Grant Agreement No.: 730468

Project acronym: Nature4Cities

Project title: Nature Based Solutions for re-naturing cities: knowledge diffusion and decision support platform through new collaborative models

Research and Innovation Action

Topic: SCC-03-2016: New governance, business, financing models and economic impact assessment tools for sustainable cities with nature-based solutions (urban re-naturing)

Starting date of project: 1st of November 2016

Duration: 48 months

D4.1 – Development of a multi-scale system dynamics assessment framework for nature-based solutions in cities

Organisation name of lead contractor for this deliverable: LIST		
Version 4 – Rev.2	Due Date	04/30/2018
	Submission Date	04/30/2018
	Authors	Babí Almenar, J., Petucco, C., Rugani, B.; (**LIST**) Egusquiza, A., Arana Bollar, M.; (**TEC**) Larrey-Lassalle, P., Pousse, M.; (**NBK**) Musseti, A.; (**RINA**) Yilmaz, Ö., Basoglu, D.; (**EKO**) Szkordilisz, F., Körmöndi, B.; (**MUTK**) Kraus, F.; (**G4C**) Laïlle, P.; (**P&C**) Serna, V., Martín, S.; (**CAR**) Köroglu, T.; (**CAN**) Hevizi, B.; (**SZEG**) Breton Ramos, E. M.; (**AH**) Donati, R., Colombo, S.; (**CMM**) –

Dissemination Level		
PU	Public	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Document history

History			
Version	**Date**	**Author**	**Comment**
1	03/05/2018	LIST (Javier Babi Almenar; Benedetto Rugani)	1st Draft of the deliverable to share with internal reviewers to obtain their inputs and comments about the structure of the document and initial content.
2	04/13/2018	LIST (Javier Babi Almenar; Benedetto Rugani, Claudio Petucco)	2nd Draft of the deliverable to share with the internal reviewers (TEC (Aitziber Egusquiza), NBK (Pyrène Larrey-Lassalle).
3	04/23/2018	LIST (Javier Babi Almenar; Benedetto Rugani; Claudio Petucco)	3rd Draft of the deliverable to share with the external reviewer (Marjorie Musy)
4	04/30/2018	LIST (Javier Babi Almenar; Benedetto Rugani, Claudio Petucco)	Final version of the deliverable after the revisions of internal and external reviewers

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

List of Figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

List of Tables

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Glossary

Acronym	Full name
CICES	Common International Classification of Ecosystem Services
D2.1	Deliverable 2.1 (Nature4Cities) "System of integrated multi-scale and multi-thematic performance indicators for the assessment of urban challenges and NBS"
EC	European Commission
EbA	Ecosystem-based Adaptation
EEA	European Environment Agency
ES	Ecosystem Service(s)
GI	Green Infrastructure
HAVC	Heat, Air Ventilation, and Cooling
IUCN	International Union for Conservation of Nature
LULC	Land Use Land Cover
MAES	Mapping and Assessment of Ecosystems and their Services
MEA	Millennium Ecosystem Assessment
MIMES	Multiscale Integrated Modelling of Ecosystem Services
NBS	Nature-based Solutions
NUTS	Classification of Territorial Units for Statistics
PET	Physiological Equivalent Temperature
SEEA	System of Integrated Environmental-Economic Accounting
SDM	System Dynamics Model
SME	Small and Medium Enterprise
SPE	Service Providing Elements
SPU	Service Providing Unit
SUDS	Sustainable Urban Drainage Systems
TEEB	The Economics of Ecosystems and Biodiversity
UC	Urban Challenge
UES	Urban Ecosystem Service(s)
USC	Urban Sub-Challenge
UE	Urban Ecology
UK NEA	United Kingdom National Ecosystem Assessment
UM	Urban Metabolism
UN	United Nations
UPE	Urban Political Ecology
USLE	Universal Soil Loss Equation
WFD	Water Framework Directive
WP	Work Package

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Executive Summary

The mainstreaming of Nature Based Solutions (NBS) in cities requires an overall understanding of their economic benefits and co-benefits againsts existing benchmarks established by traditional solutions, as well as an evaluation of the impacts and tradeoffs that might be generated on the provision of urban ecosystem services (ES). The analysis of ES associated with NBS can hence be used as a mechanism to assess the costs and benefits associated with the implementation of urban NBS and, in turn, as a decision support tool to address several urban challenges. In this regard, an approach based on ES quantification, valuation and monitoring is expected to bring a relevant added value to the socio-economic evaluation of NBS in Nature4Cities. Moreover, the behaviour of complex systems underpinning the provision of ecosystem functions and ES can be captured by using a systemic thinking, which can inform on the cost-effectiveness of urban NBS in a more realistic form. Aim of the Task 4.1 was therefore to define a system dynamics modelling framework to assess ES supplied by NBS at different spatial and temporal scales. The conceptualization of such an integrated model was supported by the identification of the biophysical structures and socio-ecological processes related to the provision of selected ES, following the ES cascade framework. To this end, a large body of literature on ES, NBS and urban challenges was analysed, complemented by a review of scientific evidences investigating the relations between structures and processes as well as the existing ES process-based models.

The critical review of the literature allowed to depict main variables (input, intermediate variables and outputs) and processes to be considered in the system dynamics modelling framework, and facilitated the identification of suitable proxy parameters to use as ES indicators. Moreover, urban system boundaries (primary: metropolis/city level, and secondary: urban region level) and urban typologies were identified at different spatial levels (urban region, city/metropolis, and neighbourhood) via descriptive indicators based on an integrated urban metabolism and urban ecology perspective. On top of this, a first evaluation of the model structure was done making use of data gathered from pilot cities and small and medium enterprises. While a second evaluation was supported on expert knowledge and feedback gathered through a workshop with external advisors. With this background, an initial representation of NBS and urban systems in modelling framework was developed by extending and adapting the "Multiscale Integrated Model of Ecosystem Services" (MIMES) to urban systems, providing the model conceptualization and a basic model formulation. Two main modules were defined following the MIMES approach: NBS module and urban system module. The NBS module focuses on the calculation of ES as final outputs, while the urban system module aims to understand how the supply of ES by NBS could affect the urban metabolism. The developed modelling framework, the selected ES classes and their parameter proxies provided a basis for the implementation of an economic assessment scale in the Task 4.2, which aims to monetarise the values of ES provided by NBS and compare them with the NBS life cycle costs.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

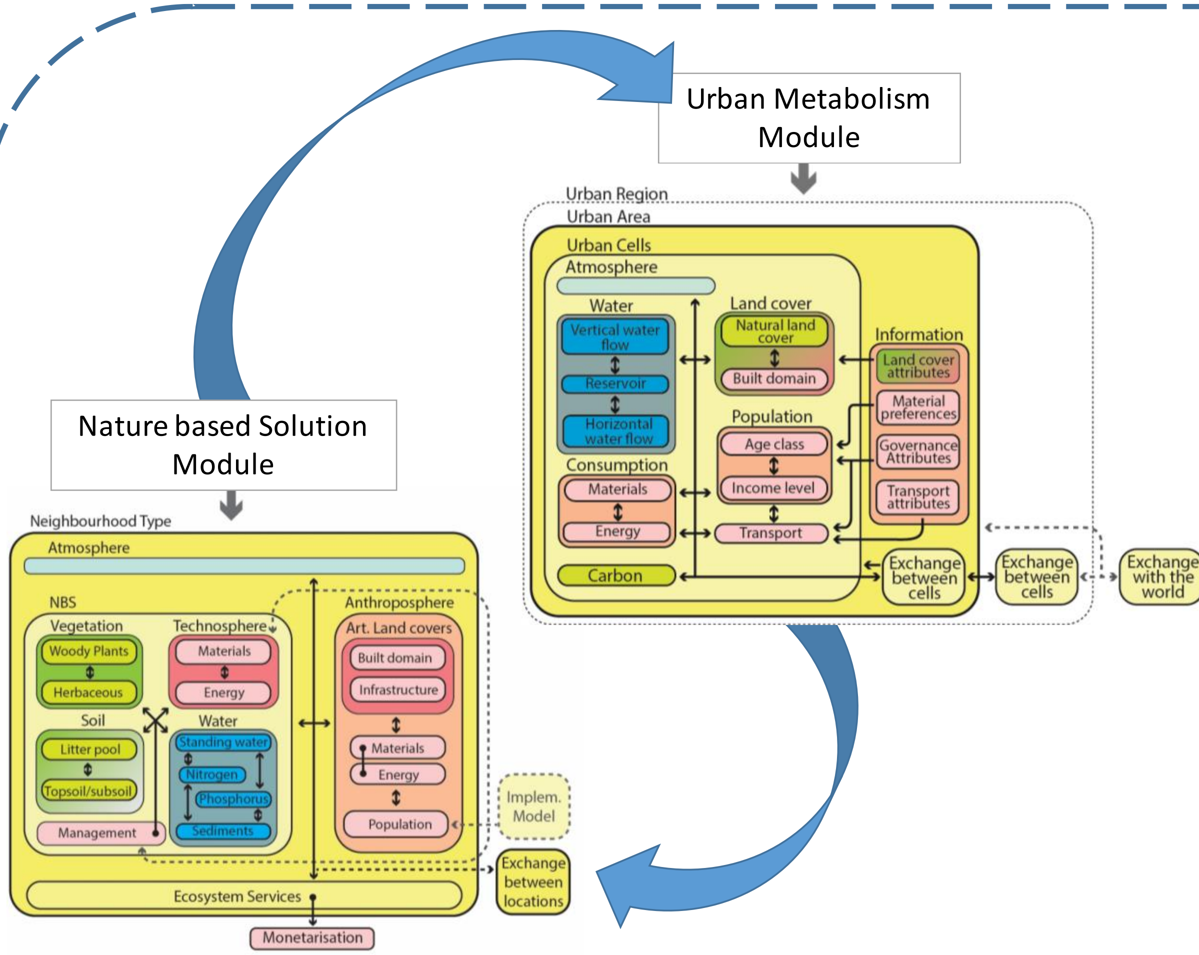
The NBS system dynamics model will be integrated into the Nature4Cities platform in the form of archetypal outputs obtained after running the model. These outputs will be visualized by first defining NBS selection criteria, then filtering urban challenges and/or ES and then plotting changes in key environmental and anthroposphere factors that can inform on a set of future plausible conditions in which to evaluate NBS impacts on the provision of ES.

On one hand, the work performed in the Task 4.1 of Nature4Cities shows that a critical knowledge gap exists regarding the explicit relationship among biophysical structures, processes and supply of urban ecosystem services. It also highlights that there is a general lack of environmental, economic and social data for urban systems which could hamper the development and generalization of system dynamics models for assessing cost-effectiveness of NBS, but also for those assessing urban sustainability at high temporal and spatial resolution. This implies that further efforts are required to develop methods for easy data collection, which would minimise the impact that data scarcity might have in the implementation of future system dynamics models.

