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Assessing Net Environmental and Economic Impacts of Urban Forests: An Online Decision Support Tool

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Abstract: Nature-based solutions (NBS) are becoming popular in urban planning and policy making as cost-effective solutions capable of delivering multiple ecosystem services and addressing several societal challenges. So far, however, the cost-effectiveness of urban NBS projects has not been consistently quantified by built environment professionals, who lack user-friendly tools to account for the environmental costs and benefits of NBS. This paper presents a prototype online decision support tool (NBenefit$®) that calculates the negative and positive environmental impacts, externalities, and financial values of planned urban forests over their entire life cycle. NBenefit$ relies on a modelling framework that combines system dynamics, urban ecology, and life cycle thinking approaches, and it is presented as a visual web-based interface. An online map and a grid of cells is used to map the site of intervention, to delineate the size of the urban forest, and to define variations in abiotic, biotic, and management attributes in each site. Outputs are provided by year, for the entire site and NBS life cycle. The potential value of NBenefit$ as a supporting tool was exemplified with the calculation of 48 urban forest archetypes, a few of which were used to set scenarios for a hypothetical urban forest in Madrid (Spain). The results showcase the impact that decisions taken during the planning, design, or management of an NBS project may have on its long-term performance. Future works will expand the scope of NBenefit$, including other types of urban NBS.

Keywords: nature-based solution (NBS); green infrastructure; ecosystem service; life cycle assessment (LCA); life cycle costing (LCC); urban sustainability

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Citation: Babí Almenar, J.; Petucco, C.; Navarrete Gutiérrez, T.; Chion, L.; Rugani, B. Assessing Net Environmental and Economic Impacts of Urban Forests: An Online Decision Support Tool. *Land* **2023**, *12*, 70. https://doi.org/10.3390/land12010070

Academic Editors: Thomas Panagopoulos and Vera Ferreira

Received: 4 December 2022
Revised: 19 December 2022
Accepted: 22 December 2022
Published: 26 December 2022

1. Introduction

The use of nature-related concepts such as green infrastructure, ecosystem-based approaches, or nature-based solutions (NBS) have been recently pushed forward by policy makers, researchers, and innovative built environment professionals [1–3]. These concepts frame natural features or actions applied on them as solutions that supply or enhance the provision of ecosystem services (ES), i.e., ecosystem flows from which some societal benefits derive [4]. In particular, NBS are described as solutions inspired and supported by nature that address multiple societal challenges and produce multiple environmental, social, and economic benefits in a cost-effective way [5,6]. Specific examples of urban NBS include solutions such as urban forests, green roofs, green walls, and bioswales (see [7] for a detailed list). Urban forests, i.e., any woodland, group of trees, or individual trees present in urban or periurban areas [8], have especially attracted attention due to the wide range of ES that they supply [7,9].

To mainstream NBS, including urban forests, as a sustainable solution for urban areas, it is necessary to quantify their capability to address multiple societal challenges and their potential to provide multiple co-benefits in a cost-effective way. Cost-effectiveness is a key factor in the case of NBS, and it is rarely included in other nature-related concepts (see definitions in [10]). NBS are thus cost-effective solutions that should provide social, economic, and environmental benefits. When considered together, these benefits are expectedly higher than costs, generating a net benefit.

To assess the costs and benefits of urban NBS projects, ES accounting is considered a suitable approach [7,11]. In this approach, the benefits derived from nature, which are typically positive externalities, can be internalised. However, ES assessment methods tend to be framed ad hoc, i.e., they are non-generalizable, which hampers their widespread application to inform NBS projects over multiple urban settings [12,13]. In addition, ES methods do not usually account for the negative environmental impacts produced by NBS (e.g., CO_2 emissions from life cycle management actions) or for their associated negative externalities (i.e., expenditures resulting from environmental damages, for which a market does not exist) and other financial costs (e.g., tree planting material costs). To cover these gaps, some studies assessed the "disservices" associated with NBS [14–16], others the life cycle financial costs making use of life cycle costing (LCC) [17,18], and some others negative environmental impacts by applying life cycle assessment (LCA) [19–23]. Overall, those studies suggest that other flows, beyond ES, should be accounted for in order to plan, design, and manage cost-effective urban NBS. Such efforts should be accompanied by the development of generalizable assessment methods that are potentially applicable to a broad range of urban settings and NBS.

Several generalizable ES assessment methods were already developed in the form of ES modelling tools that can be used as decision support tools for NBS planning. Some of these tools (e.g., InVEST, LUCI) assess ES supply based on land use/cover classes [24–27] and mainly focus on large spatial levels and rural contexts. However, land use/cover classes do not offer baseline data to assess some types of urban ES, such as regulating services [13], and might not be adequate for the assessment of specific urban NBS interventions either. Attempts at modelling that focus on urban systems are thus being developed for some of those tools (e.g., urban cooling InVEST) by considering additional variables beyond land use/cover classes. A second group of ES modelling tools originally developed for rural systems, such as RothC [28], SWAT [29], and BIOME [30], although requiring a higher and more diversified number of inputs (e.g., leaf area index, tree species), are able to identify spatio-temporal changes in ES at a scale suitable for modelling urban ES flows. A third group of tools, e.g., i-Tree [31], ENVI-met [32], and SWMM [33], were developed to specifically assess urban ES flows, for which they consider detailed attributes of NBS and their surrounding urban contexts.

Despite their strengths, all these tools still suffer from one or more of the following drawbacks [13,34,35]: (i) time-consuming data collection; (ii) lack of monetisation of ES values; (iii) missing consideration of negative environmental impacts or ES demand; (iv) inability to perform the simultaneous modelling of multiple ES over time. More details about these limitations are provided in Supplementary Material (SM) 1.

To become operational, generalizable assessment methods for NBS should be integrated in urban planning and design workflows via new tools. These tools need to be user-friendly and should require a low computational/technical effort, facilitating access to targeted users (e.g., architects, landscape architects). Scholars identified that a strong reliance on high environmental modelling knowledge would hamper the use of environmental analysis by practitioners [36]. Those knowledge accessibility barriers could explain, in part, why environmental assessments are generally absent or conducted only at advanced project stages [37,38]. Nevertheless, as suggested in the MacLeamy curve (Figure 1), applying environmental assessments at early planning/design stages is more desirable than at advanced stages because time (and budget) effort is reduced and there is more room to influence functionality and performance [39,40]. In the case of urban NBS, complexity and knowledge uncertainty about their capacity to deliver net benefits, together with a lack of decision support tools suitable for practitioners, currently represent knowledge barriers for NBS implementation [41–43]. Hence, user-friendly, low computational, and practitioner-oriented decision support tools might encourage the integration of NBS assessment procedures at early planning/design stages.

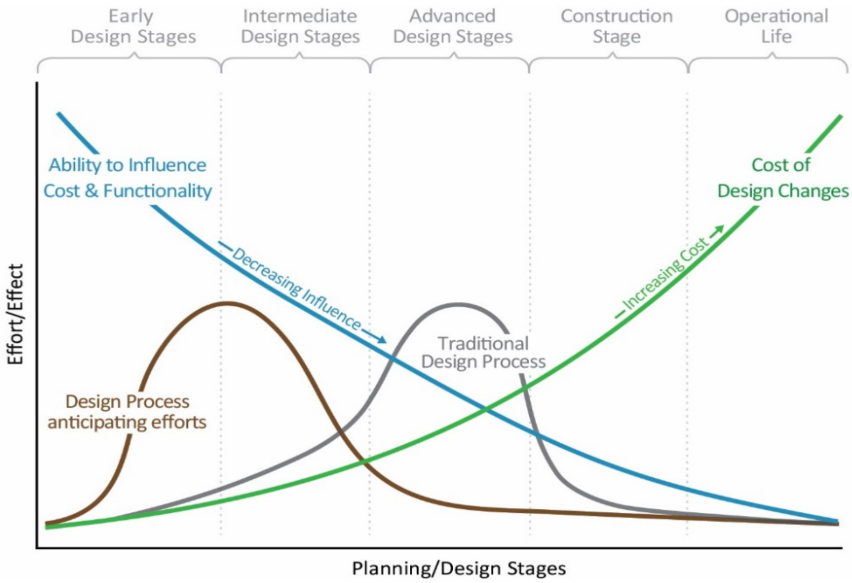

Figure 1. The MacLeamy curve (see [40,44]) for a detailed description). It illustrates the increasing cost of modifications in projects as the design/planning process progresses.

This paper aimed to overcome the abovementioned limitations in urban NBS assessments. It strived for a more comprehensive assessment of net environmental and economic impacts of NBS over their entire life cycle through the development of a generalizable online prototype decision support tool. The decision support tool was named NBenefit$® and calculates negative and positive environmental impacts, externalities, and financial values of planned urban forests, as an example of relevant NBS. The software relies on an underpinning modelling framework that combines system dynamics, urban ecology, and life cycle thinking methods, allowing it to go beyond the mere quantification of ES flows. Moreover, NBenefit$ can be easily integrated in urban planning and design workflows because it was conceived as a user-friendly tool with low computational requirements and can inform urban NBS decisions at early planning and design stages. The SM2 includes access details to an online demo of NBenefit$.

The next section conceptualises NBenefit$ and its framework and describes its design, building, and operation for urban forests. Section 3 illustrates the value of NBenefit$ via two simple urban forest examples. Section 4 discusses the current limitations and advantages of the tool and anticipates future work.

2. Methods: NBenefit$ from Concept to Online Decision Support Tool

NBenefit$ conceptualises and models urban forests as pre-calculated archetypes. Archetypes represent the combination of abiotic (e.g., soil texture, climate), biotic (e.g., plant species), and management (e.g., irrigation) attributes that influence spatio-temporal variations of an NBS. The environmental and economic performance of the archetypes is pre-calculated, making use of an underpinning modelling framework and a specific urban forest model derived from it.

This framework was developed at two modelling levels: foreground and background. The foreground is based on a system dynamics model that computes the externalities occurring in the sole "use" phase of the NBS life cycle, i.e., from NBS implementation on site until the solution remains operational. The background is based on a steady state model that accounts for externalities and financials costs all along the life cycle phases: "implementation", "use", and "end-of-life". The NBS implementation phase extends from raw material extraction (e.g., minerals for fertilisers) until the delivery of seeds or plants to the NBS site, whereas the end-of-life phase spans from the management and collection of dead components (e.g., leaf litter, dead branches or trees) up to waste treatment. From this modelling framework, specific foreground models can be developed for each NBS type (e.g., urban forest, green roof, urban wetland). So far, only an urban forest model has been created for NBenefit$ using Simile, i.e., a visual declarative modelling software [45]. Section 2.2 provides an overview of the calculations performed for the urban forest model. Further details are included in the SM3, and a full description of the modelling framework and the urban forest model is provided in [46].

