species.

Scenarios were defined based on differences in design/planning actions (NBS implementation phase), operational management actions (NBS use phase) and the management of the biological waste (NBS end-of-life phase).

Regarding design/planning and management actions, two alternatives were considered:

- *Real La Mancha*: It corresponds to the real implementation of the urban forest as described in the documentation provided by the Council of Madrid (summarised in Fig. 7a). Few modifications were required to adapt the case study to the current capacities of the model. For example, *Tamarix boveana* and *Tamarix canariensis* needed to be modelled at genus level (*Tamarix spp*).
- *Paved La Mancha*: a hypothetical alternative that only includes a monoculture of *Quercus ilex* planted at two years old on paved ground (Fig. 7a). Unlike the previous alternative, the density of trees corresponds to only one tree per cell. In terms of management, security pruning (i.e., pruning to avoid the risk of branch falling on people) is expected each five years and leaf and branch litter should be always collected. This alternative emulates the typical planning and management of street trees.

In terms of management of the biological waste, three options (i.e., *composting, biomethanation, and re-utilisation of dead wood as raw material*) were considered for each design/planning alternative, making the six scenarios. For the options *composting* and *biomethanation*, it was assumed that all the biological waste is transported to Valdemingomez waste treatment plant, as it currently occurs with the biological waste generated in Madrid. For both options, the financial cost per kilogram of biowaste is obtained from the yearly financial reports of Valdemingomez (see Supplementary Material 5 for details). For the option *re-utilisation of dead wood*, it was assumed that dead stem wood could be used as raw material for lumber wood, chipped dead branch wood as raw material for woodchips, and that leaf litter is treated through biomethanation. The financial benefit from re-using lumber is obtained from national woody industry databases (see Supplementary Material 5 for details). This last alternative considered the transport from La Mancha to sawmills and panel board industries as the last process of the end-of-life. The average transport distance was estimated to be 25 km for Valdemingomez waste treatment plant, 40 km to panel board industries placed in Madrid, and 80 km to near sawmills transforming wood logs into lumber that are placed in the Region of Madrid and adjacent regions (see life cycle inventory in Supplementary Material 7).

3. Results

3.1. Performance of the urban forest cell types

This section visualises and describes the individual performance of each cell type for three key ES classes over the 50-year use phase. First, monthly changes in the average daily *filtration of air pollutants by plants* over the 50-year use phase are visualised in Fig. 8. Second, the differences over time in tree transpiration, a process contributing to the ES *regulation of temperature and humidity,* are visualised in Fig. 9. Then, Fig. 10 visualises how tree mortality might influence the long-term supply of the cultural ES *characteristics of living systems that enable activities promoting health*, and therefore the potential recreational benefits derived from it.

Regarding the average daily *filtration of air pollutants* (CO, PM_{10}, SO_2, NO_2 and O_3) *by plants*, Fig. 8 clearly shows that after 25 years of the urban forest implementation, *Quercus ilex* planted 2–3 years old on non-paved ground performs better than the rest for all the pollutants in every month of the year. During the first 10 years, *Olea europaea* (non-paved and paved) are the best performers due to their already mature condition (planted at 20 years old), and much higher leaf area. Between 10 and 25 years after implementation, also *Pinus halepensis* planted at 2 and 5 years old on non-paved ground overcome both cell type of *Olea europaea* in performance. For some substances (e.g., PM_{10}, NO_2), the differences over time between *Quercus ilex* non-paved and *Pinus halepensis* non-paved are not relevant and might not imply significant differences in their capacity to mitigate air pollution. For example, for both urban forest cell types, the daily filtration of PM_{10} on summer months is quite similar. These are the months when atmospheric PM_{10} ambient level is higher in Madrid (see Fig. 8) and in several occasions surpasses

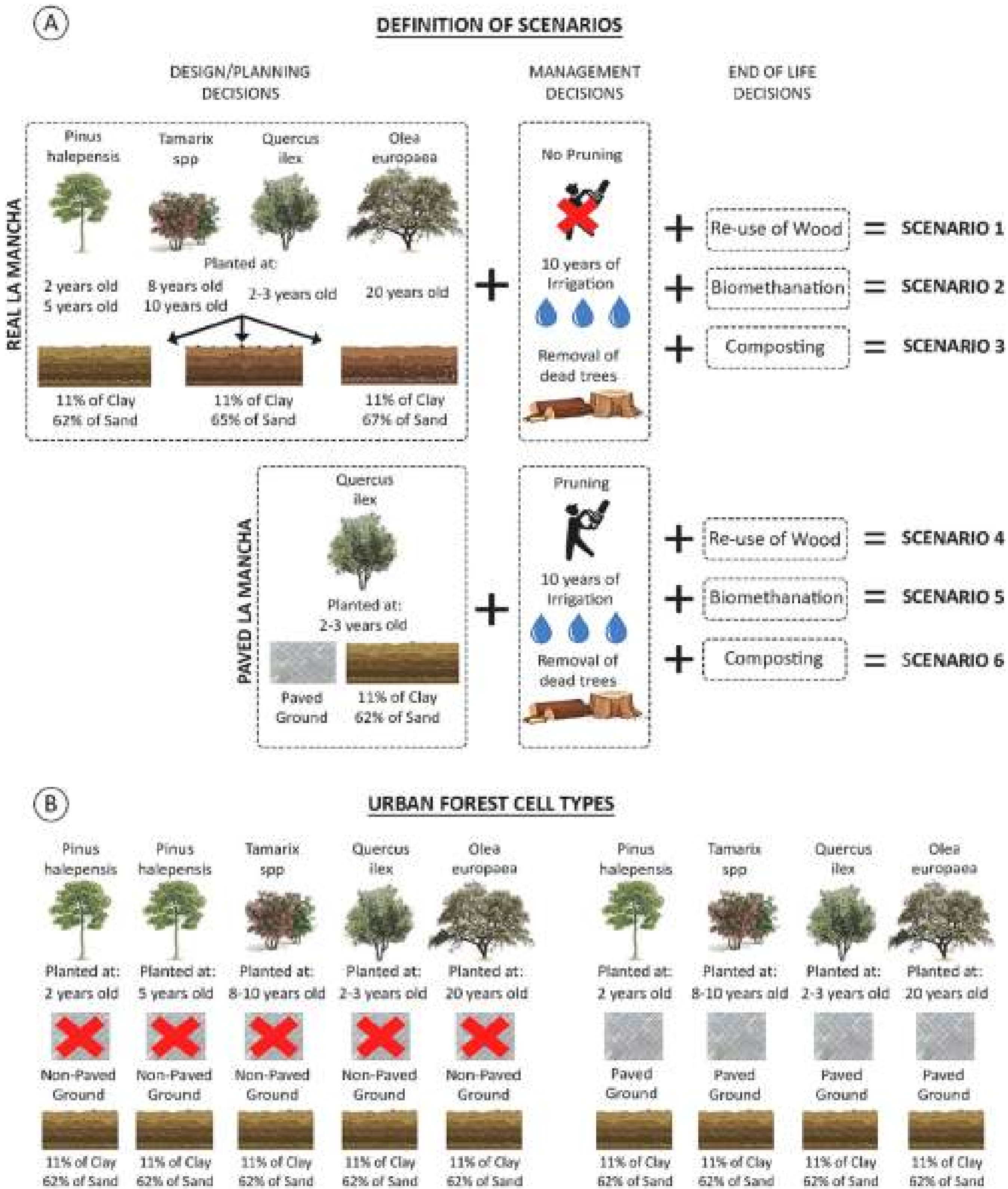


Fig. 7. A) Graphical summary of the definition of the six different scenarios assessed; B) Graphical summary of the nine different urban forest cell types assessed.

the recommended threshold of 5•10^{-8} μg/m^3 (World Health Organisation, 2005). For the rest of the urban forest cell types, the differences with *Pinus halepensis* and *Quercus ilex* are substantial. Therefore, since Madrid surpasses the legal maximum ambient levels of NO_2 and O_3 (Air Quality Directive 2080/50/EC) several times each year, favouring a greater planting of one of the low performing species in the municipality could miss potential mitigation value of such NBS against air pollution.