On the other hand, the Task 4.1's team proves that the development of a systemic thinking and the related use of a system dynamics modelling perspective can certainly foster the multi-stakeholder involvement through participatory processes. This can contribute with scientific evidences and quantitative figures to the enhancement of strategies for the sustainable implementation of NBS in cities and, more generally speaking, to the development of an integrated (European) reference framework on nature-based solutions based on robust cost-benefit assessments.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Summary Picture



D4.1 – Development of a multi-scale system dynamics assessment framework for nature-based solutions in cities

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

1. Introduction

1.1. Background and Purpose

Innovation related to Nature-based Solutions[1] (NBS) is associated with the supposed benefits that their implementation provides on the long-lasting sustainability of urban contexts. In the WP4 of Nature4Cities, economic benefits, co-benefits and their alternatives underpinning NBS are considered as a means to support the feasibility and advantages of implementing NBS in cities. These benefits and co-benefits can be quantified through the valuation of so-called urban ecosystem services (UES, i.e. the benefits individuals and communities can get from urban ecosystems (Elmqvist *et al.*, 2015; Kremer *et al.*, 2016).

Among the most suitable and effective approaches to allow understanding and quantifying the sustainability of NBS are those that explicitly consider the nexuses between the human/technosphere and the eco-spheres. This can help incorporating more human and natural components simultaneously, accounting for feedbacks, integrating multiple temporal and spatial scales, and translating information for policy and practice.

According to this focus, the main objective of Task 4.1 in WP4 was to define a modelling framework for the assessment of ecosystem services (ES) provided by NBS in urban environments at different spatial and temporal scales by making use of a system dynamics approach that has been developed to describe the behaviour of complex systems over time. This modelling framework aims to provide information on the cost-effectiveness of implementing different NBS in cities to address specific urban challenges (UCs) through the provision of ES. The system dynamics model (SDM) proposed in Task 4.1 is based on the framework of the Multiscale Integrated Modelling of Ecosystem Services (MIMES) initially built to assess ES trade-offs at regional spatial scales (Boumans *et al.*, 2015). MIMES can be considered as having the most comprehensive simulation of the mechanisms underlying the entire driver-ecosystem-ES chain, considering exchange and feedbacks between human and ecological systems (Oosterbroek *et al.*, 2016). MIMES is adapted in Nature4Cities to encompass urban region, city, and neighbourhood scales.

As part of Task 4.1, urban systems, NBS, and their respective components and flows, including ES were defined. Concurrently, indicators for urban types, and a NBS typology adequate for modelling purposes were supported in the work carried out in WP1 and WP2. Their works was extended in the Deliverable 4.1 and also included a selection and definition of ES and their

[1] NBS are defined as *living solutions inspired by, continuously supported by and using nature* (Bauduceau *et al.*, 2015). A more specific definition developed as part of WP4 and aligned with the initial definition used at Nature4Cities is provided in Chapter 3.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

indicators. Data from the case studies of the pilot cities and from the NBS developed by small and medium enterprise (SME) partners of Nature4Cities were collected for the future calibration and validation of the SDM. Ultimately, the modelling of ES trade-offs will provide the basis for the development of a monetary value scale for NBS in Task 4.2.

1.2. Contribution of partners

The contribution of each partner to the present report (Deliverable of Task 4.1, hereafter "D4.1") is illustrated in Table 1. Chapters 2, 3, 4, 5, and 6 of D4.1 were mainly performed as part of an on-going PhD thesis work (Babí Almenar, in preparation).The information contained in those chapters therefore represents an extract of his PhD dissertation.

Table 1: Contribution of partners to D4.1.

Partner	Contribution
LIST*	Responsible of All Chapters
NBK	Collaboration in Chapters 1 and 4; Review of the deliverable
RINA	Collaboration in Chapter 4.
G4C	Collaboration in Chapter 7.
TEC	Collaboration in Chapter 1, and 4; Review of the deliverable
P&C	Collaboration in Chapter 7.
MUTK	Collaboration in Chapter 3.
CAR	Collaboration in Chapter 6.
CMM	Collaboration in Chapter 7.
ÇKY	Collaboration in Chapter 7.
SZE	Collaboration in Chapter 7.
AH	Collaboration in Chapter 7.
CER	Review of the deliverable

1.3. Target audience

The main target audience of this report are the Nature4Cities Project Officer, the Nature4Cities commission members and the reviewers of the project appointed by the European Commission, and, in particular, the Nature4Cities members working on or interested in the results of, Tasks 4.2, 3.1, and 5.4 (see further information in section 1.4). In addition, the report aims to inform about the capabilities of the modelling framework for application to the case studies located in the municipalities of Cankaya (TR), Alcalá de Henares (SP), Szeged (HU), and Città Metropolitana di Milano (IT), which are all partners of Nature4Cities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

1.4. Relation to other tasks of Nature4Cities

Task 4.1 is directly related to other Tasks in the Nature4Cities work packages (WPs) from WP1 to WP6, as it either receives inputs from them, provides outputs to them, or exchanges information with them in an iterative process (Figure 1). These links are explained below:

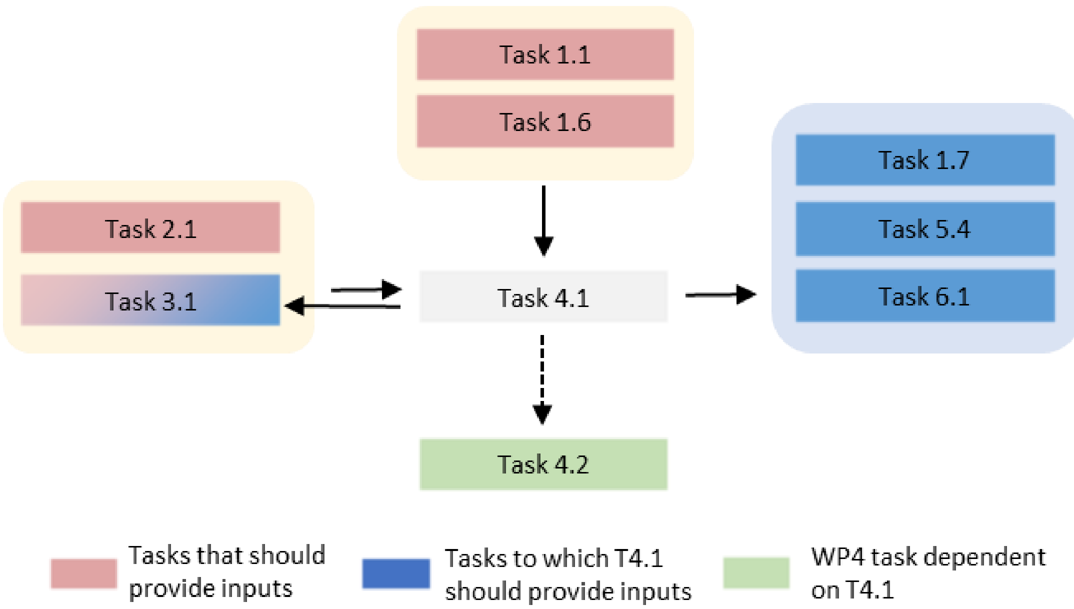


Figure 1. Diagram of direct relations with Task 4.1

Work package 1

<u>Task 1.1. Definition of typology of NBS and building an NBS database</u>

The typology of NBS developed in Task 1.1 is used as a basis for the typology used in Task 4.1. The typology is adapted to be adequate for modelling purposes and to ensure compatibility with NBS projects and ES assessments in urban and rural contexts (see section 3.3 for further details).

<u>Task 1.6. Geocluster4NBS tool</u>

The variables identified and mapped using the Classification of Territorial Units for Statistics (NUTS level 3; EC, 2003) contribute to the list of indicators used within the characterised background urban system boundaries (see section 5.4. for further details).

<u>Task 1.7. Urban Data Collection Methodologies</u>

The data limitations identified in Task 4.1 will inform Task 1.7 about current data gaps for the assessment of urban NBS. These data gaps would be considered to fill the types of urban data for which new collection methodologies might be required (see section 7.1 and 7.2 for further details).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Work Package 2

Task 2.1. Definition of urban performance indicators (and urban challenges)

This task provides the list of UCs investigated in Nature4Cities, from which specific urban challenges for Task 4.1 and Task 4.2 are then selected. The list of indicators selected in this task supports the selection of ES indicators used in the SDM in Task 4.1 (see section 4.2 for further details).

Work package 3

Task 3.1. Development of Nature4Cities urban metabolism framework

A relevant exchange of information between Task 3.1 and Task 4.1 exists regarding the definition of urban system boundaries and the selection of indicators. This link ensures the harmonisation between the urban metabolism (UM) elements that need to be modelled in both WP3 and WP4 (see section 5.4 for further details).

Work package 4

Task 4.2. Development of a monetary value scale in MIMES

The modelling framework developed in Task 4.1 will be finalised during Task 4.2, where a monetary value scale to account for the benefits associated with the provision of UES and the costs related to NBS implementations will be integrated (see section 6.2. and Chapter 9 for further details).

Work package 5

Task 5.4. Socio-economic assessment of NBS implementation models

Task 5.4 will be informed by the outputs from the modelling framework developed in Task 4.1, which is finalised during Task 4.2. The link between T4.1, T4.2 and T5.4 will facilitate the understanding of the contribution of implementation models to the social and economic values of NBS (see section 6.2 for further details).

Work package 6.

Task 6.1 Platform architecture definition

An exchange of information between Task 6.1 and Task 4.1 occurred to ensure the future integration of the system dynamics modelling tool into the integrated platform of Nature4Cities (see section 6.4. for further details).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

1.5. Report structure

The structure of the report is as follows:

- Chapter 2 illustrates the methodological steps underpinning the activities performed in the Task 4.1, starting from the identification of links among UCs, ES and NBS, the identification of ES, biophysical structures, and socio-ecological processes, moving to the characterization of urban systems, and the representation of NBS and urban systems in the modelling framework, down to the selection of case studies and data gathering necessary for the calibration and validation of the SDM.
- Chapter 3 defines the relations among NBS, ES, and UC. It also defines the NBS typology considered for modelling purposes, and describes the specific NBS, ES, and UC under investigation.
- Chapter 4 defines the relation between NBS biophysical structures and processes responsible for the ES supply considered in the modelling framework. Later, suitable ES indicators are identified.
- Chapter 5 provides an introduction to urban areas as complex dynamic systems and the adequacy of studying them through a system dynamics modelling approach. This is followed by the identification of descriptive indicators for urban system boundaries and urban typologies and the justification of the scales of study.
- Chapter 6 introduces MIMES and the steps required for its adaptation into a new SDM to the scales and context of urban systems. The chapter also illustrates the different stages for the validation of the SDM. A brief introduction to the integration of the SDM in the platform is eventually provided.
- Chapter 7 introduces the pilot cities and the collection of urban data. Later, case studies and the data provided by the Nature4Cities partners are described. The data provided is described in relation to the modules of the SDM.
- Chapter 8 illustrates the feedbacks from external advisors, which were used for a revision of the MIMES framework and an initial set-up of the new SDM.
- Chapter 9 provides a summary and a conclusion for the activities performed in the Task 4.1. Limitations and additional works required for the upgrade of the SDM are indicated as well as the future steps to integrate the monetary scale value to be developed during the Task 4.2.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

2. Methodological approach

Task 4.1 was developed through five methodological steps:

i) identification of links among UCs, ES and NBS;
ii) identification of ES, biophysical structures, and socio-ecological processes;
iii) characterisation of urban systems;
iv) representation of NBS and urban systems in the modelling framework;
v) selection of case studies and data gathering necessary for the calibration and validation of the SDM.