The development of NBenefit$ was split into three steps: the design step, the building step, and the operation step (Figure 2). The design step covers the selection of benefit and cost items, and the definition of archetypes for each NBS type. The building step corresponds to the creation of the specific NBS-type model, the NBenefit$ platform, and the pre-calculation of archetypes. The operation step defines the interaction of built environment professionals (users) with the platform.

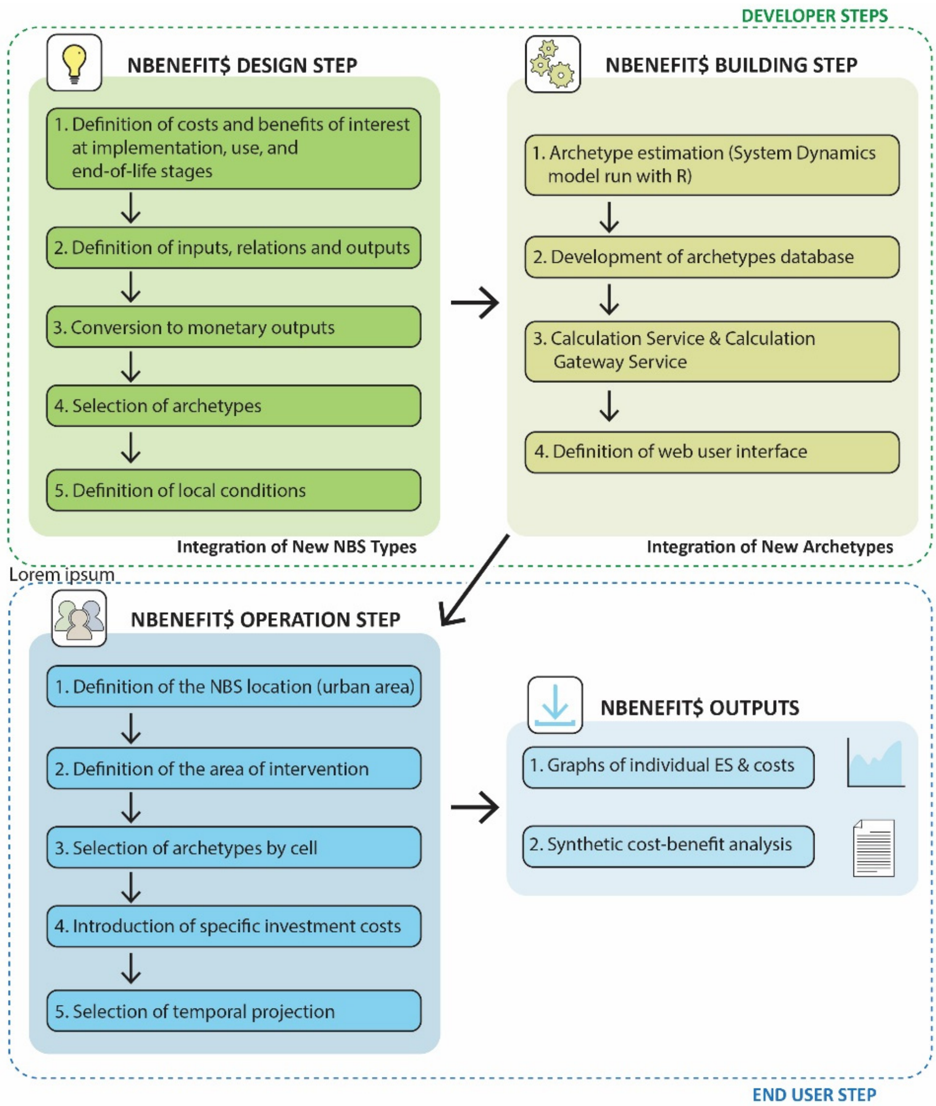

Figure 2. Schematic diagram of the design, building, and operation steps characterising NBenefit$.

2.1. NBenefit$ Design Step

In the first step, the NBS type of interest is identified together with the relevant positive and negative environmental impacts, externalities, and financial values in each

NBS life cycle phase (implementation, use, and end-of-life). NBS costs comprise negative externalities (i.e., the monetisation of detrimental environmental impacts) and financial expenditures (e.g., payment for plants or management actions). NBS benefits include positive externalities (mainly the monetization of ES flows, not representing real cash flows) and financial revenues (e.g., from selling wood or timber, whose generation is also an ES flow).

In the second step, the relevant socio-ecological processes, human actions, and NBS attributes affecting environmental impacts, externalities, and financial values are identified. Table 1 summarises the actions and ES from which costs and benefits are derived in the current prototype of NBenefit$. It also indicates the life cycle phases in which these costs and benefits occur, the socio-ecological processes modelled to calculate them, and the main attributes influencing those processes. Those attributes become inputs in the urban forest model and the NBenefit$ platform. Figure 3 summarises the biophysical indicators used to represent positive and negative environmental impacts in biophysical units. It also indicates for which categories positive and negative impacts are equivalent but inverse in value. For example, *Global Warming Potential*, calculated by accounting for CO_2-equivalent emissions, and *Regulation of the chemical condition of the atmosphere*, calculated by accounting for the mass of biogenic CO_2 storage, are equivalent impact indicators for which a net gain (benefit) or loss (cost) can be estimated from their difference.

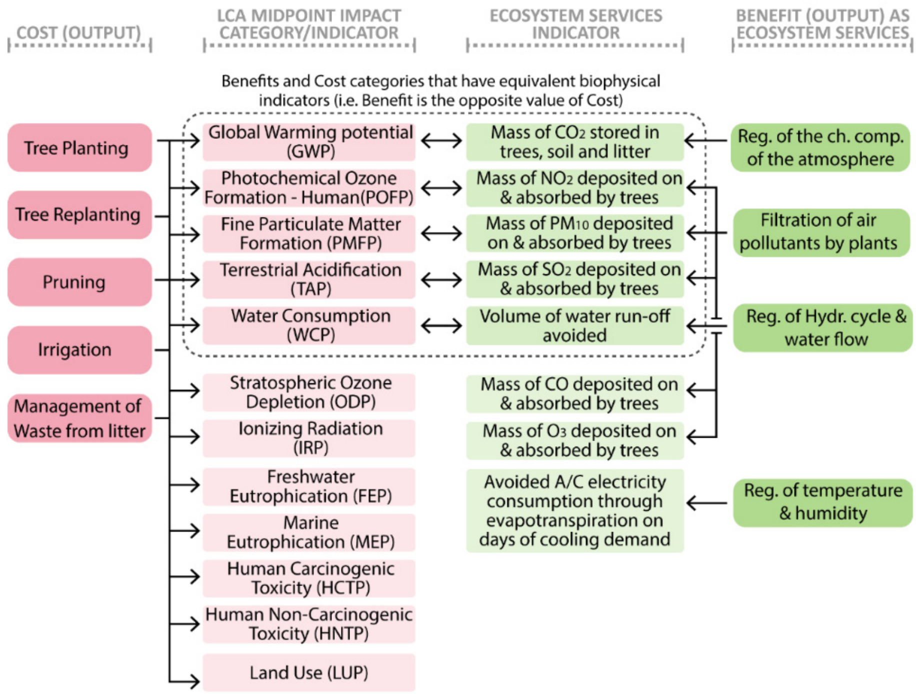

Figure 3. Biophysical indicators that represent cost and benefits in the form of negative and positive environmental impacts. The cost and benefits with equivalent indicators are highlighted. All the costs (outputs) contribute to environmental impacts represented by life cycle assessment (LCA) midpoint impact categories.

In the third step, positive and negative environmental impacts are monetised to calculate externalities by making use of value transfer methods. These methods rely on monetary values from other studies that are initially obtained through primary valuation methods. Values are then transferred and adapted to new case studies for which conditions are considered equivalent. Value transfer is common practice in ES monetary valuation (e.g., [47–49]). Moreover, a number of platforms and inventories/databases collect economic values on ES and life cycle assessment (LCA) to provide data for value transfer (e.g., [50–52]).

Table 1. Costs and benefits of urban forests, the main processes influencing outputs, and the main attributes influencing processes.

	Costs and Benefits	Life Cycle Phase	Main Processes	Main Biotic, Abiotic, and Management Attributes
Management Actions (COSTS)	**Tree planting ***	Implementation	Tree management in nurseries, transport to site, planting	Species, initial tree size/age at planting, average transport distance, planting techniques and machinery
	Amount of tree replanting ** (due to premature death)	Operational	Plants morbidity and plant mortality	Species, initial tree size, stress factors (paving, drought, waterlogging), mortality statistics ***
	Pruning	Operational	Vegetation growth (branches)	Species, initial tree size, percent of branch to be pruned, pruning techniques and machinery
	Irrigation	Operational	Storage of available soil water, soil evaporation, vegetation transpiration, infiltration, percolation	Soil texture, initial available soil water
	Management of waste from litter and dead wood	End-of-life	Leaf, branch decay, and plant mortality	Species, initial tree size, mortality records, branch and leaf decay rate, plant management
Ecosystem Services (BENEFITS)	**Regulation of the chemical composition of the atmosphere**	Operational	Vegetation growth, drought and waterlogging, death	Species, initial tree size, growth rate, decay rate, soil texture, threshold to stress factors
	Regulation of temperature and humidity	Operational	Free evaporation during rainy days, soil evaporation, vegetation transpiration	Species, initial tree size, growth rate, ratio tree size to leaf area, daily precipitation, daily temperature, dormant periods (deciduous trees), soil texture, available soil water
	Hydrological cycle and water flow regulation	Operational	Vegetation interception, infiltration, percolation, soil evaporation, vegetation transpiration	Species, initial tree size, growth rate, ratio tree size to leaf area, daily precipitation, daily temperature, dormant periods (deciduous trees), soil texture, available soil water
	Filtration of pollutants by plants	Operational	Dry deposition, vegetation transpiration	Species, initial tree size, tree height, growth rate, ratio tree size to leaf area, precipitation, temperature, air pollutant levels (CO, NO_2, SO_2, O_3, PM10), wind, solar radiation

Notes: * Specific tree-planting schemes are decided by the landscape designer, the client, and in some cases, guided by external consultants as part of the design process. The model only accounts for the differences in cost due to species, size (age = amount of time in the nursery), and planting system. It does not integrate the fees paid to professionals working on a project. ** The model assumes that the same species and initial planting size are used for replanting if the tree dies. It assumes mandatory replanting after one year if the dead tree was planted less than 10 years ago, and after three years, if the dead tree was planted for the first time more than 10 years ago. *** Currently mortality statistics are taken from the existing literature but can be obtained from available local data.