Concerning *regulation of temperature and humidity* for all the cell types, Fig. 9 illustrates a clear difference between the average daily transpiration when air temperature is below the thresholds of comfort (Fig. 9a), and when they are exceeded (Fig. 9b). Only in the second case ES demand is present, and therefore there is actual ES flow and positive

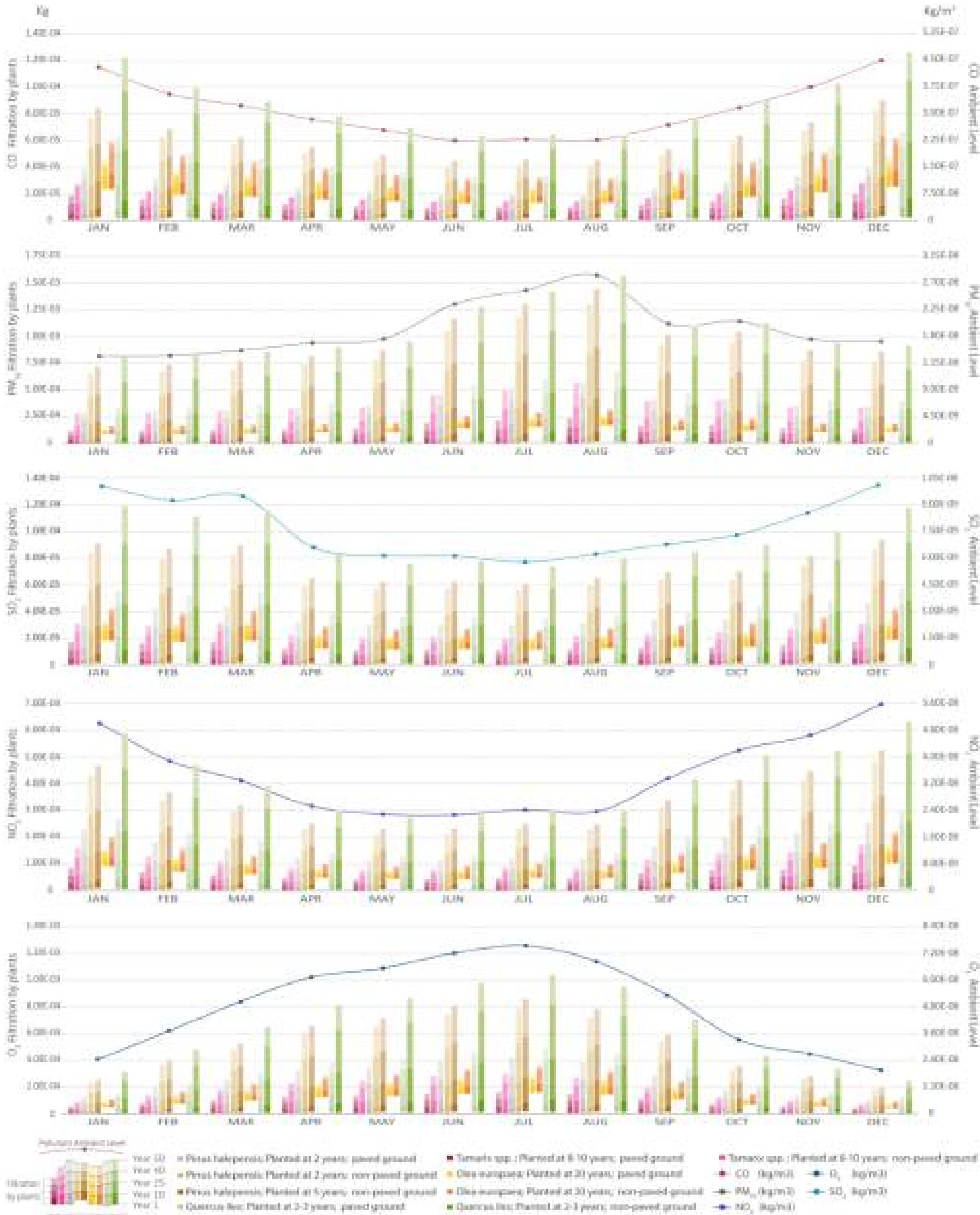


Fig. 8. Evolution over 50 years of average daily *filtration of air pollutants* per month visualised against average monthly air pollutant ambient levels (visual overlapping between lines of Ambient Level and bars of Filtration by plants do not have a quantitative meaning).