Figure 2 summarizes the actions and results of each methodological step. A detailed explanation for each step and related set of actions and results is provided in the following sections.

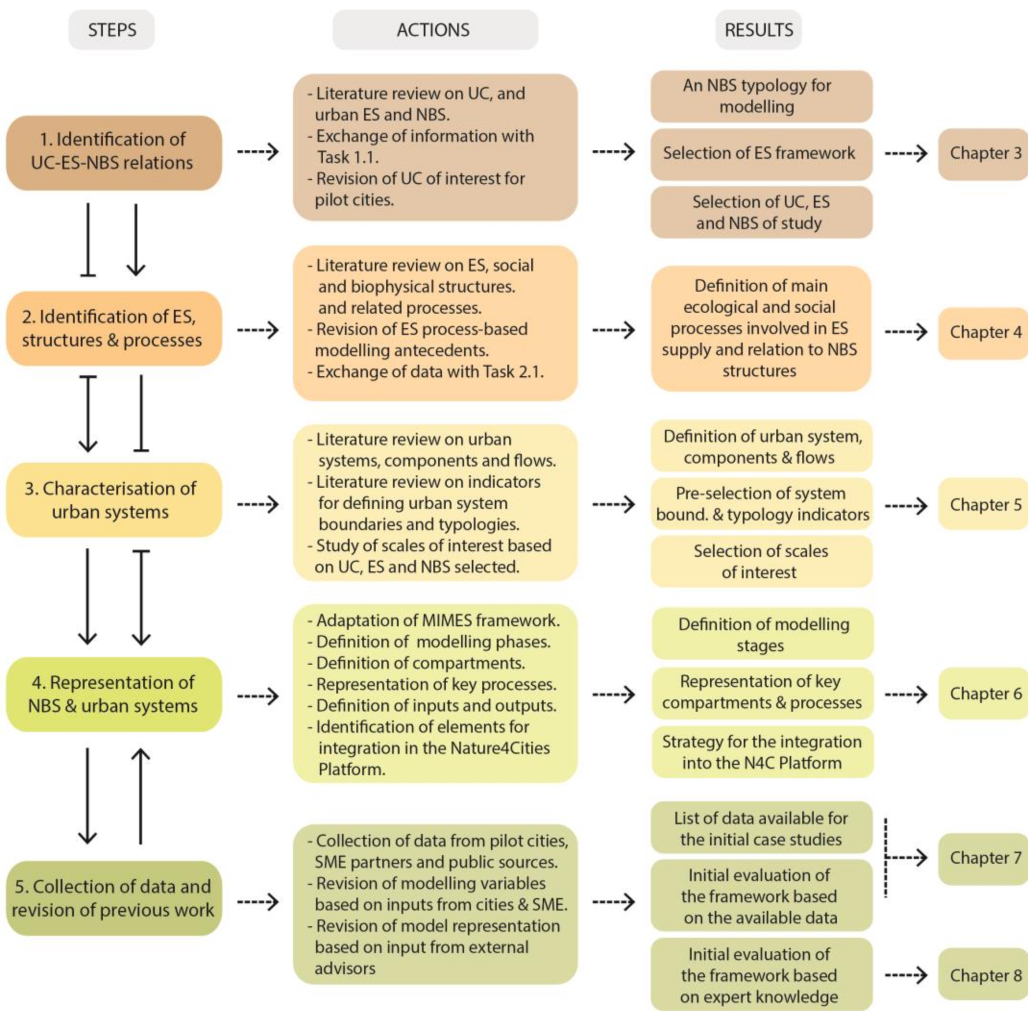


Figure 2. Methodological steps, related actions and results

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

2.1. Identification of UC-ES-NBS relations

In order to assess the suitability of NBS to address urban societal challenges, the links between specific UCs and NBS needed to be established. These links required an understanding of the ES that different NBS can supply as well as their relevance for addressing specific UCs. An extended literature review supported the establishment of these relations and the selection of specific UCs, ES, and NBS to be investigated.

For the selection of specific UCs of interest, the work developed at Task 2.1 and problematics observed in the pilot cities were taken into account making use of an initial questionnaire shared with the municipalities anticipating a future integrated assessment in WP7 ("Nature4Cities tools and platform field-test in cities"), in particular Task 7.4 (M32) and Task 7.5 (M37). A scientific review also helped to select and categorize ES based on their relevance to address UCs and to define an urban NBS typology for ES modelling purposes.

More specifically, the literature review performed by LIST to support the Deliverable 2.1 (D2.1) was extended for Task 4.1 with a critical revision of studies focusing on ES and NBS concepts. The literature reviewed was performed in the Web of Science platform according to the review protocol employed by Luederitz *et al.* (2015) and Brink *et al.* (2016), which is summarised in Table 2 (see search string in Supplementary Material, Table S1). The review was limited to the last 20 years (from 1998 to 2018) since the development of nature-related concepts (including NBS) as well as the study of their impacts in terms of ES is quite recent. This also allows filtering out historical UCs that are not relevant nowadays.

Table 2. Protocol adopted for the systematic literature review performed in Task 4.1; after Luederitz et al. (2015) and Brink et al. (2016).

Steps	Procedure	Results
1. Data gathering	Database search on Web of Science	1059 results
2. Data screening & cleaning	Screening of abstracts by the following criteria: – Focus on (peri)urban areas and/or UC types identified or variants of them. – Mention of types/classes of ES or specific ES classification system. – Focus on ecosystem function and/or ES assessment/valuation. – Assessment/valuation related to one or several nature-related solutions.	300 results
3. Data scoping	Accessible Full text download	257 results
4. Article appraisal & analysis	– Screening full text to confirm their adequacy with respect to criteria of step 2. – Analysis of the articles based on 7 categories.	135 results

An analysis of the papers from the literature review was developed based on eight categories: (i) considered UCs; (ii) ES classification framework (e.g. Millennium Ecosystem Assessment, CICES, TEEB); (iii) specific ES studied; (iv) type of data (e.g. quantitative); (v) type of values (i.e. biophysical, monetary, social) (vi) specific ES assessment method (e.g. expert-knowledge, modelling, simple parameter proxy); (vii) nature-related concepts (e.g. NBS, green infrastructure,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

ecosystem-based approaches) and specific NBS studied; (viii) key biophysical and socio-ecological processes identified.

The analysis of these categories allowed a better understanding of the main UCs studied and the development of an ES classification frameworks adopted for studies in urban contexts and specific ES. Furthermore, it allowed identifying the most common NBS investigated in urban areas for which quantitative ES assessment procedures exist and determine which biophysical attributes influence the socio-ecological processes responsible for the supply of ES.

The revision of conceptual NBS frameworks, land management and ecological restoration techniques, and the exchange of information with Task 1.1 informed the development of an urban NBS typology for modelling purposes. The typology also considered the main biophysical structures employed to study ES in rural contexts to facilitate transfer of information and compatibility in future studies. The exchange of information with Task 1.1 ensured the compatibility of both typologies. The literature review supported the selection of specific UC, ES, and NBS to be considered in the modelling framework which were checked against the case studies of the pilot cities to ensure this selection will fit to the purpose of WP7.

2.2. Identification of ES, structures & processes

The literature review, supported by additional references covering gaps of information regarding relations between structures and processes, also aided to relate biophysical structures to ecological and social processes, and both of them to the ES supplied by NBS. This approach follows the ES cascade modelling framework developed by (Haines-Young and Potschin, 2010) (Figure 3).

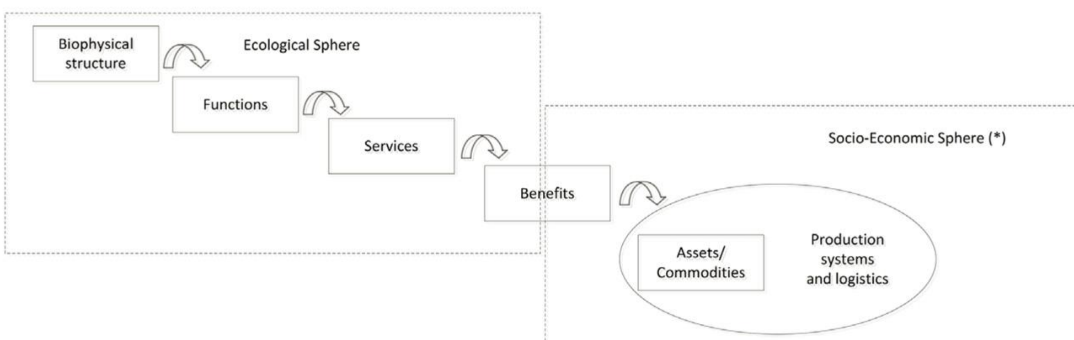


Figure 3. ES Cascade model from (La Notte et al., 2017).

The information from the literature review and additional references were complemented with a review of existing ES process-based models in order to compare biophysical structures and ecological processes considered in existing modelling systems. Process-based models represent mathematically one or several processes that characterise the functions of defined biological systems, with the aim of using ordinary or partial differential equations that consider the key

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

variables of each processes, including their inputs and outputs (Buck-Sorlin, 2013). In the case of ES process-based models, the outputs could be intermediate ones, needed for other processes, or final outputs in the form of proxy-parameters used as ES indicators (Turner *et al.*, 2015). Both reviews aided to identify the variables (input, intermediate variables and outputs) and processes to consider in the NBS model. Together with the revision of indicators included in D2.1, such step also allowed the identification of proxy-parameters to use as ES indicators.

2.3. Characterization of urban systems

Concurrently to the literature review on NBS, urban systems, their components and flows were characterised from an urban ecology (UE) (e.g. Alberti, 2016) and urban metabolism (UM) (e.g. Ferrão and Fernández, 2013) disciplinary perspectives.