For the current prototype of NBenefit$, monetary estimations of negative externalities are mainly obtained from a handbook of environmental prices valuable for the European Union [50]. For positive externalities, values from the same handbook [50] are complemented with those obtained in a review of monetary ES valuation provided by NBS [53]. Ultimately, specific literature is used to cover the gap of values not disclosed by those two sources. Values that are transferred are corrected for the purchasing power parity, inflation, and the income effect [53–55]. Current monetary values used in NBenefit$ are summarised in SM4.

In the fourth step, the archetypes for an NBS type are defined at different levels of detail to meet the needs of different planning/design stages in NBenefit$ (Table 2).

At early planning/design stages, e.g., strategic definition and concept design (see [56] for an example of design stages), archetypes are similar to land cover classes, such as deciduous forests (First and Second levels in Table 2). This level of definition of the archetypes is coherent with data availability on site condition and with how professionals plan/design NBS in early stages, i.e., mainly as zoning diagrams equivalent to land-use/cover maps.

For intermediate and advanced stages, NBenefit$ offers urban forest archetypes differentiated for vegetation species, plant size/age at planting, soil texture, and management actions. This is to align with the high granularity of data (e.g., tree species, size of trees to be planted, management actions) needed for the design stages. It is also coherent with what professionals expect from decision support tools, i.e., to compare alternatives in a detailed manner and to capture changes in benefits and costs when specific abiotic, biotic, or management attributes are modified in an NBS project.

For urban forests, Figure 4 presents the configuration of biotic, abiotic, and management attributes (and their potential combination) currently available in NBenefit$.

Figure 4. Biotic, abiotic, and management attributes that define urban forest archetypes in the system dynamics model underneath NBenefit$.

Table 2. Levels of aggregation of archetypes according to tree species attribute. The first and second levels correspond to a combination of several species (disaggregated archetypes) and represent land use/cover classes.

<table>
<tr><th colspan="2">Early Planning/Design Stages</th><th>Intermediate and Advanced Planning/Design Stages</th></tr>
<tr><th>Second Level Archetypes ***</th><th>First Level Archetypes **</th><th>Disaggregated Archetypes *</th></tr>
<tr><td rowspan="10">Mixed urban forest (75% evergreen/25% deciduous)</td><td rowspan="14">Evergreen urban forest</td><td>Quercus ilex</td></tr>
<tr><td>Eucaliptus globulus</td></tr>
<tr><td>Brachychiton populneum</td></tr>
<tr><td>Acacia melanoxylon</td></tr>
<tr><td>Magnolia grandiflora</td></tr>
<tr><td>Ceratonia siliqua</td></tr>
<tr><td>Cedrus deodara</td></tr>
<tr><td>Juniperus virginiana</td></tr>
<tr><td>Ilex Opaca</td></tr>
<tr><td>Prunus caroliniana</td></tr>
<tr><td rowspan="9">Mixed urban forest (50% evergreen/50% deciduous)</td><td>Pinus sylvestris</td></tr>
<tr><td>Pinus nigra</td></tr>
<tr><td>Pinus strobus</td></tr>
<tr><td>Pinus radiata</td></tr>
<tr><td rowspan="14">Deciduous urban forest</td><td>Platanus acerifolia</td></tr>
<tr><td>Tilia cordata</td></tr>
<tr><td>Acer palmatum</td></tr>
<tr><td>Prunus serrulata</td></tr>
<tr><td>Aesculus hippocastanum</td></tr>
<tr><td rowspan="9">Mixed urban forest (25% evergreen/75% deciduous)</td><td>Quercus palustris</td></tr>
<tr><td>Fraxinus americana</td></tr>
<tr><td>Celtis occidentalis</td></tr>
<tr><td>Populus balsamifera subsp. Trichocarpa</td></tr>
<tr><td>Pyrus calleryana 'Bradford'</td></tr>
<tr><td>Robinia pseudoacacia</td></tr>
<tr><td>Carpinus betulus 'fastigiata'</td></tr>
<tr><td>Betula pendula</td></tr>
<tr><td>Liquidambar styraciflua</td></tr>
</table>

Notes: * Disaggregated archetypes are perennial and deciduous species extensively used in European urban areas, for which there are available allometric equations. Species were selected with the support of French experts on plants and landscape design, making use of a 2007 French street tree census [57] and a compilation of species from 81 nursery catalogues and collections (including botanical gardens). ** First level aggregated archetypes are made by the equal combination of disaggregated archetypes split by evergreen and deciduous. *** Second level aggregated archetypes are made by the combination of evergreen and deciduous First level archetypes.

The last operation in the design step of NBenefit$ is the definition of the local context, which focuses on meteorological conditions (i.e., temperature, wind speed, and precipitation) and air quality (i.e., concentration of CO, SO_2, NO_2, O_3, and PM10). The system dynamics model underpinning NBenefit$ includes a weather and air pollutant ambient levels generator, which provides those variables at a daily level and allows for the modelling of socio-ecological processes. The generator provides daily values inside a realistic range to keep accuracy at a monthly level without disregarding the seasonal variations.

2.2. NBenefit$ Building Step

In this step, the modelling of archetypes per NBS type are related to the web user interface by making use of four core components: offline archetype model, archetype database, calculation service, and web user interface (Figure 5).

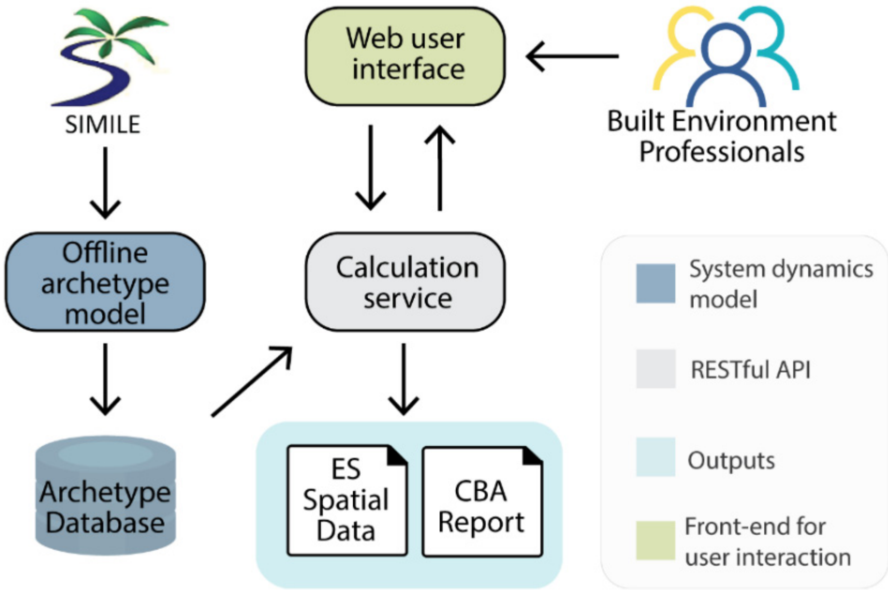

Figure 5. Relationship between the main components of NBenefit$ and their outputs; CBA = costs-benefits analysis; ES = ecosystem services; API = application programming interface.

2.2.1. Offline Archetype Model and Archetype Database

In the offline archetype model, the urban forest archetypes defined in the design step are pre-calculated. First, their environmental performance (i.e., supplied ES and applied management actions) during the NBS life cycle operational phase is estimated in biophysical units. Such a performance is calculated using the system dynamics model for urban forests (the foreground level) built in Simile, which is compiled and run via the open statistical software R [58]. Outputs are calculated at daily and monthly temporal resolutions and then aggregated into yearly time steps. Yearly aggregations are used because the scope of NBenefit$ is to inform about the performance of NBS over their entire life cycle. However, modelling at a detailed temporal resolution is necessary because most of the socio-ecological processes are scale-sensitive due to their non-linearity (e.g., water infiltration, transpiration). Otherwise, the model would fail to account for dynamics (e.g., soil water balance) that occur at a much shorter time scale than years [59].

Due to the stochasticity of some ecological processes in the system dynamic model (e.g., rainfall, tree mortality, replanting), several simulations are run to obtain representative estimates of the archetypes (i.e., the mean and standard deviation of each output are representative of the range of potential values). To achieve a satisfactory number of replications, successive differences in the yearly mean and standard deviation for all the outputs are analysed for each additional replication [60] (see SM5 and SM6 for details about this analysis).

Once the performance of an urban forest archetype is calculated for the operational phase, its inputs (main abiotic, biotic, and management attributes) and part of the outputs from the system dynamics model are used to characterise the negative environmental impacts generated in all phases of the NBS life cycle. These impacts are assessed in the background level (steady state model), applying a life cycle impact assessment (LCIA) approach [61] with the support of the LCA software SimaPro, making use of the ReCiPe 2016 method at mid-point level [62]. To characterise midpoint level impacts, substance flows that have the potential to contribute to the same environmental effect are grouped in single impact categories (e.g., eutrophication, climate change). Such an operation of aggregation is similar to the quantification of positive environmental effects that occur in the ES biophysical assessment.

Once the negative and positive environmental impacts (i.e., ES classes and life cycle impact categories) are calculated in biophysical units for all the life cycle phases, their values are monetised (i.e., estimation of externalities) and stored in the archetype database. Lower and upper monetary values are also computed to provide the level of uncertainty in the monetisation of each environmental impact. The lower and upper boundaries depend on two factors: (i) on the range of values found in different source studies computing the total economic value of a specific ES; (ii) on the standard deviation of each type of environmental impact (in biophysical units) modelled. This helps to showcase that monetary values should be understood as indicative ranges and not as exact outputs and to show how the variability (uncertainty) from the environmental assessment propagates in the calculation of externality values.

On top of the externality values, the financial values (representing expected cash flows related to the NBS project) are added based on publicly available national cost databases and local datasets on expenses. Similarly, for financial values, central, lower, and upper monetary values are also provided. Accordingly, the valuation of economic impacts combining externality and financial values provides a better understanding of the net economic value of an NBS archetype (by year and for its entire life cycle).

Once all environmental impacts, externalities, and financial values are calculated for an archetype, values are stored in the archetype database of NBenefit$. End users of NBenefit$ do not need to re-calculate archetypes, as it is a time-consuming task on the side of the NBenefit$ developers. In this sense, the archetype database acts as a repository of disaggregated values for all the pre-calculated archetypes. The database is linked to the web user interface through a RESTful API, i.e., the calculation service (Figure 5).

2.2.2. Calculation Service

The calculation service is a RESTful API written in Python language, in which all the environmental impacts, financial values, and externality values for a specific urban forest intervention are produced. Once the combination of different archetypes for a specific urban forest intervention is defined in the web user interface, the calculation service obtains the disaggregated values and calculates the overall balance of environmental impacts and monetary values (financial and externality) for the specific intervention.