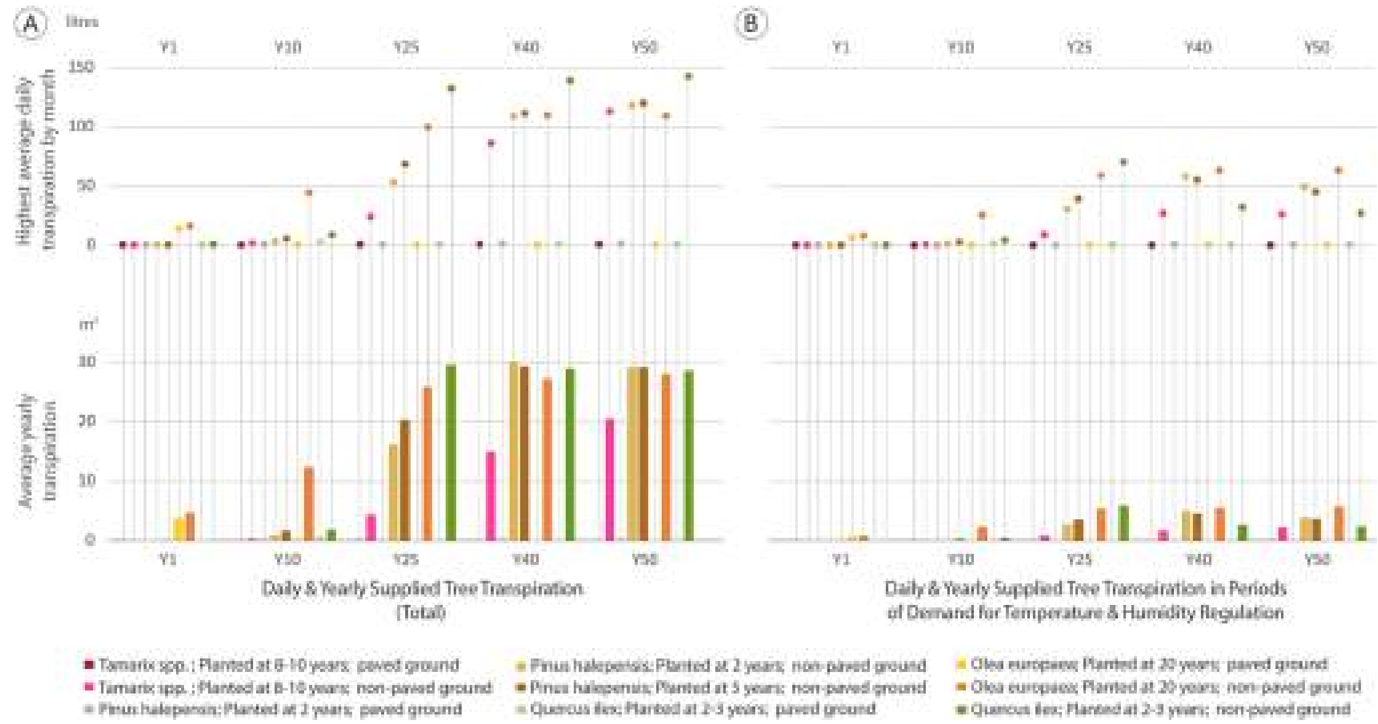


Fig. 9. a) Evolution over 50 years of average daily and yearly total supplied tree transpiration b) Evolution over 50 years of daily and yearly supplied tree transpiration when society demands it (i.e., when maximum and average daily air temperature surpasses comfort thresholds).

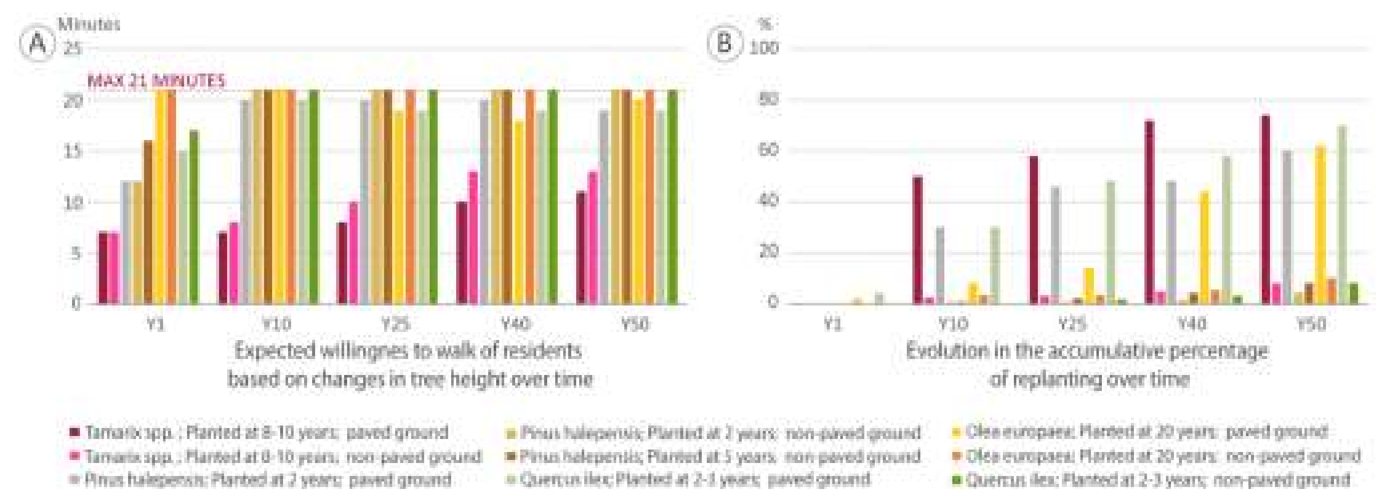


Fig. 10. a) Evolution over 50 years in the expected willingness to walk of residents to visit urban forests only formed by each cell type as result of changes in tree height; b) Evolution over 50 years in the expected accumulative percentage of tree replanting.

environmental and economic impact. In that case, water is also scarce for trees, given that the water soil balance is low due to the increased soil evaporation and tree transpiration. This is a consequence of continuous high temperatures and a low occurrence of rain in Madrid, which is on average around two days per month in July and August. Fig. 9 also shows differences between specific urban forest cell types. For example, after 25 years *Quercus ilex* on non-paved ground appears as the best performer for average and highest daily transpiration. However, when looking the supply of this ES during periods of ES demand by citizens, it is not always the best performer. In fact, during ES demand periods *Olea europaea* on non-paved ground performs like *Quercus ilex* after 25 years, and at 40 and 50 years clearly outperforms it in average and highest transpiration. This result can be explained by the low maximum transpiration of Quercus ilex as indicated in Fernández and Moreno (2008). Regarding differences between paved and non-paved cells, transpiration in paved cells is much lower, being close to zero. Notwithstanding, a lower transpiration could be expected in paved cells due to less access to water, although the values obtained are likely underestimated by limitations of the model, as discussed in Section 4.

Regarding the expected willingness to walk, Fig. 10 shows that an increased cumulative mortality of trees could reduce it in the long term. For example, in the case of *Quercus ilex* paved and *Olea europaea* paved expected willingness to walk is slightly reduced after 25 and 40 years. The increased cumulative mortality of these cell archetypes implies that dead individuals are substituted by younger ones (same age as those planted the first time) or are not present for several years. This could end making the urban forest look younger (smaller) and less attractive to users, i.e., reducing the associated willingness to walk, and therefore, the population serviced by the NBS.

3.2. Cumulative long-term performance of La Mancha scenarios

In terms of positive environmental impacts (Table 1a), scenarios 1 to 3 perform much better than scenarios 4 to 6. Due to their non-paved condition, scenarios 1 to 3 reduce water run-off more than scenarios 4 to 6. Furthermore, scenarios 4 to 6 filtrate much less air pollutants due to the lower number of trees, canopy growth (and their associated leaf area) and transpiration rates. The latter process is strongly influenced by the canopy stomatal resistance, which also influences deposition of air pollutants (Baldocchi et al., 1987). Scenarios 4 to 6 perform slightly better on *characteristics of living systems that enable activities promoting health* (i.e., physical recreation activities) than scenarios 1 to 3 because of their higher values for willingness to walk during years 1 to 10 and 29 to 34. Consequently, during several years scenarios 1 to 3 have a lower potential number of visitors (Fig. 11 shows how potential visitors are obtained based on willingness to walk values).

The monetisation of positive environmental impacts (Table 1b) informs on the most valuable ES in terms of societal benefits. For example, in this case study *characteristics of living systems that enable activities promoting health* is the most valuable ES by two orders of magnitude, due to the great amount of population serviced. However, an urban forest placed far from residential areas or developed in a private open space (e.g., in a private garden, intensive green roof with limited access) would generate a very low outcome for this ES class. Table 1b also emphasises the higher value of *regulation of hydrological cycle and water flow*, *regulation of chemical condition of the atmosphere*, *regulation of temperature and humidity* and *filtration by plants* of PM_{10} compared to other regulating ES.

The input data of each scenario and the quantitative modelling of management actions applied during the use phase and end-of-life are summarised in Table 2a. They are needed to calculate the financial costs (Table 2b), the negative environmental impacts in biophysical units (Table 3) and the related negative externalities (Table 4).