An initial identification of descriptive indicators for defining the urban system boundaries (principal and secondary[2]) and urban typologies at different spatial scales was done using key references from the grey and scientific literature, and included variables identified in the Task 1.6. This was complemented with a second systematic literature review. The methodology of the latter followed the procedure indicated in section 2.5, and it is summarised in Table 3 (search string in Supplementary Material, Table S2).

An analysis of the papers from the literature review was developed based on six categories:

- type of indicator (social, economic, environmental, governance);
- detailed type and name of the indicators;
- type of data used for the indicator (qualitative or quantitative);
- availability (the data needed to calculate the indicator can be easily obtained from public sources or not);
- indicator for system boundary or urban typology or both;
- spatial level (urban region, city/metropolis, neighbourhood) for which the indicator could be adequate.

[2] Principal system boundary spatially defines the urban system and corresponds to the city/metropolitan level. Secondary system boundary defines the surrounding landscape with strong socio-ecological relations with the urban system and corresponds to the urban region level

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 3.Protocol of the systematic literature review

Steps	Procedure	Results
1. Data gathering	Database search on Web of Science	252 results (environmental); 65 (material flows); 246 (economy, social, governmental, energy, infrastructure)
2. Data screening & cleaning	– Screening of abstracts by the following criteria: – The articles should mention a set (at least 2) of indicators or metrics. – The indicators are used to define urban typologies, urban system boundaries (city/metropolis, urban regions or similar) based on social, governance, material flows, economic, environmental attributes.	18 results (environmental); 5 results (material flows); 43 results (economy, social, governmental, energy, infrastructure)
3. Data scoping	Accessible Full text download	16 results (environmental); 5 results (material flow); 33 results (economy, social, governmental, energy, infrastructure)
4. Article appraisal & analysis	– Screening full text to confirm their adequacy with respect to criteria of step 2. – Analysis of the articles based on 6 categories.	12 results (environmental); 3 results (material flow); 22 results (economy, social, governmental, energy, infrastructure)

This literature review allowed the selection of indicators to use as parameter proxy to define primary and secondary system boundaries based on threshold values. It also helped to identify key variables useful for characterising urban types from an UM and an UE perspective at neighbourhood, city/metropolis, and urban region spatial levels. Once an initial list of indicators was selected, these were narrowed down based on the following two criteria: easiness (i.e. calculated from available data and without requiring specific tools or models); and replicability for different urban areas in Europe. In addition, indicators for urban typologies adequate for all or several of the spatial levels (e.g. housing density, average or median income of residents) were favoured against others during the selection process to ensure consistency among different levels and ultimately obtain a reduced set of core indicators.

While the system boundary indicators allowed the spatial definition of the urban system boundaries, the urban typology indicators could inform about the characteristics of different urban areas or their subsets. These, in turn, could support the initial selection of NBS and inform the SDM with information on the specific dynamics of different urban types.

2.4. Representation of NBS & urban systems

System dynamics models integrate qualitative and quantitative methods to represent and simulate structure and processes of complex systems, making use of cause-effect networks and feedback loops (Kelly *et al.*, 2013; Elsawah *et al.*, 2017). In these models, the qualitative information is as relevant as the quantitative information, since both are necessary to develop the structure of the model, which usually involves an iterative process (Luna-Reyes and Andersen, 2003). As other causal-descriptive (or process-based) models, system dynamics models should fulfil two conditions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

to be valid: first, the structure of the model should provide an adequate representation of the real system; and, second, it should generate accurate output behaviours (Kelly *et al.*, 2013). Therefore, the validation of system dynamics models requires different stages, which are usually synthesized as follows (Luna-Reyes and Andersen, 2003; Martinez-Moyano and Richardson, 2013):

i) problem identification and definition;
ii) system conceptualization;
iii) model formulation;
iv) verification and evaluation of structure and behaviour;
v) implementation.

The first three stages were considered in the present deliverable and the fourth stage was only introduced, and addressed in Task 4.2 together with the fifth stage.The information obtained from steps 1-3 (see Figure 2) was used as the basis for adapting the MIMES framework to urban scales, representing NBS and urban systems as linked system dynamics modules of an integrated SDM where the compartments and processes influencing the UM and the provision of ES are included.

Specifically, sections 2.1 and 2.3 explain how the “problem” (i.e. UCs studied and the ES and NBS to be modelled, spatial levels of interest in urban assessment studies) was identified and/or defined. The qualitative information from sections 2.1 (NBS typologies), 2.2 (identification of biophysical structures and processes influencing ES supply and identification of ES indicators), and 2.3 (definition of urban system, components and flows, and definition of system boundaries) supported the SDM conceptualisation. The quantitative information from sections 2.2 and 2.3 was used for the formulation of both SDM modules. A first evaluation was performed taking into account the information obtained from the pilot cities and SME partners, as illustrated in section 2.5, whereas a second evaluation of the structure of the model was done in a workshop with external advisors (see Chapter 8). Finally, an initial strategy for the integration of the models in the Nature4Cities platform is under definition through discussions with the leading partner of Task 6.1.

2.5. Collection of data and revision of previous works

During Task 4.1 some considerations were held with the pilot cities and three partners of Nature4Cities (G4C, P&C). A questionnaire was provided to them to collect socio-economic and environmental input data for the SDM. This questionnaire was made either by specific target information requests, petitions or tables to be compiled. The data sent by the municipalities was collected and a database was developed at the end of Task 4.1. The urban data and NBS case studies sent from the pilot cities and other partners could confirm the availability of input variables for the model, including their temporal and spatial resolution. This knowledge was used for an additional evaluation of the structure of the model that helped to understand if substantial modifications to the initial MIMES framework were required. In a future stage, this data will be used to evaluate the behaviour of the model.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

3. Relation among Urban Challenges, Ecosystem Services, and Nature-based solutions

This chapter describes (i) the specific UCs and subchallenges (USCs) studied in the Task 4.1; (ii) the adopted ES classification framework and the selection of target ES to address those challenges; (iii) the definition of an NBS typology adequate for modelling purposes; and (iv) the identification and selection of NBS to be investigated based on the UC and the selected ES.

3.1. Urban challenges and sub challenges selected

The work of D2.1 (Table 4) was used as a basis for the selection of the UCs and USCs in the Task 4.1.

Table 4. UCs and USCs extracted from D2.1.

TOPICS	URBAN CHALLENGES	URBAN SUBCHALLENGES
CLIMATE	1 | Climate issues	1.1 | Climate mitigation
		1.2 | Climate adaption
	2 | Water management and quality	2.1 | Urban water management and quality
		2.2 | Flood management
ENVIRONMENT	3 | Air quality	3.1 | Air quality at district/city scale
		3.2 | Air quality locally
	4 | Biodiversity and urban space	4.1 | Biodiversity
		4.2 | Urban space development and regeneration
	5 | Soil management	5.1 | Soil management and quality
RESOURCE	6 | Resource efficiency	6.1 | Food, energy and water
		6.2 | Raw material
		6.3 | Waste
		6.4 | Recycling
SOCIAL	7 | Public health and well-being	7.1 | Acoustics
		7.2 | Quality of Life
		7.3 | Health
	8 | Environmental justice and social cohesion	8.1 | Environmental justice
		8.2 | Social cohesion
	9 | Urban planning and governance	9.1 | Urban planning and form
		9.2 | Governance in planning
	10 | People security	10.1 | Control of crime
		10.2 | Control of extraordinary events
ECONOMY	11 | Green economy	11.1 | Circular economy
		11.2 | Bioeconomy activities
		11.3 | Direct economic value of NBS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Among those UCs and USCs, the most mentioned in the systematic literature review of NBS were then identified, which are reported in Table 5. It was not possible to adjust completely the organization of the UCs mentioned in the literature according to the categorization of D2.1. In some cases few categories did not exist or the scope was broader in D2.1 than in the literature. Hence, the integration might have lost the specific focus identified changing their original meaning. For example, in many cases the literature clearly differentiated between physical and mental health as independent but related USCs. As another example, in the literature people security was not only related to control of crime but also with the perception of safety.

Table 5. UCs and USCs identified from the literature review which relate to NBS.

Ranking	UC & USC	Number of Papers
1	Physical health	54
2	UC and USC was not stated	47
3	Mental health	45
4	Water management & quality	27
5	Climate issues (mitigation and adaptation)	26
6	Urban heat island	25
7	Loss of biodiversity (or its enhancement)	20
8	Control of extraordinary events	14
9	Environmental justice	8
10	Energy saving and performance	7
11	Food security	5
12	Urban liveability (& place-making)	5
13	Wastewater and solid waste management	4
14	Green economy	4
15	Social cohesion	4
16	People security (violence, safety)	2

The most mentioned UCs were physical health (in many cases in relation to air quality and water quality), mental health (stress mitigation, benefits of physical activities, to which contact with nature was associated in many cases), water management & quality (in many cases in relation to flood risks), climate issues (usually associated with urban heat island effect), loss of biodiversity, and natural disasters. The aggregation of the remaining challenges according to D2.1 structure shows that resource efficiency and environmental justice and social cohesion represented the other two most mentioned groups. A revision of the initial table of potential sites of intervention from the pilot cities (WP7) and their main UCs intended to be addressed per site showed that mental health, physical health, biodiversity, water management & quality, environmental justice and social cohesion, and climate issues were dominant challenges.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

The comparison between the challenges identified in the literature review and the ones of D2.1 supported the selection of UCs and USCs considered in the Task 4.1 (Table 6). From the list reported in D2.1, few USCs overlaps were readjusted to avoid double counting, while other challenges were further disaggregated to facilitate the relation to specific ES, and the assessment foreseen to be conducted in the Task 4.2.

Table 6. UCs and USCs selected in the Task 4.1.

TOPICS	UC	USC
Climate	Climate issues	Climate mitigation
		Climate adaptation
	Water management	Storm water management
Social (Public Health)	Physical health	Air Quality
		Water Quality
		Soil Quality
	Mental health	Stress relief
		Psychological relaxation
		Enhanced opportunities for outdoor activities
Resource	Resource efficiency	Food Security
		Raw Material
		Energy performance
		Energy production
Environment	Biodiversity	Loss of habitat
		Loss of ecological connectivity

From the list of most mentioned UCs, environmental justice and social cohesion were not selected because of the uncertainty to relate them directly and in an unbiased form to specific NBS, which depend heavily on the implementation models envisaged. Therefore, those UCs could not be adequately considered in the Task 4.1, and their assessment will be carried out in future tasks (e.g. Task 5.4) where implementation models are considered.