2.2.3. Web User Interface

The web user interface is split into two sections: the mapping component and the sidebar (Figure 6). The mapping component is presented as a window that embeds an Openstreet map. It also holds the cell grid. The sidebar helps the user to introduce the different NBS types (urban forest in this research) and archetypes applied to each cell in the grid. It also contains the button to run the decision support tool.

2.3. NBenefit$ Operation Step

This step allows for the user to define location, area of the project, and archetypes of the planned urban forest to be evaluated by NBenefit$. The mapping component can be used to identify the specific urban area and site where the urban forest project will be located. Locations are associated with the parametrisation of meteorological conditions. Once the site of intervention is identified in the mapping component, the main biotic, abiotic, and management attributes of the urban forest can be defined, and their combination automatically calls the pre-calculated archetypes to be retrieved for the NBS assessment.

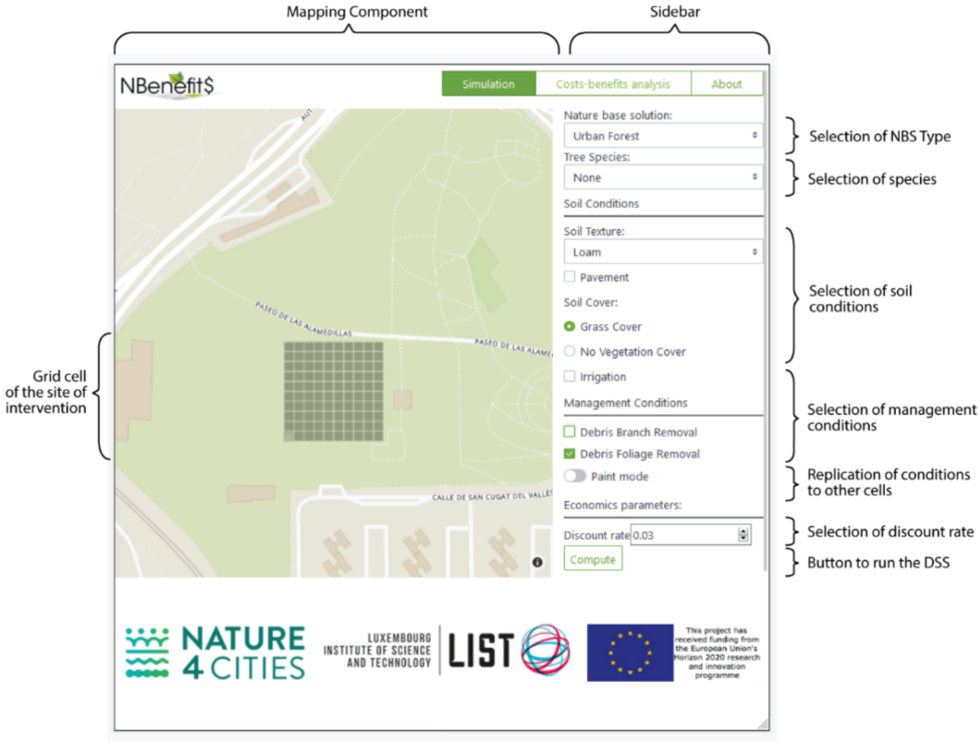

Figure 6. NBenefit$ web user interface, components, and description.

The sidebar provides qualitative options for each attribute (those presented in Figure 4). Attributes can be input cell by cell, since some attributes, e.g., tree species and their upstream archetypes, may change over space in a same project. This means that NBenefit$ allows multiple combinations of archetypes to ensure its applicability to complex urban forest projects. A discount rate can also be applied to future costs and benefits if needed. Once the inputs are set for each cell, the simulation can start by clicking on "Compute". This action sends the data from the web application to the calculation service, where they are processed.

2.4. *NBenefit$ Outputs*

NBenefit$ provides two main types of outcomes: (1) a graph of the evolution of each environmental impact (in biophysical units), externality, and financial value (in monetary units) over time (Figure 7); and (2) a simplified cost-benefit analysis for the entire life cycle of the specific NBS intervention.

This second output is also provided as a downloadable report in PDF format that includes a balance of positive and negative environmental impacts and the cost-benefit analysis of financial and externality values. For the balance of positive and negative environmental impacts, the outputs are provided by process/activity per life cycle stage (e.g., pruning) and as an aggregated total for the entire life cycle. The outputs are also shown as bar charts. The average value by impact category for an evaluated alternative (i.e., sum of all cell values divided by number of cell) is compared against a reference value. This comparison is intended to inform on the magnitude of the impacts associated with the NBS, and thus, to allow for an immediate understanding by non-experts (see for instance Figure 15). The environmental reference used is the impact of an average person in the world for the year 2010 (values are provided in SM7). Alternative environmental references for the normalisation of graphical outputs may also be applied in the decision support tool if considered more suitable for a specific project.

Figure 7. Online summary of the cost-benefit analysis and graph visualisation generated by the web user interface in NBenefit$.

In the case of cost-benefit analysis, outputs are provided by process/activity per type of cost and benefit (externality or financial) as well as a net value for the entire life cycle of the planned NBS in both tabular and graphic format. By default, the graphical format of the results is normalised, making use of the total value of the alternative with the highest net benefits as a reference value (see for instance Figure 16). The selection of a reference value intends to provide an easy comparison of total and disaggregated outputs. As in the case of the environmental assessment, the reference can be replaced by other options.

3. Application of NBenefit$ to Evaluate Urban Forests

To illustrate the functionality of NBenefit$, 48 urban forest archetypes were prepared for the environmental conditions of Barajas, in the northeast of Madrid (Spain). Section 3.1 provides an overview of these archetypes. Detailed output data for the 48 archetypes are provided in SM8. In Section 3.2, three alternatives using three archetypes are tested for a hypothetical project of a small urban forest (0.1 Ha, 10 cells).

3.1. Biophysical and Monetary Outputs of NBenefit$ for 48 Urban Forest Archetypes

The archetypes are represented in this paper as a grid of cells (Figure 8) such as the ones used in NBenefit$. The overall performance of each archetype in biophysical units as well as in monetary units is illustrated in Figures 9 and 10. Discounting is not applied for this illustrative exercise. Standard deviation values are shown in Figures 11–13, which were used to compute the lower and upper monetary values.

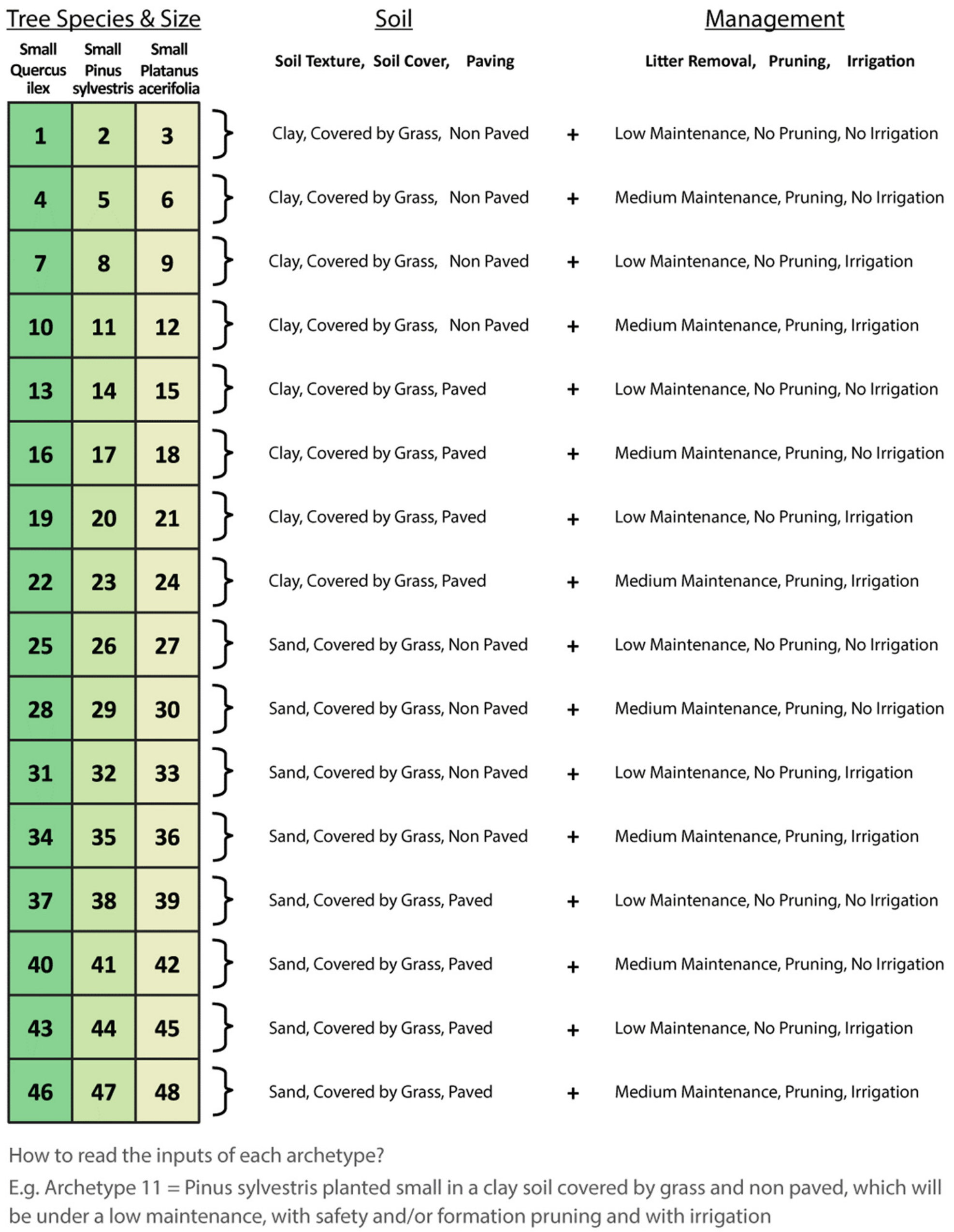

Figure 8. Figure 8. Attributes of 48 illustrative urban forest archetypes modelled for the local conditions of Barajas in the northeast of Madrid (Spain). An example of how to read the attributes of each archetype, and which combination of attributes corresponds to each archetype number, is provided at the bottom.