Table 3 shows two mid-point impact categories (stratospheric ozone depletion and terrestrial acidification) for which in scenario 5 and 6 a positive environmental impact is generated. These values correspond to avoided environmental impacts due to the generation of biogas from biological waste. In the case of scenario 2 and 3, the biological waste is so low that it does not overcome the negative impacts from other management actions. The monetisation of negative environmental impacts (Table 4) helps to identify *global warming potential*, *particulate matter formation*, *human non-carcinogenic toxicity*, and *land occupation and transformation* as the most relevant impacts categories in terms of negative externalities.

As a final output, the monetisation of environmental impacts permits the integration of financial costs and externalities, providing a simple overall value of the economic performance of the urban forest over all the life cycle phases (Fig. 12). From a societal perspective, it helps to identify when the break-even point occurs and net benefits are starting to be generated as well as when different scenarios reach similar levels of net benefits.

When ES and LCA midpoint impact categories are equivalent, the net environmental impact can also be calculated in biophysical units by simple subtraction (as applied in Elliot et al., 2022a). This is the case of *global warming potential* and *regulation of chemical condition of the atmosphere* (Fig. 13a) and *particulate matter formation* and *filtration by plant* of PM_{10} (Fig. 13b). As a result, the overall performance for some environmental impacts (negative and positive) over time can be assessed considering all the life cycle phases. Further details on yearly outputs per each scenario can be found in Supplementary Material 8.

4. Discussion

The modelling framework intertwines ES and life cycle thinking approaches to account for the positive and negative environmental impacts generated over an urban NBS life cycle. The proof of concept presented here can provide the foundations for the development of future urban NBS models. Considering that the urban forest model has a modular structure, specific modules of interest for other urban NBS models can be easily transposed. For example, the soil sub-module can be useful for other urban NBS (e.g., urban meadows or green roofs), and does not require modifications beyond addition of few constraints, such as further limiting soil depth. In addition, to model complex NBS interventions (e.g., projects combining more than one NBS type) new modules can be integrated, or existing modules can be updated to include further biophysical structures and variables and their dynamics over time. As an example, the vegetation sub-module presented in the case study only includes woody plants, but herbaceous plants can be integrated to represent green open spaces with a mix of urban forests, semi-improved grasslands and wildflower meadows. In addition, some functions and processes already modelled in the proof of concept are relevant for the calculation of future new ES classes. For example, changes in biophysical attributes over time such as tree height, crown width, leaf area and living trees can be intermediate outputs for integrating the estimation of ES classes such as *characteristics of living systems that enable aesthetic experiences, wind protection* or *visual screening*.

By accounting for detrimental impacts, the modelling framework allows quantifying the net contribution of NBS to urban sustainability, offering an added value to existing modelling and assessment approaches (Hamel et al., 2021). The general lack of consideration of the negative environmental impacts in the form of disservices was recently stressed by some scholars (Keeler et al., 2019). Works interlinking LCA and ES to quantify beneficial and detrimental environmental impacts of urban actions are emerging in the literature (e.g., Oliveira et al., 2022), but those are mainly developed for the detail necessary for spatial planning actions at strategic and city levels (Elliot et al., 2022b; Rugani et al., 2022; Xue and Bakshi, 2022).

The proposed modelling framework is conceived to evaluate the impact of spatial planning actions at site level, i.e. specific urban NBS projects at neighborhood or urban block levels. Consequently, it goes beyond land use/cover class assessments, and differentiates among specific biotic, abiotic and management attributes influencing the net contribution of NBS to urban sustainability. For example, the comparison of Real La Mancha (scenarios 1 to 3) against Paved La Mancha (scenarios 4 to 6) highlights the relevant negative impact that design/planning decisions, such as extensive paving of an urban forest, can have on the supply of multiple ES. Similarly, management decisions on the end-of-life phase of dead wood can have a significant effect on the level of particulate matter formation, as illustrated by the comparison between Paved La Mancha-dead wood re-use scenario (scenario 1) and Paved La Mancha – Composting scenario (scenario 3).

Building and running models such as the proof-of-concept urban forest model risk being excessively time consuming to support daily planning and design decisions. It requires the application of multiple methods, steps, and needs multiple types of input data to compute environmental impacts. Therefore, advancements should be made to move the current modelling framework, and future derived models, to a practical decision support instrument for built environment professionals, where the most time-consuming tasks for the calculation of environmental impacts remain on the side of the modeller. Interestingly, a user-friendly prototype online decision support tool has been recently developed and tested building upon the urban forest model presented here (Babí Almenar et al., 2023).

The modelling framework attempts to acknowledge the importance of short and long-term spatio-temporal dynamics in the accounting of actual ES flows. In fact, the case study shows that the model is sensitive to changes in ES flow resulting from changes in meteorological conditions, tree species, tree age (dimensions), ground conditions (soil texture, initial soil organic matter, and soil sealing), and basic management actions (irrigation, pruning, harvesting, and removal of plant residues). In addition, the modelling framework represents spatial-

Table 1

A) Evolution over 50 years of cumulative positive environmental impacts in the form of ecosystem services provided by the urban forest; B) Evolution over 50 years of cumulative positive externalities provided by the urban forest (Values in Euro 2018). The relative colour scale orders values from lowest (light brown, less than 10 % of the maximum value) to highest (dark green, 75–100 % of the maximum value), per environmental impact category (A) and overall (B). S = Scenario.

A) CUMULATIVE POSITIVE ENVIRONMENTAL IMPACTS

Positive Environmental Impacts (Biophysical Units)	Units	Year 1				Year 10				Year 25				Year 40				Year 50			
		S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6
Regulation of hydrological cycle & water flow	1000 m^3 avoided run-off	16.99		0.2		172.26		2.64		430.15		10.74		686.85		25.94		859.72		39.69	
Filtration of pollutants by plants	kg CO filtrated	0.57		0.18		12.11		6.33		71.71		43.06		198.84		123.47		322.66		196.4	
	kg NO_2 filtrated	2.14		0.7		45.76		24.29		289.61		167.89		865.86		498.48		1481.52		811.45	
	kg SO_2 filtrated	0.49		0.16		10.46		5.53		65.73		38.26		195.19		113.28		332.32		184.18	
	kg O_3 filtrated	3.24		1.05		70.07		37.02		444.42		257.17		1331.73		764.49		2280.74		1246.57	
	kg PM_{10} filtrated	3.83		1.36		84.47		45.76		586.27		319.51		1906.16		989.34		3422.06		1657.25	
Regulation of chemical condition of the atmosphere	t CO_2 stored in trees, litter & soil	52.3		5.92		239.13		83.66		1070.06		451.16		2662		1193.79		3959.49		1751.25	
Regulation of temperature & humidity	1000 kWh A/C Avoided	32.23		3.26		361.16		35.5		1210.76		143.03		2401.53		334.82		3248.59		505.58	
Characteristics of living systems that enable activities promoting health*	Willingness to walk (min.)*	15		16		20		20		21		19		21		19		21		20	
	1000 Potential Visitors/ year	8.28		8.43		143.02		218.66		498.86		505.5		854.71		892.72		1091.94		1110.12	
Fibres & other materials from cultivated plants**	t lumber wood from dead trees	0.0007	-	0.07	-	0.17	-	3.55	-	0.32	-	33.82	-	1.07	-	94.33	-	2.1	-	191.2	-
	t woodchips from dead trees	0.0004	-	0.04	-	0.15	-	2.75	-	0.24	-	30.79	-	0.75	-	103.18	-	1.5	-	196.49	-