3.2. Ecosystems services

3.2.1. Classification framework

The systematic literature review identified four ES classification frameworks used in ES assessments across urban contexts: 1) Millennium Ecosystem Assessment (MEA) (MA (Millennium Ecosystem Assessment), 2005), 2) UK National Ecosystem Assessment (UKNEA) (UKNEA, 2013), 3) The Economics of Ecosystems and Biodiversity (TEEB) (TEEB, 2011), and 4) Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018). However, most of the papers (around 75%), especially if focused on one specific

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

ES, did not mention the classification framework used. Therefore, it was difficult to further understand which was the most common framework used for the study of ES in urban contexts.

Most of the literature using CICES and TEEB classification systems proposed case studies from European countries (e.g. Schmidt *et al.*, 2016; Fusaro *et al.*, 2017; Meri and Lian, 2017; Garcia *et al.*, 2016). Conversely, many of the studies using the MEA classification system focused on analyses of cases from outside European countries, although few of them were developed in the European context (e.g. Ribeiro and Ribeiro, 2016; Sun *et al.*, 2017). UKNEA is a specific framework only used for UK case studies.

The last version of CICES (v5.1), released on January 2018, includes a correspondence table with MEA and TEEB frameworks to help harmonize the results from different ES assessment studies. In addition, CICES is a framework proposed by the European Environment Agency (EEA) (Haines-Young and Potschin, 2018) and developed for the System of Integrated Environmental and Economic Accounting (SEEA) (SEEA, 2012). It is currently employed within the Mapping and Assessment of Ecosystem Services (MAES) reports (Haines-Young and Potschin, 2014, 2017), including the MAES pilot studies focusing on urban areas (Maes, Liquete, *et al.*, 2016). Therefore, to enhance the consistency among European NBS assessments, CICES was selected as the reference classification framework for Tasks 4.1 and 4.2.

3.2.2. Selection of ecosystem services

A revision of the ES classified using CICES v5.1 permitted an initial identification of ES classes, groups and sections provided by biotic systems[3] (i.e. NBS) related to the selected UCs (Table 7).

A comparison between the selected ES and the ES mentioned in the literature review shows that regulation services were part of the most assessed section of ES (110[4]), followed by cultural services (64), and then provisioning services (32). Previous critical reviews also showed that regulation services were the urban ESs most assessed (Ziter, 2016; Luederitz *et al.*, 2015; Haase, Frantzeskaki and Elmqvist, 2014). In the case of Haase, Frantzeskaki and Elmqvist (2014) and Ziter (2016) the number of studies assessing cultural services were slightly higher. However, Luederitz *et al.* (2015) found that provisioning services were more assessed than cultural services, but less times mentioned in the literature[5].

[3] ES of CICES v.5.1 provided by abiotic structures are not considered because their supply is not significantly influenced by NBS. In the Nature4Cities project, it was decided to only focus on NBS or actions inspired, supported and applied on living solution. For this reason the focus is placed on the ES provided by biotic structures.

[4] 10 papers only focused on the ES class “Maintaining nursery populations and habitats”, which in CICES is under the regulation section, but in other classification systems – e.g. MEA– is part of the “supporting services” section (not included in CICES).

[5] Luederitz et al (2015) include also ES introduced in the papers, but which later were not assessed.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

The higher presence of regulation services in urban assessments is also coherent with the most mentioned UCs, since climate issues, water management, and biodiversity relate only to them. Physical health and mental health are linked to regulation and cultural services, and resource efficiency is also associated with regulation services. In addition, most of the demand of provisioning services in cities is satisfied by rural areas, and inhabitants could also benefit from rural cultural services, which is not the case for regulation services. Moreover, the most frequently assessed ES classes (in general and making use of biophysical valuation) per ES section (Table 8) are also related to the most mentioned UCs and USCs. However, few ES classes initially identified turned out to be rarely or never assessed in the reviewed literature.

Table 7. Relation of Urban Challenges to ES Class, Group and Section of CICES v 5.1.

UC	USC	ES Class	ES Group	ES Section
Climate issues	Climate mitigation/Climate adaptation	Regulation of chemical composition of atmosphere	Atmospheric composition and conditions	Regulation Services
		Regulation of temperature and humidity		
Water management	Storm water management	Hydrological cycle and water flow regulation	Regulation of baseline flows and extreme events	
Physical Health	Air Quality	Filtration, sequestration, storage, accumulation by microorganisms, algae, plants, and animals	Mediation of wastes or toxic substances of anthropogenic origins by living processes	
	Water Quality			
		Regulation of the chemical condition of freshwaters by living processes	Water conditions	
		Bio-remediation by microorganisms, algae, plants and animals	Mediation of wastes or toxic substances of anthropogenic origins by living processes	
	Soil Quality			
		Filtration, sequestration, storage, accumulation by microorganisms, algae, plants, and animals		
		Weathering processes and their effect on soil quality	Regulation of soil quality	
		Decomposition and fixing processes and their effect on soil quality		
	Enhanced opportunities for outdoor activities	Characteristic of living systems enabling activities promoting health or enjoyment[6]	Intellectual & Representative Interactions with the natural environment	Cultural Services
Mental Health	Psychological relaxation	Characteristic of living systems enabling aesthetic experiences		
	Stress relief	Visual screening	Mediation of nuisances of anthropogenic origin	Regulation Services
		Smell reduction		
		Noise attenuation		
Biodiversity	Loss of Habitat	Maintaining nursery populations and habitats (Including gene pool protection)	Lifecycle Maintenance, Habitat and gene pool protection	
	Loss of Ecological Connectivity			
Resource efficiency	Energy Performance	Regulation of temperature and humidity	Atmospheric composition and conditions	
	Energy Production	Cultivated plants grown as source of energy	Cultivated terrestrial plants for nutrition, materials or energy	Provisioning Services
	Material Security	Materials from cultivated plants for direct use or processing		

[6] This is the combination of two ES classes, which differentiates between active and passive interactions.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

UC	USC	ES Class	ES Group	ES Section
	Food Security	Cultivated plants grown for nutritional purposes		

Table 8. . ES classes most assessed in the literature review.

ES Section	ES Class	Number of papers	Number of papers assessing ES in biophysical values
Regulation Services	Filtration, sequestration, storage, accumulation by plants (soil, water, air)	70	57
	Regulation of chemical composition of atmosphere	48	40
	Regulation of temperature & humidity	46	38
	Hydrological cycle and water flow regulation	45	37
	Maintaining nursery populations and habitats	35	24
	Regulation of chemical condition of freshwaters by living processes	19	12
	Bioremediation by microorganisms, algae, and plants	16	14
	Erosion regulation	12	11
	Pollination	12	9
Cultural Services	Characteristics of living systems that enable activities promoting health/enjoyment through active or passive interactions [7]	50	27
	Characteristics of living systems that enable aesthetic experiences	30	15
	Characteristics of living systems that enable education and training	20	11
	Characteristics of living systems that are resonant in terms of culture or heritage	15	6
	Elements of living systems that have symbolic meaning	14	6
Provisioning services	Cultivated plants grown for nutritional purposes	27	19
	Materials from cultivated plants for direct use or processing	11	7
	Cultivated plants grown as source of energy	6	4

With respect to regulation services, visual screening and smell reduction were not mentioned in the literature. Furthermore, the former could be difficult to differentiate from aesthetic experiences. Noise attenuation, weathering processes and decomposition and fixing processes of soil were assessed only in 7 out of 110 papers on regulation services. Regarding bioremediation, most of the papers were related to the bioremediation of water, while the bioremediation of soil was only considered in 12% of the cases. For provisioning services, cultivated plants grown as source of energy was only assessed six times, which represents 19% of the entire set of 32 papers investigated in this case. Finally, the two cultural services initially selected appeared in more than half of the papers focused on cultural services, but only around 1/2 of them were assessed making use of biophysical values.

The result of this literature review, together with specific comments from the pilot cities included in the questionnaires about the potential sites of interventions (WP7), guided the final selection of ES. Using the same criteria (occurrence in the literature review and relevance for the pilot cities), ES were prioritised within the modelling framework (Table 9).

[7] It was not possible to differentiate passive and active interactions in the ES assessments. Therefore it was considered only as one class despite the differentiation in CICES v.5.1.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 9. Selected ES and their prioritization in relation to UC and USC studied.

UC	USC	ES (Class)	Modelling priority
Climate issues	Climate mitigation/ Climate adaptation	Regulation of chemical composition of atmosphere	High
		Regulation of temperature and humidity	High
Water management	Storm water management	Hydrological cycle and water flow regulation	High
Physical Health	Air Quality	Filtration, sequestration, storage, accumulation by plants	High
	Water Quality		
		Regulation of the chemical condition by living processes	Medium
		Bio-remediation by plants	Low
	Soil Quality		
		Filtration, sequestration, storage, accumulation by plants	Medium
Mental Health	Enhanced opportunities for outdoor activities	Characteristic of living systems enabling activities promoting health or enjoyment	High
	Psychological relaxation	Characteristic of living systems enabling aesthetic experiences	Medium
	Stress relief	Noise attenuation	Low
Biodiversity	Loss of Habitat	Maintaining nursery populations and habitats	Medium
	Loss of Ecological Connectivity		
Resource efficiency	Energy Performance	Regulation of temperature and humidity	High
	Energy Production	Cultivated plants grown as source of energy	Low
	Material Security	Materials from cultivated plants for direct use or processing	Medium
	Food Security	Cultivated plants grown for nutritional purposes	High

3.3. Nature-based solutions

3.3.1. Conceptualization

The concept of NBS was initially developed and used by policy makers (e.g. Cohen-Shacham *et al.*, 2016; Bauduceau *et al.*, 2015), but scholars have started to be involved in the definition and study of NBS (Eggermont *et al.*, 2015; Kabisch *et al.*, 2016; Tratalos *et al.*, 2016; Maes and Jacobs, 2017). IUCN and EC provided the two main definitions of NBS. The former understands NBS as *actions to protect, manage, and restore (create) natural or modified ecosystems* (Cohen-Shacham *et al.*, 2016). The latter describes NBS as *living solutions inspired by, continuously supported by and using nature* (Bauduceau *et al.*, 2015). For both institutions, the purpose of NBS is quite similar, which is to address societal challenges in an effective and adaptive form, providing human well-being and biodiversity benefits (Cohen-Shacham *et al.*, 2016) or economic, social, and environmental benefits (Bauduceau *et al.*, 2015). For the scientific community the concept is still very open and needs to be more clearly defined and distinguished from other nature related concepts (e.g. green infrastructure, ecosystem based approaches) or it might become redundant, provide misunderstanding, and create trade-offs in decision making (Nesshover *et al.*, 2017).