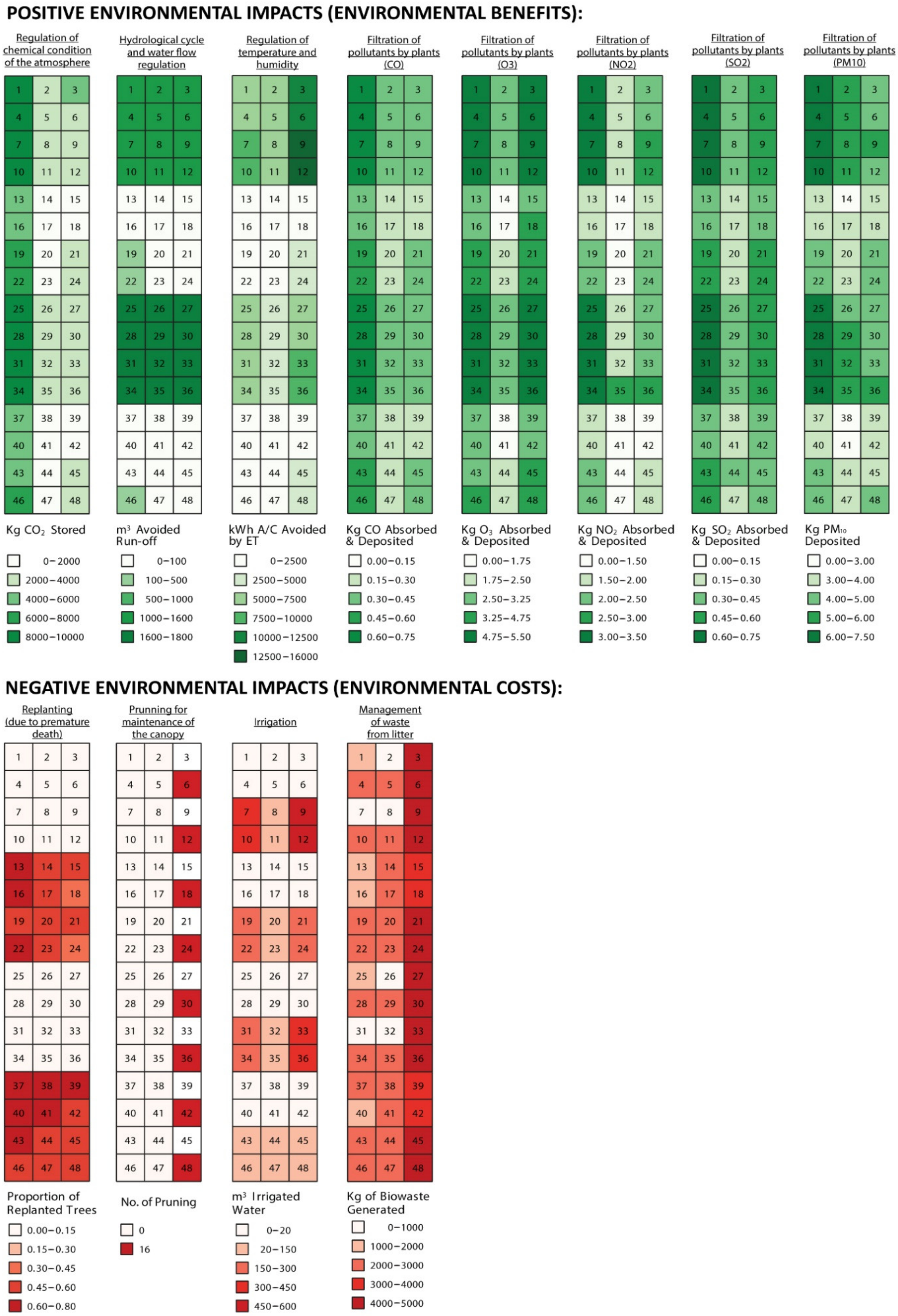

Figure 9. Mean cumulative benefits and costs over the operational stage of the 48 urban forest archetypes in biophysical units.

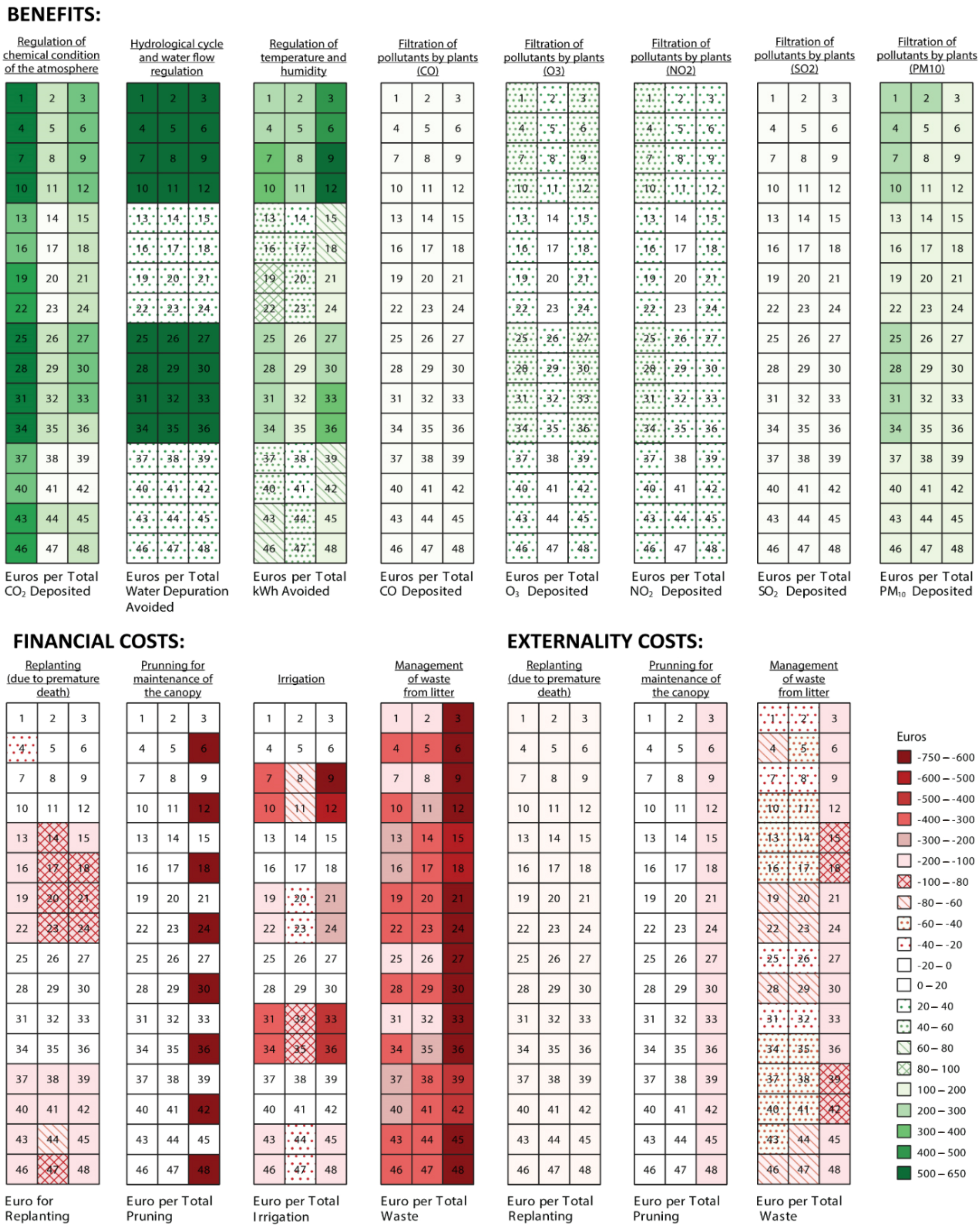

Figure 10. Mean cumulative benefits and costs (externalities and financial) over the operational phase of the 48 urban forest archetypes in monetary units.

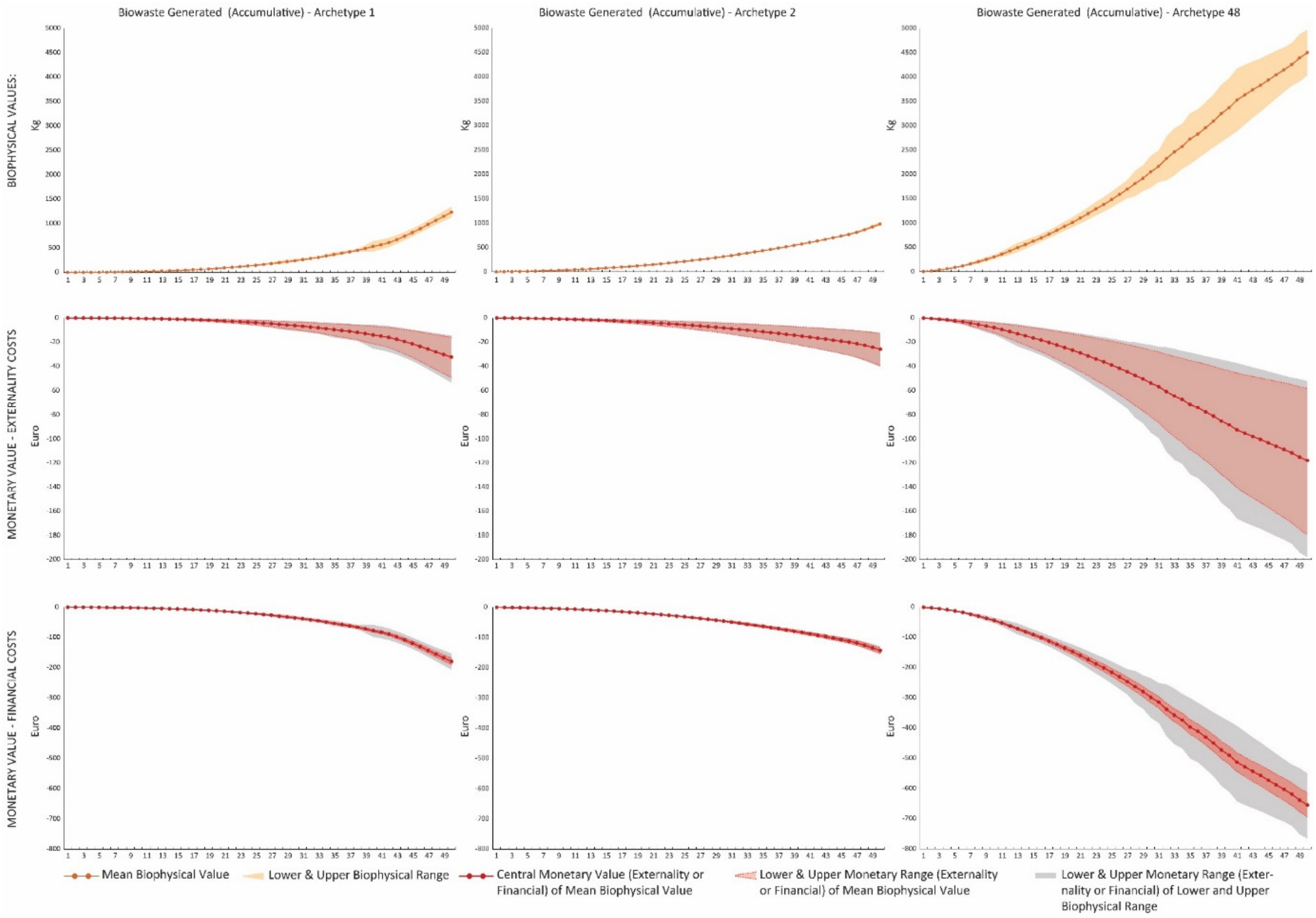

Figure 11. Comparison of biophysical and monetary performance over time for "Management of waste from litter" in archetypes 1, 2, and 48. Results are shown as cumulative values over time (i.e., value at year 50 is the accumulated value from year 1 to 50).