B) CUMULATIVE POSITIVE EXTERNALITIES

Positive Externalities (Monetary Units)	Units	Year 1				Year 10				Year 25				Year 40				Year 50			
		S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6
Regulation of hydrological cycle & water flow	Euro	6,041		70		61,255		939		152,962		3,818		244,244		9,226		305,716		14,115	
Filtration of pollutants by plants	Euro (CO)	0		0.01		0.64		0.33		3.79		2.28		11		6.53		17		10	
	Euro (NO_2)	32		10		681		361		4,307		2,497		12,877		7,413		22,033		12,068	
	Euro (SO_2)	6		1.81		121		64		760		442		2,256		1,309		3,840		2,128	
	Euro (O_3)	30		10		642		339		4,072		2,357		12,203		7,006		20,900		11,423	
	Euro (PM_{10})	151		54		3,327		1,802		23,093		12,586		75,084		38,970		134,795		65,279	
Regulation of chemical condition of the atmosphere	Euro	2,974		337		13,601		4,758		60,859		25,659		151,399		67,896		225,193		99,601	
Regulation of temperature & humidity	Euro	1,321		133		14,807		1,456		49,641		5,864		98,463		13,727		133,192		20,729	
Characteristics of living systems that enable activities promoting health	Euro	259,484		264,184		4,481,953		6,852,342		15,633,639		15,841,727		26,785,324		27,976,692		34,219,781		34,789,642	
Fibres& other materials from cultivated plants*	Euro (lumber wood)	0.09	-	2.38	-	21	-	163	-	38	-	1,826	-	125	-	6,119	-	245	-	11,654	-
	Euro (wood chips)	0.02	-	7.98	-	15	-	424	-	22	-	4,037	-	66	-	11,259	-	133	-	22,821	-

* Willingness to walk is not provided as an accumulative value. Thus, the value indicated represents the willingness to walk in minutes at the specific year presented.

** Only scenario 1 and scenario 4 includes the re-utilisation of wood waste as input material for processing. Thus, for scenarios 2, 3, 5, and 6 this service is not accounted.

Relative Colour Scale from min. to max. value

<10%	<15%	<20%	<30%	<50%	<75%	<100%

For the monetarisation, the colour scale is generated excluding values of *Characteristics of living systems that enable activities promoting health* to avoid the scale being insensitive to changes

* Willingness to walk is not provided as an accumulative value. Thus, the value indicated represents the willingness to walk in minutes at the specific year presented.

** Only scenario 1 and scenario 4 includes the re-utilisation of wood waste as input material for processing. Thus, for scenarios 2, 3, 5, and 6 this service is not accounted.

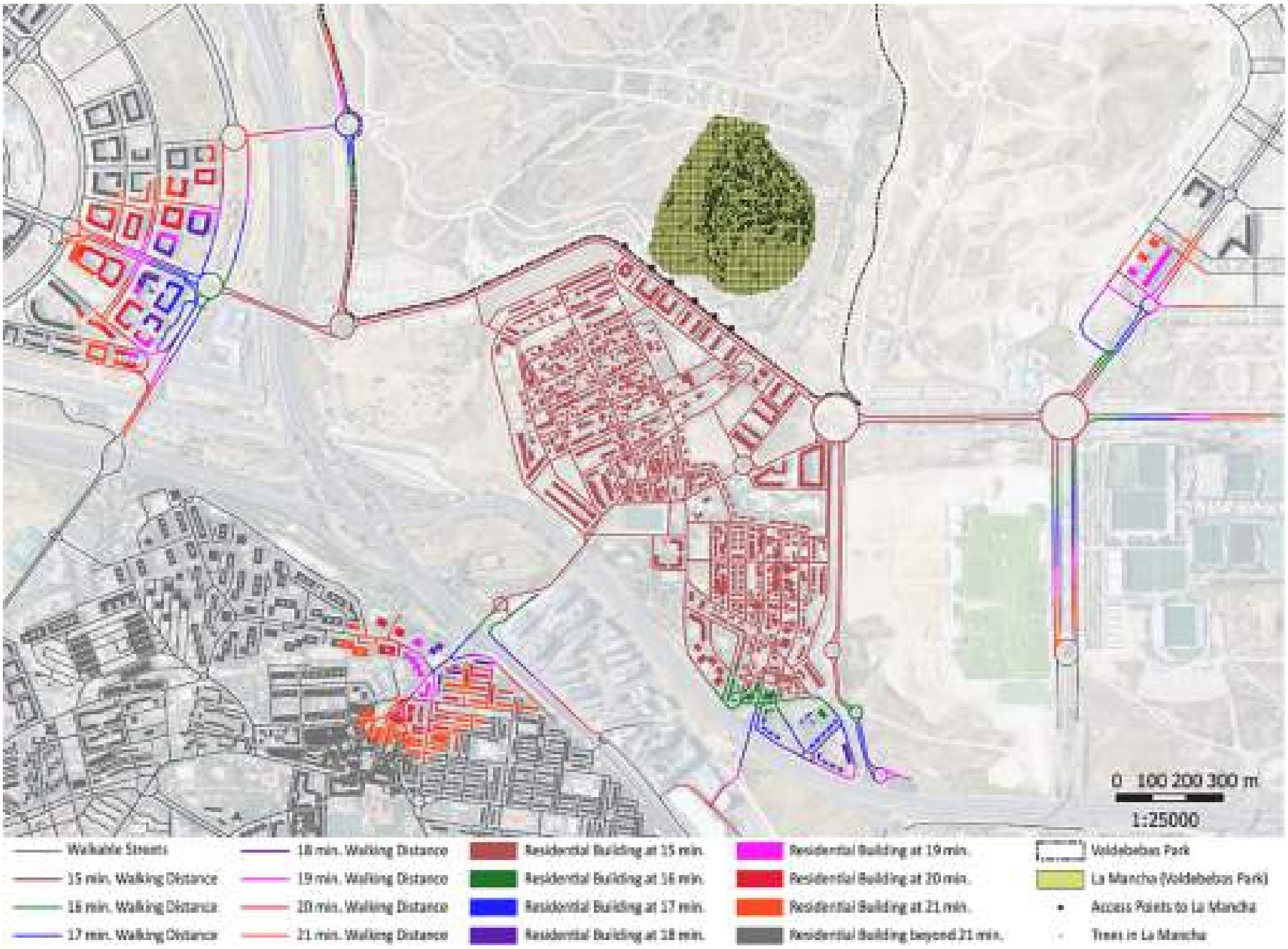


Fig. 11. Evolution of the potential visitors (residents) of La Mancha for Scenarios 1 to 3, as a function of walking distance over time associated with the increasing maturity of the urban forest. The legend includes the years after implementation (Y) that correspond with each walking distance in minutes.

ecological processes and planning/design and management decisions interrelated and changing over time as they occur in practice. In other words, different ES are modelled concurrently in an integrated model and not independently, overcoming a gap in common ES models (Cord et al., 2017; Ouyang and Luo, 2022) and accounting for ES trade-offs and synergies. For example, changes in the tree growth rate not only influence the tree and soil carbon sequestration, but also pollutants removal, the hydrological cycle, the water flow regulation as well as the temperature and humidity regulation. Moreover, the temporal resolution of the model accounts for seasonality influencing ES demand. Fig. 9 clearly illustrates this aspect, showing the difference between the tree transpiration when ES demand from citizens is present and when it is not. It therefore consistently assesses the positive environmental and economic impacts. Such results may inform science-based targets and decision-making, ensuring that NBS are able to provide actual ES flows during shocks such as heat waves. In terms of management, the model may help to anticipate when irrigation should be applied as part of annual landscape management plans. For planning/design, it may aid in the selection of components (e.g., tree species, size of trees at planting) to ensure high supply capacity of specific ES classes in the long-term.