In this sense, (Kabisch *et al.*, 2016) indicate that although the NBS notion partially overlaps with already existing concepts or builds on them, it puts further attention on how nature could be used to address societal (urban) challenges (e.g. climate change, food security). Also, several scholars,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

as well as IUCN, proposed to frame NBS as an umbrella concept for several nature-related concepts such as green infrastructure, ecological engineering or ecosystem-based approaches (Nesshover *et al.*, 2017; Pauleit *et al.*, 2017, Cohen-Shacham *et al.*, 2016). In addition, most of the existing approaches link NBS to the concept of ecosystem services and natural capital with more or less emphasis (Bauduceau *et al.*, 2015; Eggermont *et al.*, 2015; Cohen-Shacham *et al.*, 2016; Potschin *et al.*, 2016; Maes and Jacobs, 2017; Nesshover *et al.*, 2017)

Therefore, for the modelling framework of WP4, urban NBS are considered as actions which are applied to enhance living solutions or which are composed by them (integrating IUCN and EC concepts). This definition acts as an umbrella for other nature-related concepts, and has potential to address UC and USC by enhancing ecosystem services flows derived from natural capital. Based on this conceptualisation and key references about NBS conceptual frameworks, Task 1.1 has proposed a NBS typology applied to urban environment. From this typology and the outputs of the literature review, an NBS typology adequate for modelling purposes was defined in the Task 4.1, followed by the selection of the NBS cases that will be investigated in the Task 4.2.

3.3.2. An urban NBS typology for modelling purposes

The urban NBS typology follows a multi-hierarchic organisation that permits the definition of NBS archetypes for modelling purposes and allows a better understanding by professionals and decision makers. The first hierarchy of the typology follows the structure of Task 1.1 and it is based on the dominant media of the NBS: water, land, and built structures. This allows an organisation of NBS based on the main media of the area of intervention.

On the second hierarchy, the NBS classification takes into account the interrelation between NBS and the concept of ES and ecosystem classifications. This is done to facilitate the future accounting for ES provided by different NBS and the use of ES studies on natural and semi-natural ecosystems as sources of data. This hierarchy is based on the three NBS types proposed by Eggermont *et al.* (2015): first, *better use of ecosystems*; second, *sustainable and multifunctional management of ecosystems*; third, *design and management of new ecosystems*. These types are organised taking into account their contribution to an increased provision of ES and the level of engineering to be applied on the natural capital stocks (Eggermont *et al.*, 2015; Cohen-Shacham *et al.*, 2016).

The three types of Eggermont *et al.* (2015) are modified making use of the adaptation of IUCN (Cohen-Shacham *et al.* 2016), land management (Morgan, 2013; Triest, Stiers and Van Onsem, 2016) and restoration ecology (Hobbs, Higgs, & Harris, 2009; van Andel & Aronson, 2012) approaches (Figure 4):

- Type 1: Actions for a better management of existing natural or semi-natural ecosystems.
- Type 2: Actions to restore or partially reclaim existing ecosystems.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

- Type 3: Actions to completely reclaim previous ecosystems or to design novel ones.

The literature review identified green infrastructure, urban green (and blue) spaces, service providing units (SPUs) (Kain *et al.*, 2016), service providing elements (SPEs) (Kain *et al.*, 2016), sustainable urban drainage systems (SUDS), land use and land cover (LULC) classifications, and ecosystem-based adaptation (EbA) (Munang *et al.*, 2013; Zardo *et al.*, 2017) as actions composed by living solutions or applied to them studied in urban ES assessments. These actions relate the supply of ES to a biophysical structure, corresponding to the NBS type 3. Only EbA mentions protection, management, and restoration of the spatial structures (Tombolini, Munafo and Salvati, 2016) corresponding also to NBS type 1 and 2.

Based on the literature review, it was decided that biophysical structures (NBS type 3) in the form of land covers would be used as the basic spatial unit providing ES (i.e. SPUs), which can be disaggregated into SPEs (i.e. components of the NBS) onto which management and restoration actions (NBS type 1 and 2) could be applied. This will facilitate the comparability of the SDM results with other studies and the transfer of information taking into account that usually urban ES assessments, but also rural ones, refer to spatial structures. In addition, onto existing natural or semi-natural ecosystems, NBS type 2 and 1 can also be applied. These ecosystems are identified making use of the ecosystem types identified in the MAES, particularly the broad types (MAES Level 1) and detailed types (MAES Level 3). MAES Level 3 types are defined as NBS type 0 (no NBS), which have biophysical structures equivalent to NBS type 3. Moreover, artificial LULC where certain NBS type 3 could be built or installed are identified as an NBS type -1 (no NBS), taking into consideration the demand of ES and not only their supply.

The third hierarchy corresponds to spatial levels, which not only refer to the spatial levels of the NBS but also to the ones of the urban challenges that the NBS are supposed to influence. Consequently, this hierarchy includes the spatial levels already defined for the urban challenges in D2.1 (object, neighbourhood/district, and city/metropolis) and the urban region level (Figure 5).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

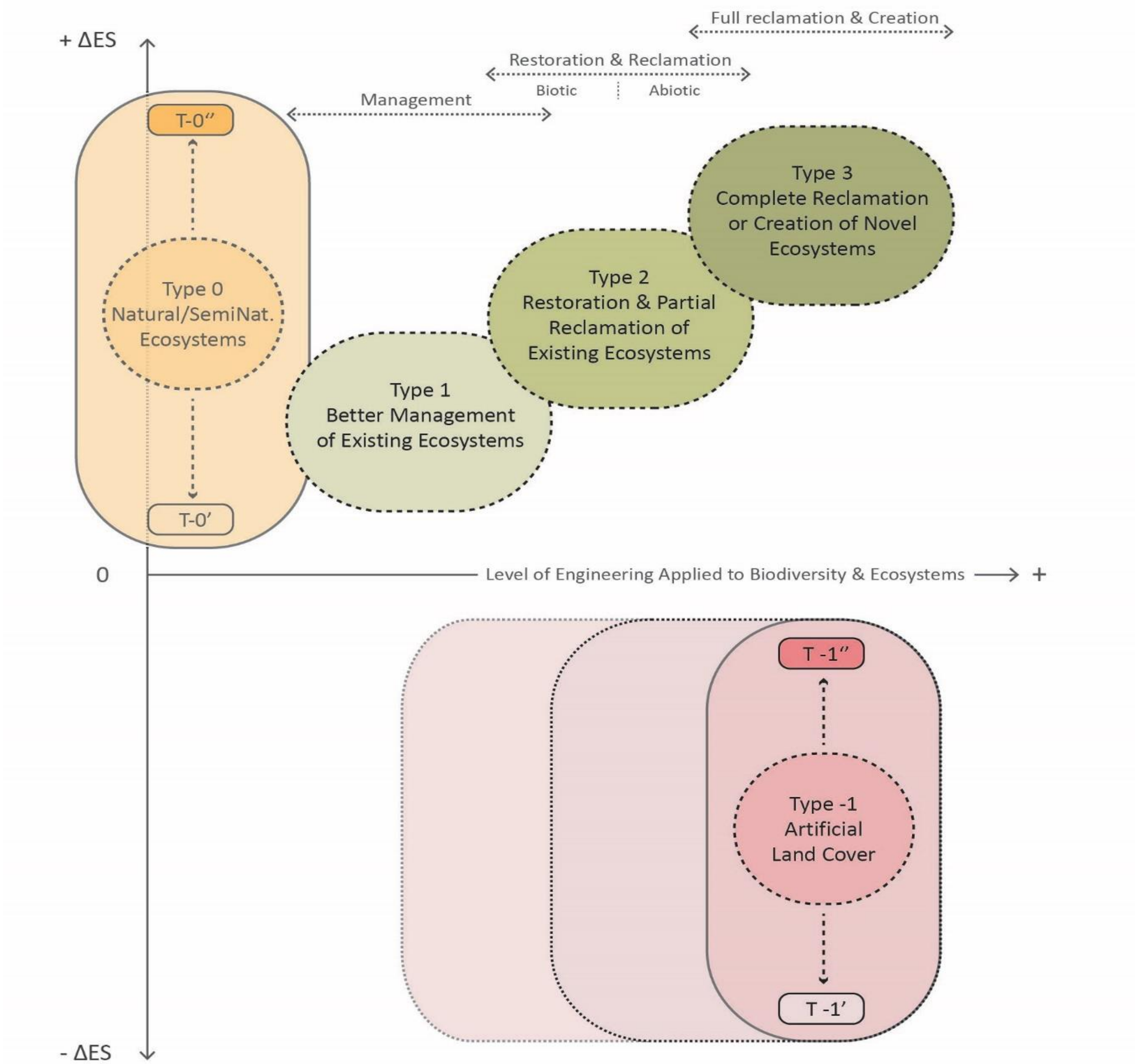


Figure 4. Conceptualisation of NBS Types; elaboration after Eggermont et al. (2015).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

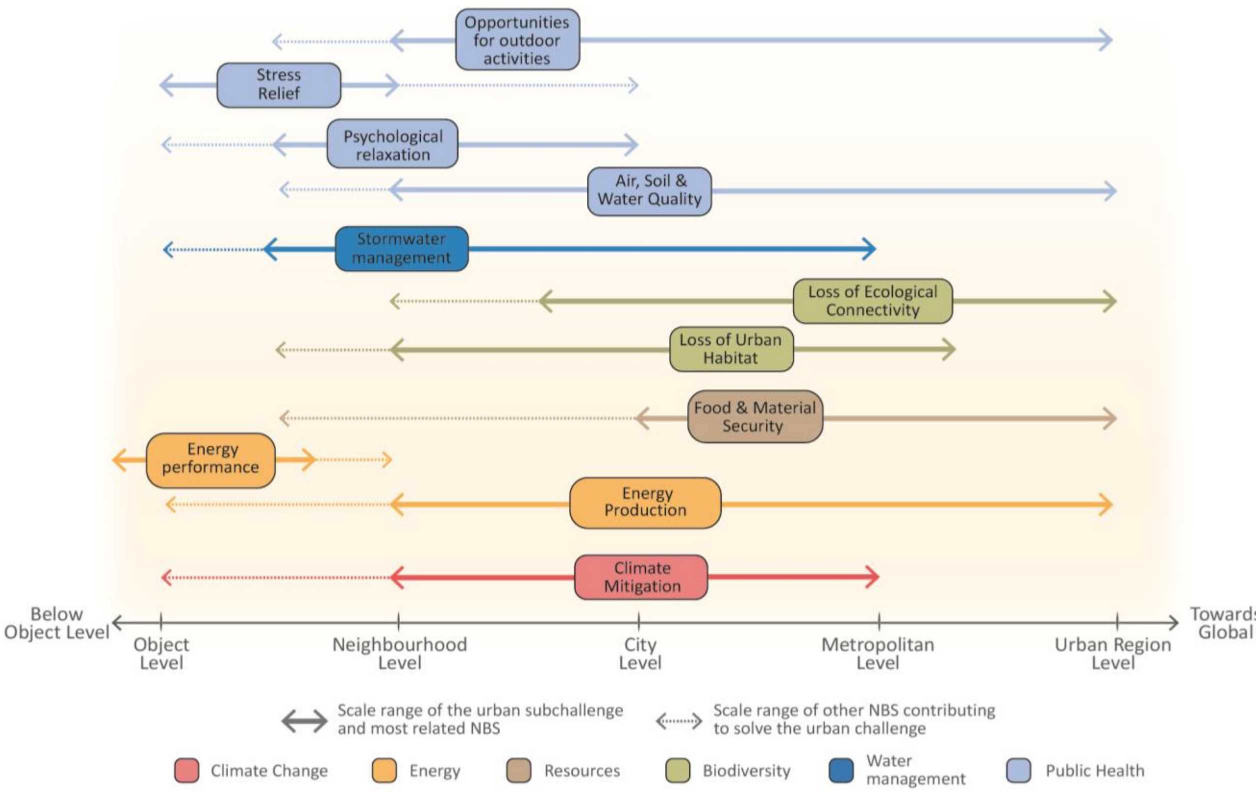


Figure 5. Scales of the urban challenges and related NBS.