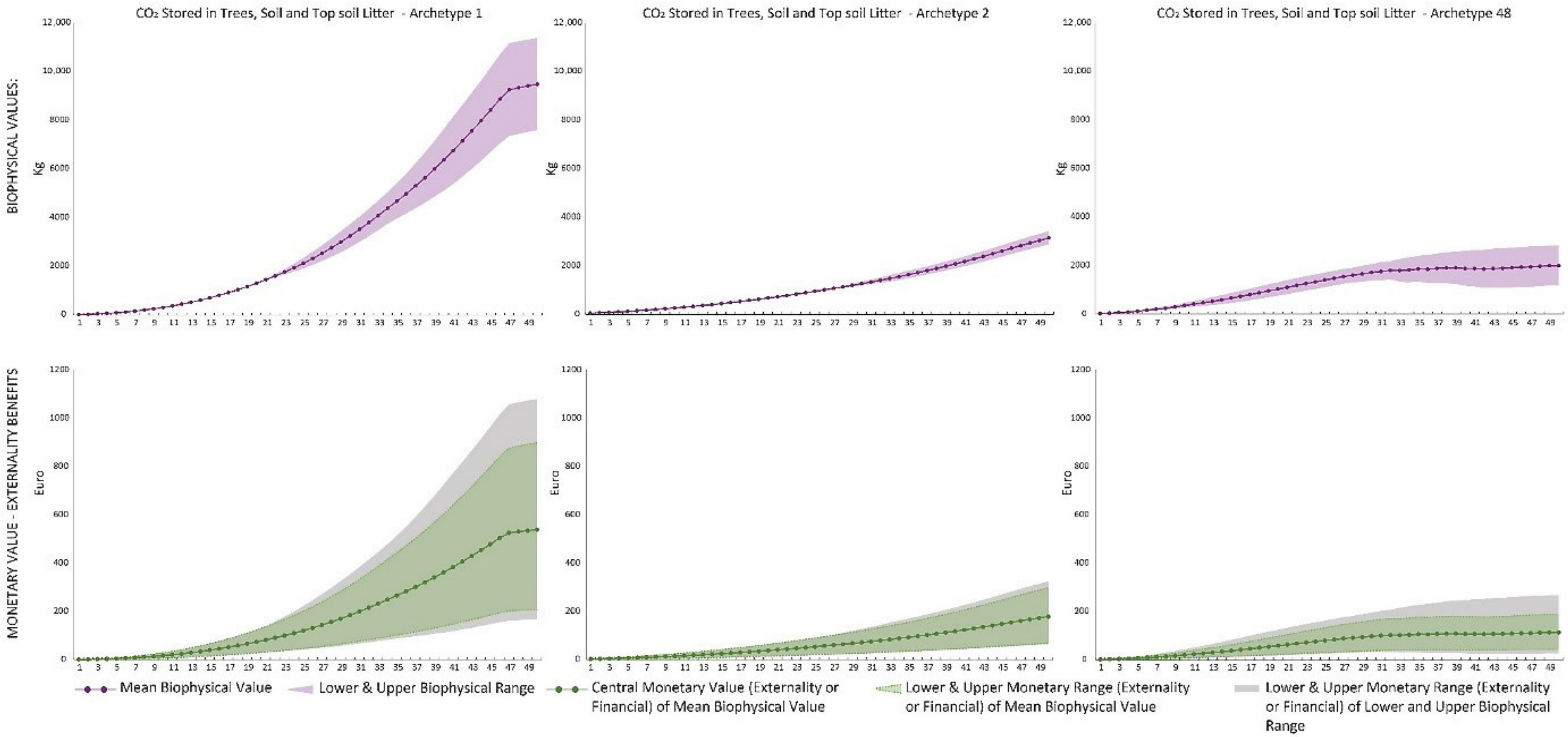

Figure 12. Comparison of biophysical and monetary performance over time for "Regulation of chemical condition of the atmosphere" in archetypes 1, 2, and 48. Results are shown as cumulative values over time (i.e., value at year 50 is the accumulated value from year 1 to 50).

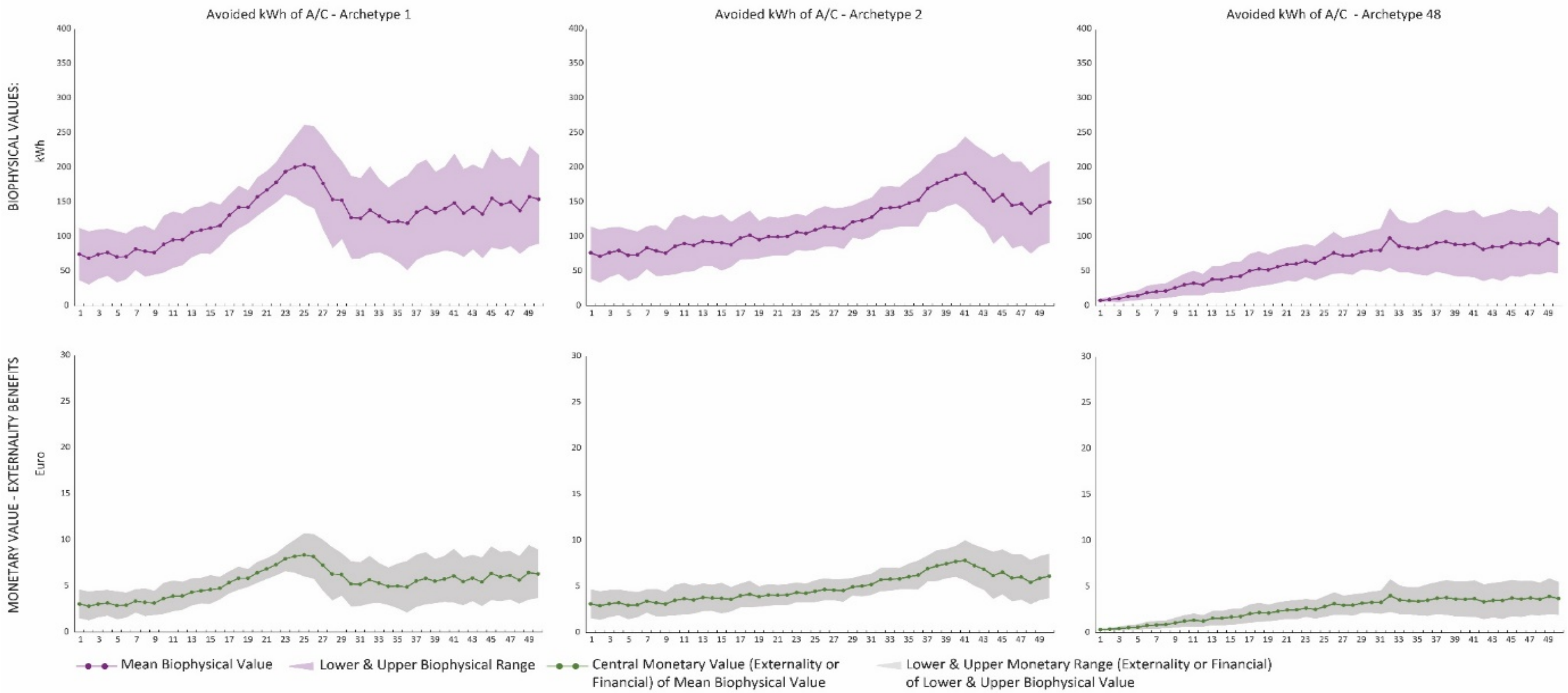

Figure 13. Comparison of biophysical and monetary performance over time for "Regulation of temperature and humidity" in archetypes 1, 2, and 48. Results are shown as non-cumulative values (i.e., values represent the ones produced each year) to illustrate more clearly that this ecosystem service is not continuously increasing over time.

As Figures 9 and 10 illustrate, the 48 archetypes performed rather differently in terms of benefits (positive externalities) and costs (negative externalities and financial values).

For example, in the case of archetype 9, the ES *Regulation of temperature and humidity* is the dominant benefit, and *Irrigation* and *Management of waste from litter* are the dominant costs. The dominant benefit is explained by the fact that *Platanus acerifolia* has a high evapotranspiration rate [63] when it is not constrained by water limitations (e.g., in irrigated conditions such as in this archetype). This high evapotranspiration translates into a higher capacity to regulate temperature and humidity. The two dominant costs can be explained by the fact that irrigation is applied and *Platanus acerifolia* is a deciduous species that becomes rather large with a high leaf area, hence generating a great amount of leaf litter and dead branches over time.

As another example, the ES *Regulation of chemical condition of the atmosphere* is the dominant benefit for archetype 19. However, when looking at the results of archetype 19 in biophysical terms, it performed quite well for all the ES *Filtration of air pollutants by plants* compared to other archetypes. In terms of benefits, the results of archetype 19 are explained by the fact that *Quercus ilex* has a great long-term supply of carbon storage and it also has a high filtration capacity of common air pollutants. This ES does not spike in monetary terms because monetary values of air filtration are much lower than other types of benefits, at least in this specific application in Barajas. This can clearly be seen across all archetypes in Figure 10. Concerning costs, *Management of waste from litter* is the dominant negative financial and externality value for archetype 19. The high cost associated with waste management is explained by the fact that this archetype is under paved conditions. NBenefit$ assigns a higher threshold of maintenance to paved conditions, even in cases of low maintenance, compared to non-paved conditions. This is due to security concerns against some NBS ecosystem disservices (e.g., risk of dead branches falling, containment of leaf litter). The tool recognises that paved areas are highly used by people and that a minimum level of security and utility is required. These examples illustrate the relevance of planning and design decisions, which sometimes inherently include (or require) certain levels of utility and security.