The proof-of-concept urban forest model still requires improvements to overcome some limitations. In terms of modelling, the interactions among cells in the foreground system are still not considered. This affects the quantification of certain regulating ES as the regulation of the hydrological cycle and water flow. In addition, although the urban forest model already includes stochastic components, and therefore each simulation output is different, only average values across multiple simulations were presented for communication simplicity. In future versions of the model, value ranges should be presented instead of only average values to better describe the performance of different alternatives over time. Such exercise has been performed for the recently published prototype online decision support tool derived from the current urban forest model (Babí Almenar et al., 2023). Specific modelling path flows should be further tested and in some cases improved. For example, this is the case of the modelling of *characteristics of living systems enabling activities promoting health* (recreational activities). The modelling path flow for this ES is strongly based on the parameters estimated via discrete choice experiment methodology by Ta et al (2020) and Filyushkina et al. (2017). This methodology offers parameters at the attribute level that facilitate the integration in dynamic models where attributes change over time. However, the use of other ES monetary valuation methods that can also differentiate the contribution of each attribute to the whole willingness to travel is not excluded. Another limitation to be considered is that the current recreational attractiveness assessment does not consider the presence of alternative green urban areas that may also offer recreational opportunities. This aspect should be integrated, for instance following the methodology recently proposed by Liu et al. (2022). As part of these improvements, the influence of demographic attributes (e.g., distribution of the urban population in terms of age or gender) on some environmental and economic impact should also be investigated. Another important aspect missing in the current framework is the impact of climate change on NBS

Table 2

A) Evolution over 50 years of cumulative management actions applied on the urban forest; B) Evolution over 50 years of the cumulative financial costs generated as a result of management actions (values in Euro 2018). In Table 1B, the relative colour scale orders values from lowest (light brown, less than 10 % of the maximum value) to highest (dark red, 60–100 % of the maximum value) overall financial cost. S = Scenario.

A) CUMULATIVE MANAGEMENT ACTIONS APPLIED ON THE URBAN FOREST

Management Actions	Unit	Year 1				Year 10				Year 25				Year 40				Year 50			
		S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6
Planting	No. Trees	641		484		641		484		641		484		641		484		641		484	
Replanting	No. Trees	0.2		19.4		5.7		145.2		10.2		203.3		17.0		280.7		21.9		338.8	
Pruning	No. Trees	-		0		-		464.6		-		1703.7		-		2904		-		3697.8	
Disposal of dead branch wood for its re-use	t of woodchips	0.0004	-	0.04	-	0.2	-	2.8	-	0.2	-	30.8	-	0.7	-	103.2	-	1.5	-	196.5	-
Disposal of dead stem wood for its re-use	t of lumber wood	0.0007	-	0.1	- -	0.2	-	3.6	-	0.3	-	33.8	-	1.1	-	94.3	-	2.1	-	191.2	-
Waste treatment of dead branch wood	t of woodchips	-	0.0004	-	0.04	-	0.2	-	2.8	-	0.2	-	30.8	-	0.7	-	103.2	-	1.5	-	196.5
Waste treatment of dead stem wood	t of lumber wood	-	0.0007	-	0.1	-	0.2	-	3.6	-	0.3	-	33.8	-	1.1	-	94.3	-	2.1	-	191.2
Waste treatment of leaf litter	t of leaf litter	0		0.5		0.1		20.3		0.1		147.9		0.4		456.8		0.9		768.2	
Irrigation	m^3 of water	1.1		0.0		29.1		0.6		38.3		8.7		38.6		14.1		38.9		14.2	

B) CUMULATIVE FINANCIAL COSTS DERIVED FROM MANAGEMENT ACTIONS

Financial Costs	Unit	Year 1				Year 10				Year 25				Year 40				Year 50			
		S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6	S1	S2-3	S4	S5-6
Planting	Euro	103890		8867		103890		8867		103890		8867		103890		8867		103890		8867	
Re-Planting	Euro	47	52	2345	2979	1508	1694	17588	22342	2589	2923	28141	35748	4379	4937	34004	43195	5650	6367	41040	52132
Pruning	Euro	-		0		-		465		-		1704		-		2904		-		3698	
Disposal of dead branch wood for its re-use	Euro	0.04	-	4.4	-	17	-	302	-	26	-	3380	-	82	-	11326	-	165	-	21569	-
Disposal of dead stem wood for its re-use	Euro	0.08	-	7.3	-	19	-	390	-	36	-	3712	-	117	-	10354	-	231	-	20988	-
Waste treatment of dead branch wood	Euro	-	0.05	-	6	-	22	-	400	-	35	-	4476	-	109	-	14999	-	218	-	28563
Waste treatment of dead stem wood	Euro	-	0.11	-	10	-	25	-	516	-	47	-	4916	-	155	-	13713	-	306	-	27794
Waste treatment of leaf litter	Euro	0.05		78		11		2956		19		21495		64		66405		129		111677	
Irrigation	Euro	1.38		0.05		36		0.74		47		11		48		17		48		17	

Relative Colour Scale from min. to max. value

<10%	<15%	<20%	<35%	<50%	<60%	<100%

Table 3
Evolution over 50 years of cumulative negative environmental impacts generated as a result of human actions on the urban forest. The table includes also positive environmental impacts (green cells) in the form avoided impacts resulting from the generation input material from NBS waste, which substitute explotation of other resources and their associated environmental impacts. The relative colour scale orders values from highest positive (dark green, less than 50 % of the maximum value) to highest negative impacts (dark red, 75–100 % of the maximum value) per environmental impact category. S = Scenario.