Based on the multiple hierarchies, a typology was created and specific urban NBS archetypes for modelling purposes were differentiated (Figure 6a & 6b). This typology is compared to the one generated in the Task 1.1 and equivalent archetypes are identified (Supplementary Material, Table S3a, S3b and S3c). The typology should help the selection of NBS to be modelled, based on identified UC, media of intervention, scale, and type of action. Furthermore, the definition of this typology should facilitate the modelling of a "complex NBS" made from the combination of simple NBS types adequate for the same land cover type (Figure 6). For example, a municipality might be interested in understanding the ES provision (quantity, quality and spatial scale) of a new urban woodland (NBS Type 3) with a phytoremediation role (NBS Type 2), which later will be managed making use of reduced grazing (NBS Type 1). The specific NBS can then be coupled or decoupled in the SDM to let understand their individual and combined contribution to the ES supply. Through this framework, practitioners, stakeholders, and decision makers can easily provide inputs to support the combination of specific NBS Types in order to model "complex NBS" in the SDM. Therefore, the proposed typology would enable the creation of a clear definition and representation of the structure of specific NBS modules, whilst reinforcing the flexibility, credibility and legitimacy (as defined by Cash et al. 2003) of the SDM for decision making.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

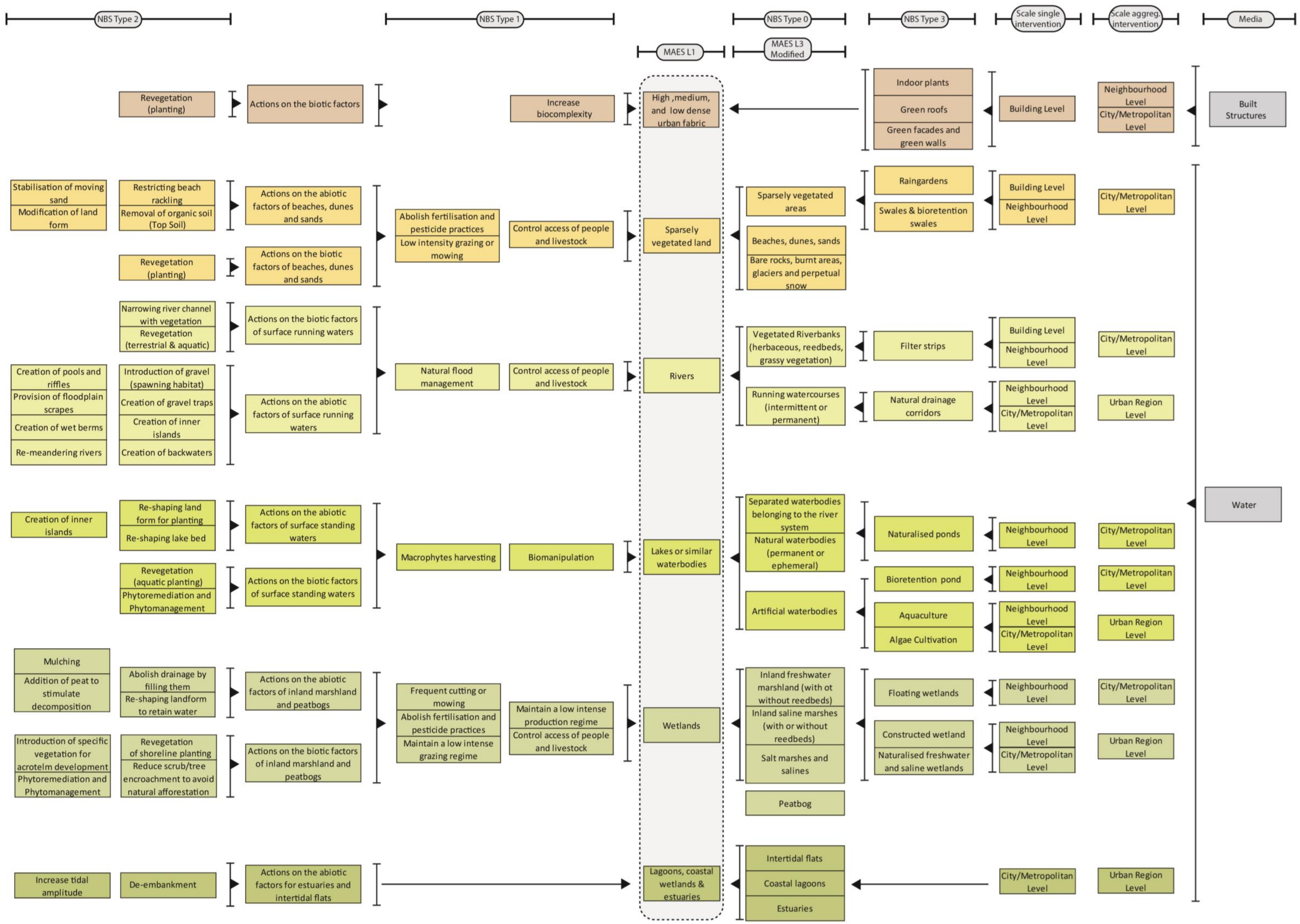


Figure 6. Built structure and water NBS archetypes for modelling purposes corresponding to MAES Level 1 land cover types.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

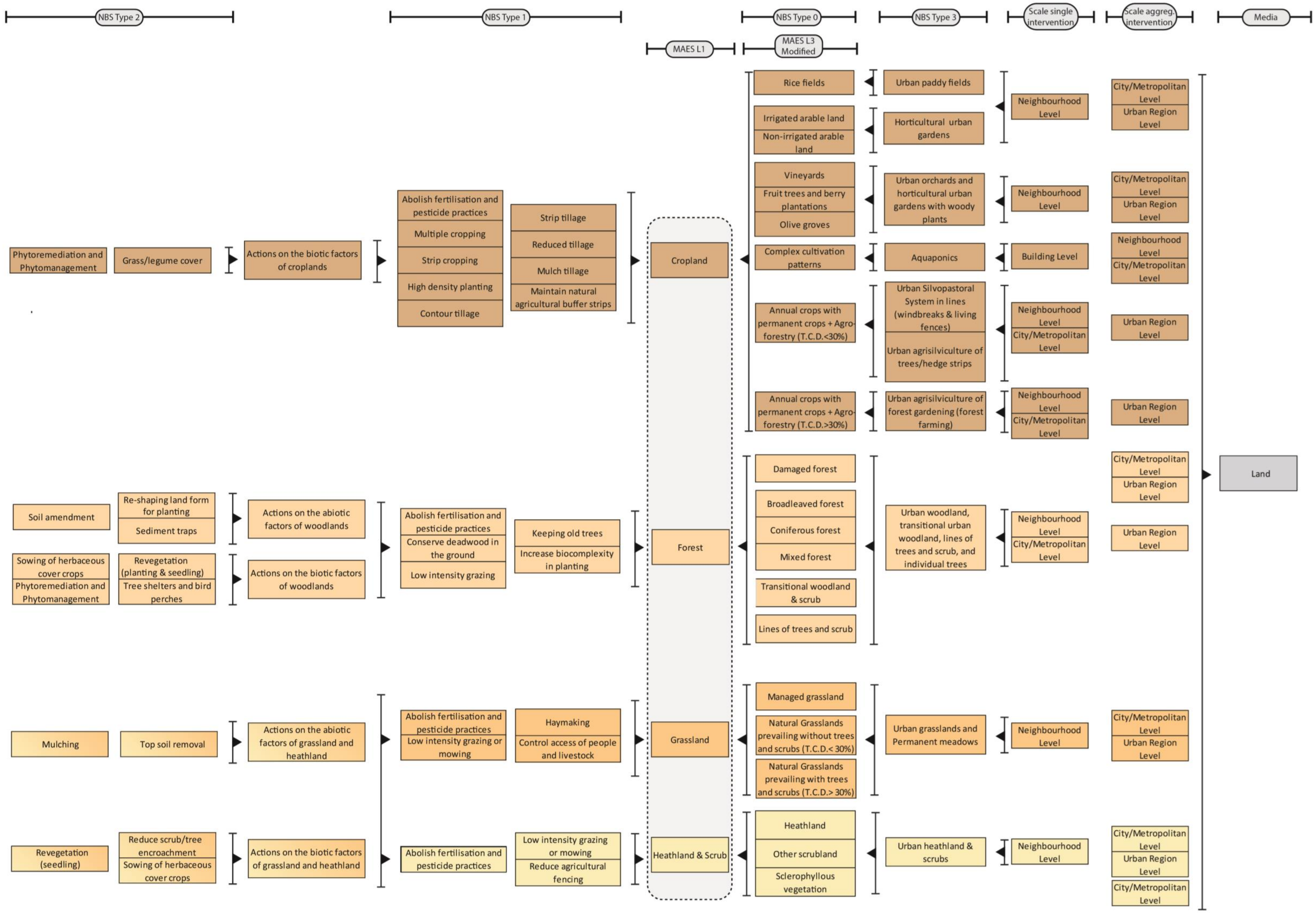


Figure 7. Land NBS archetypes for modelling purposes corresponding to MAES Level 1 land cover types.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

3.3.3. Selection of Urban NBS

3.3.3.1. Initial-selection of Urban NBS Type 3 based on the literature review

Specific land cover types or biophysical structures were identified during the literature review, which were aggregated according to the classification of NBS Type 3 and related to specific USCs (Table 10). There were several papers studying features that could not be classified as NBS (e.g. vacant lots, waste lands, green belts, agricultural land) or represented NBS Type 0 (agricultural land, running watercourses), which were eventually disregarded from the selection of urban NBS. The relation between the most mentioned NBS Type 3 (by media), the USCs and their related ES was further analysed in the papers. Later, potential NBS Type 2 and Type 1 associated with these NBS Type 3 were identified. Finally, a brief revision of the case studies of the pilot cities was done to see if these NBS could be adequate for the future integrated assessment developed in the WP7.