The results illustrated in Figures 9 and 10 also help to highlight how the change in one or two attributes could affect the performance of an NBS. For example, archetypes 1 and 13 only differ in one input attribute; the former is non-paved, and the latter is paved. Nevertheless, that difference has a strong impact on the performance of the NBS in terms of benefits and, to a lesser extent, costs. This can be explained by the fact that paved soils impede the infiltration of water, reducing water availability for the tree. Consequently, the probability of water stress increases, and the tree transpiration is limited due to the lack of available water. Additionally, reduced transpiration also limits the dry deposition of pollutants and the growth rate of the tree, therefore diminishing carbon storage. As for archetype 19, the increased utility and security thresholds assigned to paved conditions in NBenefit$ increase waste management costs.

Displaying results disaggregated by year and by category (see Figures 11–13) helps to show the performance of an archetype over time and how long it takes to generate a significant benefit or cost.

For example, in the case of *Regulation of temperature and humidity* (Figure 13), it can be noticed that the yearly benefit is not always increasing, and the change occurs at different rates. Figure 13 shows how variable this benefit can be compared to other ES, because it does not only depend on attributes of the archetype, but it also depends on the variability of the meteorological conditions. Concurrently, the inclusion of standard deviation in the graphs as well as lower, central, and upper values for the monetisation makes the result variability more transparent. It allows us to evaluate whether changes in performance between archetypes are relevant or not in each specific case. For example, archetype 2 provides a higher *Regulation of the chemical condition of the atmosphere* than archetype 48, but as Figure 12 illustrates, this difference might not be significant in terms of benefits. Instead, when both archetypes are compared against archetype 1, it clearly appears that the latter outperforms them.

3.2. Evaluation of Three Hypothetical Alternatives for A Small Urban Forest

Three alternatives for a small urban forest were defined and tested to illustrate how a cost and benefit analysis report can be synthetically provided as outputs by NBenefit$. The characteristics of each alternative are summarised in Figure 14, while Figures 15 and 16 summarise the cost-benefit analysis of each alternative in biophysical and monetary units.

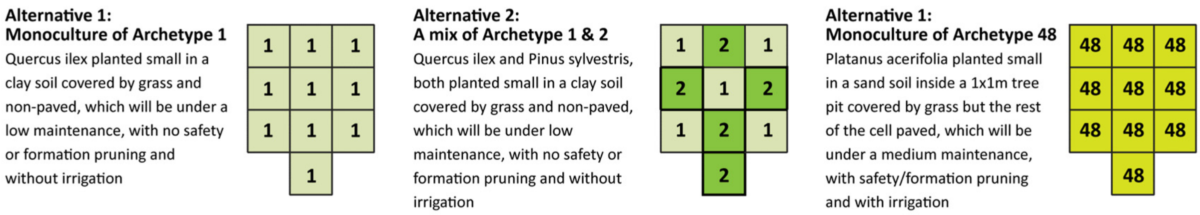

Figure 14. Characteristics of three hypothetical alternatives for a small urban forest of 0.1 Ha.

For the hypothetical alternatives, archetype 1 (including a broadleaved evergreen species) and archetype 2 (including a coniferous species) were selected because they are among the best performers for most of the benefits derived from ES as well as among the ones that have the least negative financial and externality values (costs). Similarly, archetype 48 (including a broadleaved deciduous species) was selected because it is among the worst performers of the 48 archetypes as well as among the archetypes with higher financial costs.

As illustrated in Figure 15, alternative 3 is clearly the worst option in terms of environmental impacts. In all the stages, it is the one with the highest negative environmental impact and the lowest positive environmental impact. In fact, there is only one action, i.e., planting, in which the three alternatives perform equally. This is because the elements used to characterise impacts are assumed to be the same in the underlying model (i.e., the time trees have spent in the nursery, transport distance and planting techniques). However, when comparing alternative 1 and 2, it was not clear if there was a significant difference in performance. Alternative 1 performed clearly better for *Regulation of chemical composition of the atmosphere*, but it contributed more to *Human carcinogenic toxicity*. For the rest of the categories, the numerical differences were minimal, and the graphical comparison of each category against the reference (impact of an average person) reinforced this interpretation. Since the biophysical evaluation does give only one side of the performance picture, this is one of the situations where the monetary valuation provided by NBenefit$ can complement the analysis.

As shown in Figure 16, alternative 1 had a total net benefit 10% higher than alternative 2; alternative 3 remained the worst performer, with a negative total net benefit. However, alternative 2 had slightly lower total financial costs, which means a reduced negative cash flow over the NBS life. Thus, for certain users with a stringent budget constraint, alternative 2 might be preferred, although there is a slightly lower net economic benefit. In this sense, the tool provides disaggregated information and indicators allowing the comparison across alternatives from different perspectives. Concurrently, looking at the whiskers of the net benefits, while the average value of alternative 1 is higher, this is inside a similar range of net benefit to alternative 2. By informing on the variability in outputs, NBenefit$ thus supports robust and informed decision making.

The disaggregation of cost and benefit items in the results reported by NBenefit$ can also help to identify structural differences in the economic performance. For instance, Figure 16 shows that the largest difference between the net benefits in alternative 1 and 2 was due to *Regulation of chemical composition of the atmosphere* (CO_2 storage). In NBS projects, it may occur that certain benefits have higher priority than others and, in these cases, a disaggregation such as the one provided by NBenefit$, is recommended. For example, in certain contexts, local climate regulation might be considered more relevant compared to increased CO_2 storage capacity. The tool could help to discriminate between alternative NBS projects with similar cost-benefit ratios, solve trade-offs between ES provision, or rank alternatives via lexicographic orderings. The disaggregation of outputs beyond the overall net benefit value further enhances the decision-making power.

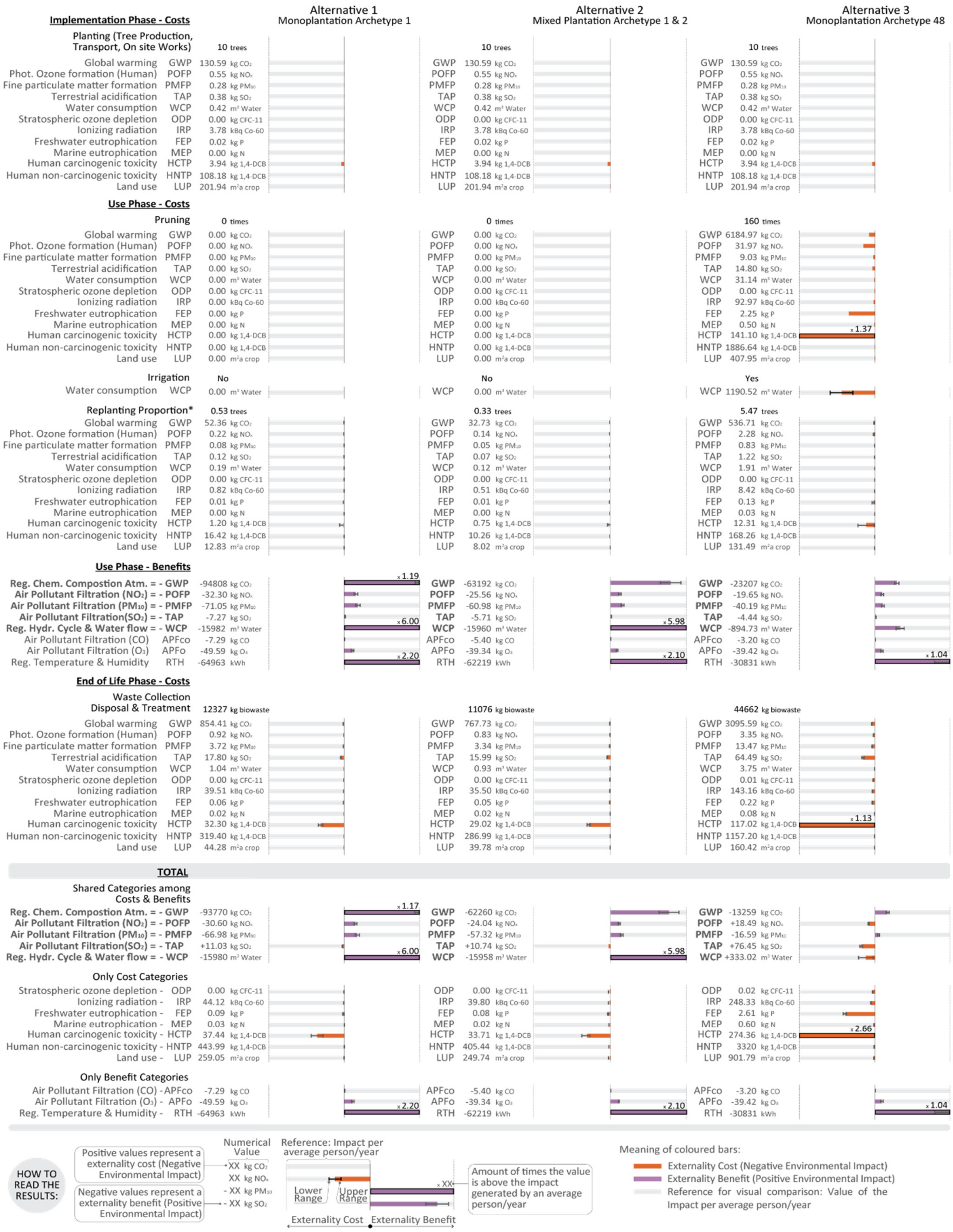

Figure 15. Comparison of benefits (positive externalities) and costs (financial and negative externalities) in biophysical units per life cycle phase and in total. Costs are represented in orange and benefits in purple.