Negative Environmental Impacts	Unit	Year 1						Year 10						Year 25						Year 40						Year 50					
		S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6
Global warming Potential	t CO_2 eq	14.8	14.8	14.8	9.8	10.1	10.1	15.3	15.4	15.4	37.6	40.2	40.9	15.7	15.9	15.9	94.2	99.7	105.8	16.3	16.7	16.7	154.9	164.3	183.2	16.8	17.3	17.4	203.2	218.2	251.5
Stratospheric ozone depletion	kg CFC11 eq	0.008	0.008	0.008	0.005	0.006	0.006	0.008	0.008	0.008	0.015	0.014	0.034	0.008	0.008	0.009	-0.009	-0.039	0.127	0.009	0.008	0.01	-0.124	-0.22	0.292	0.009	0.007	0.011	-0.25	-0.44	0.464
Ionizing radiation	MBq Co-60 eq	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.6	0.6	0.7	0.3	0.3	0.3	1.3	1.3	2	0.3	0.3	0.4	2	1.9	4.1	0.4	0.4	0.4	2.5	2.3	6.2
Ozone formation, Human health	kg NO_x eq	108.3	108.3	108.3	55.1	56.2	56.2	110.9	111.2	111.2	197.2	205.6	206.2	113	113.6	113.6	481	496	500.8	116.2	117.2	117.2	753.1	774.4	789.3	118.5	119.8	119.9	951.5	981.4	1007.8
Particulate matter formation	kg $PM_{2.5}$ eq	28.6	28.6	28.6	15.4	15.7	15.9	29.2	29.2	29.4	40.9	42.5	51	29.7	29.8	30	77.1	72.3	140.5	30.4	30.4	31.1	87.8	65.9	275.8	30.9	30.8	32.2	85.9	39.5	410.3
Terrestrial acidification	kg SO_2 eq	55.5	55.5	55.5	30.6	31.2	32.8	56.7	56.5	57.5	73.8	71.9	140.3	57.7	57.4	59.2	55.5	-10.7	535	58.9	57.4	63.2	-175.5	-393.8	1286.6	59.6	56.2	67.8	-440.1	-876.3	2092.4
Freshwater eutrophication	kg P eq	1.4	1.4	1.4	1.3	1.3	1.3	1.5	1.5	1.5	10.6	10.7	10.8	1.6	1.6	1.6	29.9	30	30.6	1.8	1.8	1.8	48.2	48.5	50.3	1.9	1.9	1.9	61.4	61.7	64.9
Marine eutrophication	kg N eq	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	2.3	2.3	2.3	0.2	0.2	0.2	6.7	6.9	6.9	0.3	0.3	0.3	11.2	11.6	11.5	0.3	0.3	0.3	14.5	15.2	15.1
Human carcinogenic toxicity	t 1,4-DCB eq	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.9	0.9	1	0.3	0.3	0.3	2.2	2.3	2.6	0.3	0.3	0.3	3.6	3.9	4.8	0.3	0.4	0.4	4.8	5.2	6.8
Human non-carcinogenic toxicity	t 1,4-DCB eq	8.3	8.3	8.3	6.2	6.3	6.3	8.5	8.5	8.5	14.1	14.3	14.6	8.7	8.7	8.7	29.6	30	32	8.9	8.9	8.9	47.9	48.3	54.5	9.1	9.1	9.2	64.2	64.7	75.7
Water consumption	m^3 water eq	62.6	62.6	62.6	37.1	37.3	37.4	92.7	92.8	92.8	169.7	171.4	172.8	103.7	103.8	103.8	438.1	440.5	451.7	106.7	106.9	107	693.9	696.3	730.6	108.9	109.2	109.4	879.3	881.7	942.2
Land occupation & transformation	ha crop eq	1.3	1.3	1.3	1	1	1	1.4	1.4	1.4	1.5	1.5	1.5	1.4	1.4	1.4	2	2	2	1.4	1.4	1.4	2.4	2.4	2.6	1.4	1.4	1.4	2.7	2.7	3.1

Relative Colour Scale from max. positive value to max. negative value

>50%	>40%	>30%	>20%	>10%	<10%	<15%	<20%	<35%	<50%	<75%	<100%

Table 4

Evolution over 50 years of cumulative negative externalities generated as a result of human actions on the urban forest (values in Euro 2018). The table includes also positive externalities (green cells) associated with avoided impacts resulting from the generation of new input material from NBS waste, instead of exploiting new raw resources. The relative colour scale orders values from highest positive (dark green, less than 20 % of the maximum value) to highest negative (dark red, 60–100 % of the maximum value) overall externality value. S = Scenario.

Negative Externalities	Unit	Year 1				Year 10						Year 25						Year 40						Year 50					
		S1-3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6
Global warming Potential	Euro	840	557	576	577	868	874	875	2,136	2,285	2,329	892	903	904	5,359	5,672	6,020	929	948	951	8,809	9,347	10,419	956	982	990	11,558	12,411	14,304
Stratospheric ozone depletion	Euro	0.20	0.20	0.20	0.20	0.30	0.20	0.30	0.50	0.40	1.10	0.30	0.30	0.30	-0.30	-1.20	3.90	0.30	0.20	0.30	-3.80	-6.70	8.90	0.30	0.20	0.30	-7.60	-13	14
Ionizing radiation	Euro	19	14	14	14	19	19	19	37	38	43	20	20	20	78	78	121	20	20	21	116	111	241	21	21	22	145	133	363
Ozone formation, Human health	Euro	120	61	62	62	123	123	123	218	227	228	125	126	126	532	548	554	128	130	130	832	856	872	131	132	133	1,052	1,085	1,114
Particulate matter formation	Euro	1,638	882	900	912	1,672	1,675	1,682	2,343	2,433	2,923	1,699	1,705	1,718	4,418	4,144	8,049	1,740	1,742	1,784	5,029	3,776	15,802	1,768	1,762	1,844	4,920	2,262	23,506
Terrestrial acidification	Euro	277	153	156	164	283	282	287	369	359	701	288	287	296	277	-54	2,672	294	287	316	-877	-1967	6,426	298	281	338	-2198	-4376	10,450
Freshwater eutrophication	Euro	2.50	2.50	2.50	2.50	2.80	2.80	2.80	20	20	20	3.00	3.00	3.00	56	56	57	3.30	3.30	3.30	90	91	94	3.50	3.50	3.60	115	115	121
Marine eutrophication	Euro	0.60	0.60	0.60	0.60	0.70	0.70	0.70	7.10	7.20	7.20	0.70	0.70	0.70	21	21	21	0.80	0.80	0.80	35	36	36	0.90	0.90	0.90	45	47	47
Human carcinogenic toxicity	Euro	30	24	25	25	31	32	32	86	92	95	32	33	33	216	228	257	34	34	35	361	385	474	35	36	36	481	520	678
Human non-carcinogenic toxicity	Euro	830	619	623	623	847	848	849	1,403	1,429	1,454	862	864	864	2,946	2,987	3,188	885	888	891	4,768	4,809	5,430	904	908	912	6,391	6,439	7,535
Water consumption	Euro	49	29	29	29	73	73	73	134	135	136	82	82	82	346	348	356	84	84	84	548	549	576	86	86	86	694	696	744
Land occupation & transformation	Euro	1,142	882	882	882	1,153	1,153	1,153	1,238	1,238	1,246	1,163	1,163	1,163	1,674	1,670	1,739	1,177	1,177	1,178	2,022	2,011	2,222	1,187	1,187	1,189	2,309	2,286	2,659

Relative Colour Scale from max. positive value to max. negative value

>20%	>10%	-5%	<10%	<15%	<20%	<35%	<50%	<60%	<100%

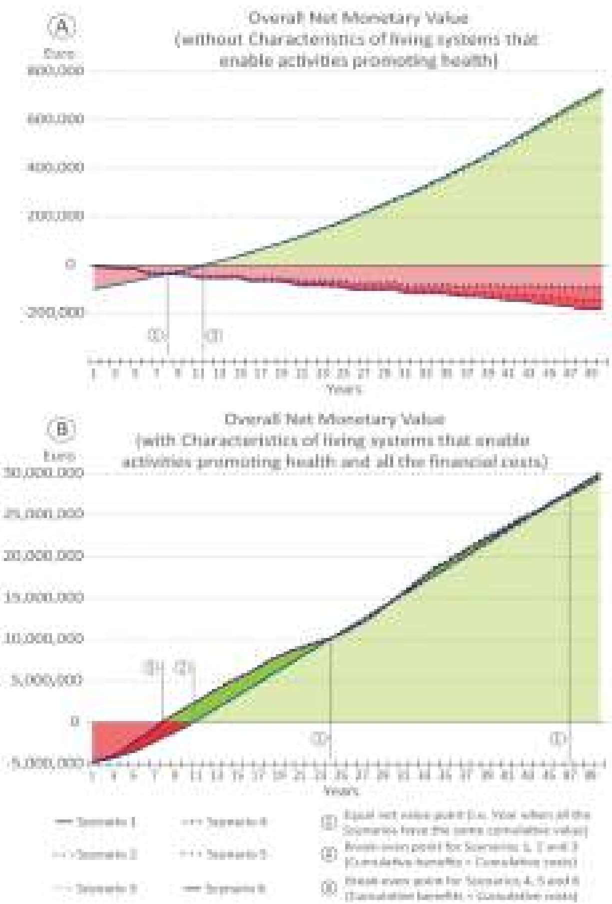


Fig. 12. A) Evolution over 50 years of the cumulative net monetary value of the urban forest without including the service characteristics of living systems that enable activities promoting health; B) Evolution over 50 years of cumulative net monetary value of the urban forest considering all costs and benefits, including financial costs not directly related to trees, as reported in the bill of quantities.