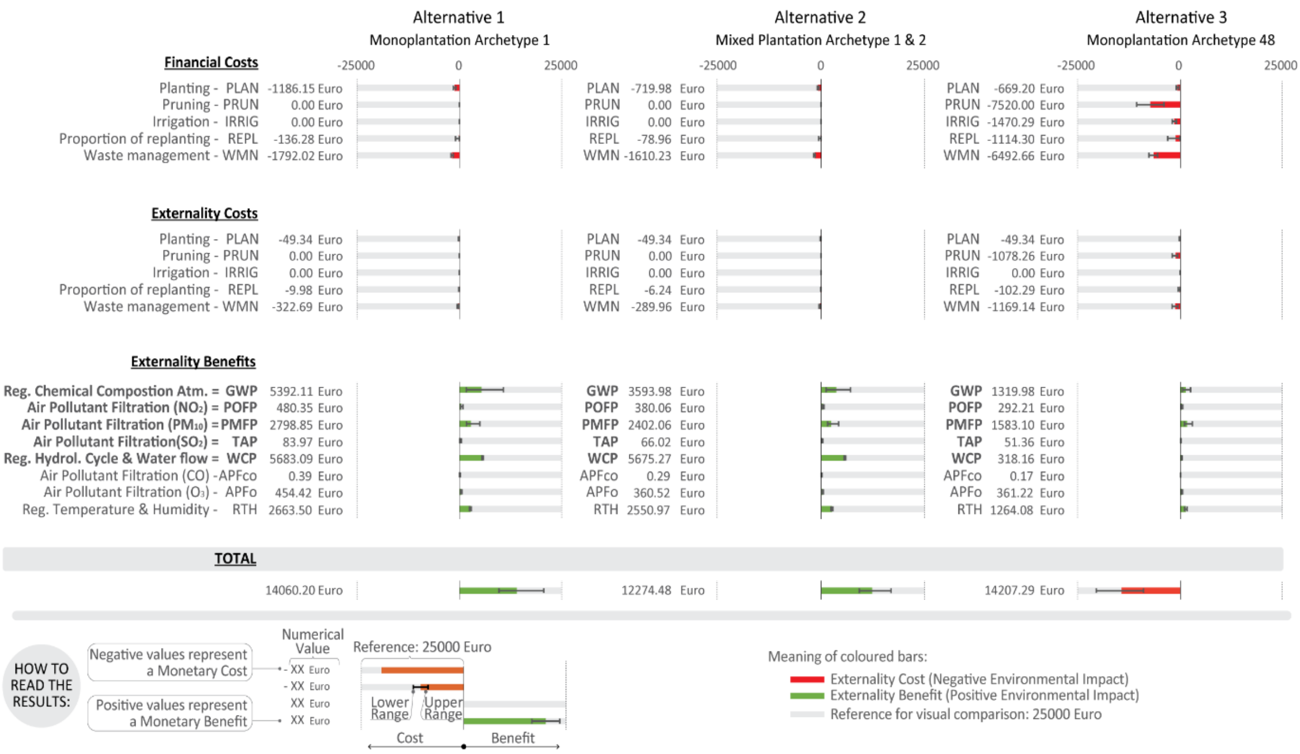

Figure 16. Comparison of the benefits (positive externalities) and costs (financial and negative externalities) in monetary units per life cycle phase and as a net total value. Costs are represented in red and benefits in green.

4. Discussion and Conclusions

This paper presents the development of NBenefit$ and its application to two illustrative case studies. NBenefit$ was developed as a prototype online decision support tool for the evaluation of urban forest interventions that considers their entire life cycle, i.e., implementation phase, use phase, and end-of-life phase. It describes how archetypes of urban forests for specific environmental conditions can be created, pre-calculated, and stored, as well as which outputs and format can be provided to potential users of the tool, i.e., built environment professionals of different kinds interested in comparing alternatives for a specific urban forest project (as an example of nature-based solution).

Archetypes are at the core of NBenefit$ and are defined by combinations of biotic, abiotic, and management attributes. Archetypes thus provide built environment professionals with a simple but science-based form to demonstrate, over different urban planning/design stages, how attribute variations influence the performance of NBS. Through the concept of archetypes, built environment professionals are released from the tedious task of collecting an excessive amount of data, which in some cases (or at some stages of the project) are unknown, putting that time burden on the side of the NBenefit$ developer. This should facilitate the uptake of NBenefit$ already from early planning/design stages, providing more room to influence functionality and performance, i.e., making future urban forest projects more cost-effective. As a drawback, the pre-calculation of new archetypes is dependent upon the availability of data. For example, in the case of urban forests, tree growth is modelled making use of allometric equations, which need to be already available in published studies or need to be estimated using local (or from similar sites) tree inventories. In addition, the use of a pre-established set of values might not be enough for practitioners who need a high specificity in the archetypes. In those cases, ad hoc assessments can be developed directly in the model underpinning NBenefit$, for which tailor-made archetypes are defined but which require more time and technical expertise.

The balance of environmental and economic impact for all the urban forest life cycle phases and its communication at a yearly basis is useful for design purposes but also for communication with a broad range of stakeholders. Nowadays, there is still a lack of decision support tools for urban NBS that offer both types of output, focus on detailed spatial scales, and provide long-term predictive performance outputs understandable by a broad audience. As anticipated in Section 1, only a few decision support tools currently provide detailed urban ES calculations. This is the case for i-Tree [31], specific for urban forests; ENVI-met [64], specific for local climate regulation; and SWMM [33], capable of modelling natural storm-water management solutions. Compared to NBenefit$, some of these tools (ENVI-met, SWMM) offer a detailed temporal resolution, able to work in hourly time steps and inform about the performance of NBS during specific events such as intense storms. Nevertheless, these tools are not focused on modelling the long-term performance of NBS, they do not explicitly consider negative externalities, and in some cases, they are not easy to use by low-computer-literate users. NBenefit$ and i-Tree are the only tools that offer both biophysical and monetary values in a format easy to communicate to stakeholders. However, NBenefit$ can also inform about the known accumulated uncertainty.

So far, NBenefit$ only relies on an urban forest model, but the tool has been specifically developed to also accommodate models (and archetypes) for many other NBS types (e.g., green roofs, urban wetlands, etc.). Implementing new models will enhance the usefulness of NBenefit$ in planning and designing complex urban green open spaces that integrate more than one NBS type. Additionally, future versions of NBenefit$ may include a more extensive coverage of externalities, financial costs, and ES, since the performance output generated for each alternative is still limited in this regard. For example, the current model and the online decision support tool still do not consider how design, planning, or management decisions might influence pest control or aesthetics and their associated costs and benefits. To the authors' knowledge, none of the urban NBS modelling tools included in the literature can perform it either. All these advancements would therefore contribute to move NBenefit$ from a prototype decision support tool to a more sophisticated one, capable of being used by professionals in real practice to support urban plans and designs of complex NBS projects.

To gather feedback from a user's perspective and guide towards further development steps, NBenefit$ was tested by partners of the H2020 project Nature4Cities (https://www.nature4cities.eu/ (accessed on 10 November 2022)), most of which are related to the built environment sector. Among the feedback collected, it appeared that the current way of inputting data by users might be lengthy for large projects. Hence, in future versions, it will be necessary to integrate additional alternatives for inputting data to improve the user experience.

Regarding outputs, improvements to the online spatially explicit visualisation of disaggregated indicators should be conducted to help users gather a better understanding of where specific strengths or weaknesses occur in a project. In this sense, the option to download disaggregated biophysical and monetary values per cell and time step in a spreadsheet and/or shapefile format is handy, allowing for the import of outputs into Geographic Information Systems (GIS). Similarly, the integration of NBenefit$ results into Building Information Modelling (BIM) software would save time for BIM practitioners and improve their workflow. In that case, it might be adequate to provide the long-term benefit and cost outputs of disaggregated archetypes (or groups of them) in the format of BIM template tables. In fact, BIM is used more and more by different built environment professionals, and in some countries (e.g., United Kingdom), a certain level of BIM adoption is required in projects [40].

Besides Nature4Cities partners, authors looked for feedback from professional chambers to understand how professionals perceived the value of the tool. This is why NBenefit$ was submitted to the UK Landscape Institute Awards 2021 (Landscape Institute is the professional chamber of landscape architects in the UK), where it was retained as a finalist in the Landscape Innovation category, which proves that the tool is of interest to landscape architecture professionals (https://awards.landscapeinstitute.org/li-awards-finalists-winners-2021-2/ (accessed on 10 November 2022)). This result reinforced the potential value of the tool for practitioners, encouraging its further development. This submission also represents a first step to establish a pathway of collaboration with groups of built environment professionals from different disciplines (e.g., landscape architecture, civil engineer, architecture), whose input is anticipated necessary to ensure the fit for purpose in the development of NBenefit$.

In future stages, NBenefit$ will continue to be developed with the aim of solving the abovementioned limitations, ensuring an adoption by urban landscape practitioners and its penetration in the market. Efforts will be greatly placed in moving the tool from a TRL (Technology Readiness Level) of 5-6 (prototype tested in intended environments) to a TRL of 7-8 (ready for industry, i.e., real practice purposes). See details about TRLs in [65,66]. This requires testing the tool in multiple urban contexts and projects and that practitioners belonging to targeted end users (e.g., landscape architects, architects) make part of those tests to provide feedback about missing functionalities, user barriers, or relevant costs and benefits gaps. Efforts will also be placed in a dissemination strategy that exploits the use of professional-tailored workshops and iconic testbed cases and looks for the support of (supra)national research funding agencies to reach a wider audience of potential collaborators and future end users.

Despite that further technical work is needed, the current prototype of NBenefit$ demonstrated, compared to existing modelling tools, its added value for assessing urban forest-based NBS projects and providing support to decision-making. It is one of the rare examples of NBS decision support tools developed to inform built environment professionals with low computer-literacy about the overall long-term costs and benefits of new specific urban NBS projects. Ultimately, it anticipates the cost-effectiveness of planned/designed urban forest projects, which further gives the knowledge basis for their informed implementation in urban environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12010070/s1: SM1—Summary table of current ES modelling tools; SM2—Basic details about NBenefit$, access and availability; SM3—Additional descriptions about the urban forest model underpinning NBenefit$; SM4—Compressed zip file with xls files for the monetisation of the biophysical indicators on ecosystem services, mid-point life cycle impacts and the average monetary value of management actions; SM5—Illustrative example of successive difference in mean and standard deviation values for three outputs of Archetype 1, 2, and 48; SM6—Compressed zip file with xls files for all the archetypes and variables of the successive difference in mean and standard deviation values. There is a README doc explaining the content of the zip file to understand how to use it; SM7—xls file with reference values for the impact of an average person in the world in 2010 for all the individual categories considered in the assessment with biophysical units; SM8—xls file of the yearly and overall output data in biophysical and monetary units. Version of the results ready to be uploaded in GIS software is also provided. There is a README sheet describing the meaning of the abbreviations of the titles of each spreadsheet

Author Contributions: Conceptualization, J.B.A., C.P. and B.R.; methodology, ALL; software, J.B.A., C.P., L.C. and T.N.G.; validation, J.B.A., C.P. and B.R.; formal analysis, J.B.A.; investigation, J.B.A. and C.P.; resources, J.B.A., L.C. and T.N.G.; data curation, J.B.A., C.P., L.C. and T.N.G.; writing—original draft preparation, J.B.A.; writing—review and editing, J.B.A., C.P. and B.R.; visualization, J.B.A. and B.R.; supervision, C.P. and B.R.; project administration, B.R.; funding acquisition, B.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the European Union's Horizon 2020 research and innovation programme under the Grant No: 730468 (www.nature4cities.eu, accessed on 10 November 2022).

Data Availability Statement: Data are contained within the Supplementary Material of this article.

Acknowledgments: The authors would like to acknowledge funding from the European Union's Horizon 2020 research and innovation programme under Grant No: 730468 (www.nature4cities.eu, accessed on 10 November 2022).

Conflicts of Interest: The authors declare no conflict of interest. Moreover, the funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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