projects, such as the effects of changes in temperature and precipitation patterns on tree mortality. It was not possible to include this aspect in the current analysis, but the modelling framework can be adapted to include changing climatic conditions by adapting the weather generator module and stochastic structure. Finally, as it occurs in other models and methods integrating economic valuation, it is important to communicate clearly the uncertainty of outputs, especially when used to support long term assessments. Users should be aware of this uncertainty and be advised to consider both monetary and biophysical values in the decision making. For this reason, the proposed modelling framework already provides both types of outputs. Next advancements should overcome remaining limitations to better communicate the uncertainty of performance over time.

The modelling framework represents outputs in biophysical and monetary units, enabling users to encompass the environmental and economic dimensions in the NBS assessment in a disaggregated form. Disaggregation allows to differentiate the performance of NBS by category or type of value (financial or externality), making evident the differences in performance between scenarios. For example, in the case study, excluding the positive externalities of *characteristics of living systems enabling activities promoting health* (Fig. 12a), makes evident that scenarios 1 to 3 performs much better than scenarios 4 to 6. Moreover, the monetary valuation converts environmental outputs in metrics that can be easily understood by a larger public. However, it remains important to improve the communication of biophysical results. In this sense, it might be useful to provide a reference against which to compare

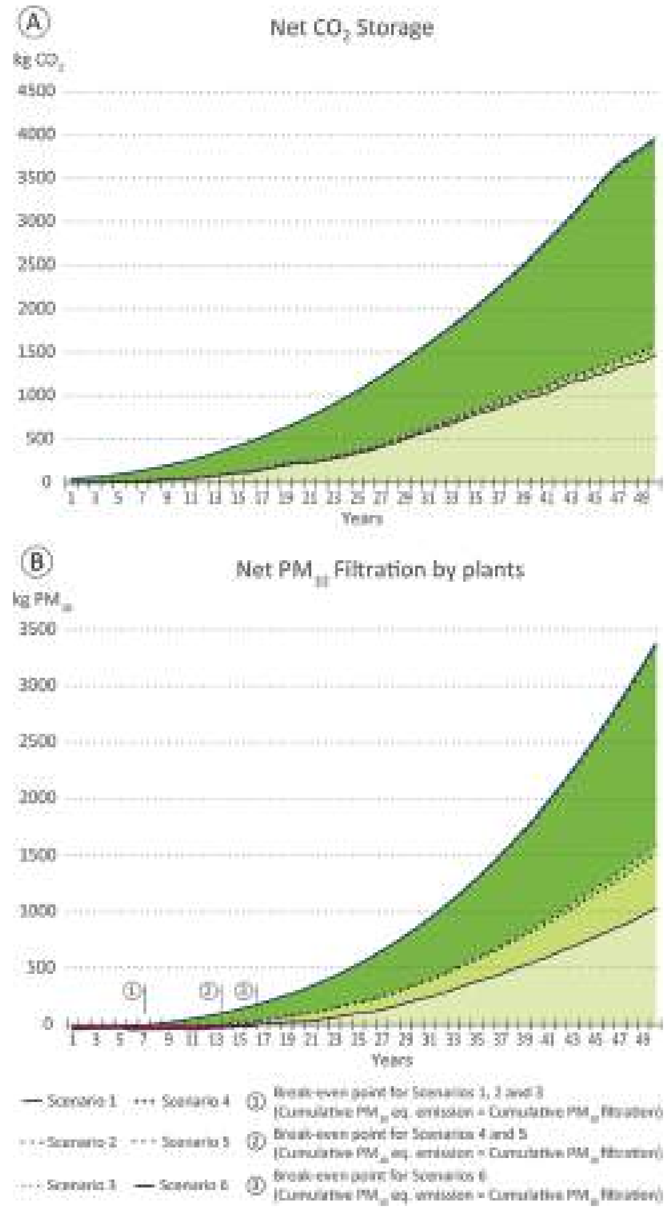


Fig. 13. A) Evolution over 50 years of net CO2 storage of the urban forest considering the CO2 eq. emissions in all the life cycle phases; B) Evolution over 50 years of cumulative net PM10 filtration of the urban forest considering PM_{10} eq. emissions in all the life cycle phases.

NBS or a reference level that informs on distance from the best attainable ecological condition or local sustainable performance (Czúcz et al., 2021; La Notte and Zulian, 2021). The use of reference biophysical and economic levels has been recently tested in the tool derived from the current urban forest model (Babí Almenar et al., 2023). In addition, if biophysical and monetary outputs were used as two independent set of impacts, there would be a risk of double counting the environmental impacts, which should be avoided in future works.

The complexity and lack of complete knowledge about the interactions of the components of an NBS requires simplification of some aspects. For example, all trees in the same cell were represented as the same species and age because cells are the minimum unit of differentiation. As illustrated in Fig. 9, simplifications, such as those applied for paved cell types, may lead to underestimating some functions, such as tree transpiration. For specific NBS models, all these simplifications provide variable and structural uncertainty, which can be mitigated by improving the collection of local data inventories. Nonetheless, the adoption of the two-level modelling framework intends to balance computational demand and data requirements against over-simplification. On one hand, the foreground level works at daily, monthly, and yearly resolutions, at a detailed spatial resolution, and with thematic resolutions that go beyond land cover classes. On the other hand, the background level offers an assessment at a larger spatial extent with reduced amount of specific data.

5. Conclusions

This paper presents a novel integrated methodological approach to assess the net environmental and economic benefits of NBS, which can contribute to urban sustainability and resilience. The approach suits the needs of planning and design at site level and considers all the life cycle phases of NBS. Through the integration of ES, LCA and LCC methods, the modelling framework offers a comprehensive assessment of NBS and capitalises on each of the individual methods' strengths. The conceptualisation into a semi-dynamic framework takes advantage of dynamic *and* static modelling approaches to overcome current limitations of both. Meanwhile fully dynamic approaches advance enough to inform specific urban NBS projects, modelling approaches such as this one could offer a good compromise to built environment professionals. In this regard, the modelling framework can support the development of robust decision support tools for urban NBS.

Future versions of the model should allow visualising the known variation in results, providing more transparency about the outputs and their reliability to support decision making. They should also acknowledge the influence of the spatial configuration on the modelling of environmental outputs in the foreground level, making the modelling framework also more suitable to evaluate medium and large NBS interventions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is shared in the Supplementary Material included in the article. The authors are available for clarifications

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2022.101506.

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