Table 10. NBS Type 3 identified in the literature review and their relation to USCs.

NBS Media	NBS Type 3	No papers	USC*
Land	Urban woodlands	73	1–13
	Horticultural urban gardens	26	2, 6 to 10, 12–14
	Grassland and permanent meadows	20	1, 6 to 8 (2–5)
	Scrub, herbaceous (and heathland)	6	1–10
	Urban orchards	4	1, 3, 5–14
Water or water-related	Natural and naturalized standing waterbodies	20	1, 2, 4, 6–11
	Natural and naturalised Wetlands	12	1, 2, 4, 6–11
	Constructed wetlands	6	1, 2, 4, 6–11
	Swales	5	2, 4
	Filter strips	5	2, 4
	Estuaries/tidal marsh	4	2, 4, 9, 10
	Bioretention pond	3	2, 4, 9, 10
	Rain gardens	2	2, 4
	Floating wetland	1	2, 4, 9
Built Structures	Green roofs	9	1–4, 9–11, (12–14)
	Green walls	2	1–4, 9–11

*1: Climate mitigation/adaptation; 2: Stormwater management; 3: Air quality; 4: Water Quality; 5: Soil Quality; 6: Opportunities for outdoor activities; 7: Psychological relaxation; 8: Stress relief; 9: Loss of habitat; 10: Loss of ecological connectivity; 11: Energy performance; 12: Energy production; 13: Material Security; 14: Food Security

( ): USCs identified in the literature, but for which relations are weakly stated.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

The literature shows that urban woodlands (including lines of trees and scrub, individual trees, and transitional urban woodlands) were the solutions most studied followed by horticultural urban gardens and grasslands, and permanent meadows. In the case of NBS applied on water, natural (NBS type 0) and naturalized waterbodies were the two most mentioned solutions followed by inland wetlands, running watercourses, and constructed wetlands. For NBS applied on built structures only green roofs and green walls were considered by the authors.

For **urban woodlands**, the literature showed their association with all the UCs, most of the USCs or related ES (e.g. Fusaro *et al.*, 2015; Bottalico *et al.*, 2017; Calderon-Contreras and Quiroz-Rosas, 2017; Reynolds *et al.*, 2017; Woldegerima, Yeshitela and Lindley, 2017). However, only few papers associate urban woodlands with ES related to food security (e.g. Dumenu, 2013; Manolaki and Vogiatzakis, 2017; Hurley and Emery, 2018). The link with these USCs is consistent with other studies assessing the capacity of urban woodlands to regulate the temperature and humidity for climate issues and resource efficiency (Howes, 1998; Park and Cho, 2016), filtrate air (Baro *et al.*, 2014; Lin *et al.*, 2017), regulate water flows and retain their pollutants (Shi *et al.*, 2016; Berland *et al.*, 2017; Setälä *et al.*, 2017), provide recreation opportunities, psychological relaxation and stress relief (Korpela *et al.*, 2010; O'Brien, Morris and Stewart, 2014), maintain habitats for birds and insects (Croci *et al.*, 2008), and supply wood biomass for different uses (Pulighe, Fava and Lupia, 2016).

In the case of **horticultural urban gardens**, the papers reviewed associate them with all the UCs, except climate issues. However, there is no relation with the USC energy performance and only few papers mention the link with air, water, and soil quality, in most cases based on people's perception (Camps-calvet *et al.*, 2016; Langemeyer *et al.*, 2018). Several authors identified a strong association of horticultural urban gardens with opportunities for outdoor activities and/or psychological relaxation, in most cases identified making use of social perception questionnaires and interviews (Chen and Jim, 2011; Haase, Frantzeskaki and Elmqvist, 2014; Dennis and James, 2016; J.-H. Kain *et al.*, 2016; Langemeyer *et al.*, 2018). In addition, horticultural gardens, like arable lands, would be able to produce plants as a source of material or energy, even if these applications were not mentioned in the papers.

Regarding **grasslands and permanent meadows**, the literature indicates links with all the UCs except resource efficiency, but in many cases this was not consistent when looking specific USCs. Several papers assessed the role of grassland on climate mitigation and adaptation. In the case of the ES *regulation of temperature and humidity*, few scholars studied how grasslands affect land surface temperature and evapotranspiration (Peters, Hiller and McFadden, 2011; Connors, Galletti and Chow, 2013). For the ES *regulation of chemical composition of the atmosphere,* also few papers indicated the role of grasslands (Vaccari *et al.*, 2013; Tao *et al.*, 2015; Grafius *et al.*, 2016; Manolaki and Vogiatzakis, 2017). In addition, other papers included both ES for grasslands, although they did it as part of social valuations or environmental valuations where several NBS were combined, making difficult to differentiate the specific role of grasslands (Kain *et al.*, 2016;

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Meri and Lian, 2017; Roussel *et al.*, 2017). For ES related to stormwater management, air, water, and soil quality, grasslands were always assessed in combination with other NBS or as part of social valuations (Kain *et al.*, 2016; Meri and Lian, 2017; Roussel *et al.*, 2017). No paper assessed the specific role of grassland for habitats, but Haase *et al.* (2012) included grassland in a combined assessment of land covers. Instead, several papers associate grasslands with opportunities for outdoor activities and psychological relaxation (Haase *et al.*, 2012a; Dou *et al.*, 2017; Montoya-Tangarife *et al.*, 2017).

For the case of **natural and naturalized standing waterbodies**, links were identified with all the UC. Not surprisingly, several papers assessed this NBS for ES related to climate mitigation and adaptation as well as for stormwater management (e.g. Lundy and Wade, 2011; Scholz *et al.*, 2013; Montoya-Tangarife *et al.*, 2017). For climate mitigation and adaptation, papers focused on the assessment of ES *regulation of temperature and humidity*, which is also related to energy performance, but no paper attempted to include this USC. In addition, ES related to water quality were also assessed in several papers (e.g. Lundy and Wade, 2011; Scholz *et al.*, 2013; Gao *et al.*, 2015; Liu *et al.*, 2017) as well as ES related to mental health and biodiversity (e.g. Scholz *et al.*, 2013; Liu, Zhang and Weschler, 2014; Mak, Scholz and James, 2017; Sikorska, Sikorski and Hopkins, 2017).

The assessment of **natural and naturalised wetlands** was similar to the one of waterbodies, and links with all the UC were indicated. Nevertheless, only Montoya-Tangarife *et al.* (2017) related this NBS to climate adaptation and mitigation. Several authors studied the contribution to stormwater management (Rooney *et al.*, 2015; Meixler, 2017; Sun *et al.*, 2017), and in some cases related to extreme events linked to climate issues. There is also a clear link with all the ES related to water quality (Adhikari *et al.*, 2011; Rooney *et al.*, 2015; De Troyer *et al.*, 2016), opportunities for outdoor activities and psychological relaxation (Dou *et al.*, 2017; Meixler, 2017; Montoya-Tangarife *et al.*, 2017) as well as habitat enhancement (Meixler, 2017; Moores *et al.*, 2017).

In the case of **constructed wetlands**, relations with all the UC were established except for resource efficiency. As expected, several papers relate this NBS with water quality and their related ES (Adhikari *et al.*, 2011; Scholz *et al.*, 2013; De Martis *et al.*, 2016; Liquete *et al.*, 2016). In addition several authors also stated a relation with the ES related to opportunities for outdoor activities and psychological relaxation (Scholz *et al.*, 2013; Garcia *et al.*, 2016; Liquete *et al.*, 2016). Only Liquete *et al.*, (2016) assessed potential for stormwater management. Similarly, only (Scholz *et al.* (2013) showed a link with climate mitigation, even if like any other water feature, the presence of water in this NBS could contribute to regulate temperature and humidity. Finally, De Martis *et al.* (2016) assessed the potential of constructed wetlands for habitat enhancement in a periurban site in Cagliari (Italy), where the enhancement of species diversity was demonstrated in the medium-term.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

With respect to **green roofs and green walls**, the papers stated a relation with all the UCs. There are several papers indicating their contribution to stormwater management (Scholz *et al.*, 2013; Gao *et al.*, 2015; Kain *et al.*, 2016; Dusza *et al.*, 2017; Grunwald, Heusinger and Weber, 2017; Pappalardo *et al.*, 2017; Zölch *et al.*, 2017), air quality (Scholz *et al.*, 2013; Feng *et al.*, 2015; Dusza *et al.*, 2017; Grunwald, Heusinger and Weber, 2017), habitat enhancement (Scholz *et al.*, 2013; Grunwald, Heusinger and Weber, 2017), some ES related to water quality (Scholz *et al.*, 2013; Gao *et al.*, 2015; Dusza *et al.*, 2017), and the ES *regulation of temperature and humidity* (Kain *et al.*, 2016; Zölch *et al.*, 2016; Dusza *et al.*, 2017; Grunwald, Heusinger and Weber, 2017). In addition, only Kain *et al.* (2016) indicates their potential for outdoor activities, psychological relaxation and provision of cultivated crops. Despite the lack of papers studying ES related to psychological relaxation, it seems logic to think that green walls could contribute to the enhancement of the aesthetic of streets and public spaces providing pleasant spaces. Similarly, in the case of accessible public green roofs it seems logic to consider their contribution to outdoor activities. In addition, there are already interventions where green roofs are used for productive purposes and these are already studied in the literature (e.g. Hui, 2011; Whittinghill and Rowe, 2011).

As a result of this analysis, urban woodland, horticultural urban gardens, naturalised waterbodies, naturalised wetlands, constructed wetlands, green roofs, and green walls were selected as NBS of study. These NBS relate with many of the USCs, and for most of them an extensive literature exists to support the development of SDM models. In the case of constructed wetlands, there is further literature studying or modelling their performance for water quality, but it is not usually framed to explicitly consider ES (e.g. Mohammed and Babatunde, 2017; Olguín *et al.*, 2017). This is also the case for green roofs and green walls, for which literature also includes empirical studies (e.g. Cameron, Taylor and Emmett, 2015; Marchi *et al.*, 2015; Collins, Schaafsma and Hudson, 2017; Cuce, 2017; Weerakkody *et al.*, 2017). However, these are the only ones focusing on NBS for built structures. Despite the number of papers, grasslands and permanent meadows were not selected because it was difficult to find adequate relations with the USC studied. Additional literature on this urban NBS was only found for psychological relaxation making use of social perception assessments (e.g. Hoyle *et al.*, 2017; Southon *et al.*, 2017). However, their study could be considered as part of urban woodlands (their understory) and green roofs models. The integration of grasslands as part of other models might facilitate the understanding of the relation between this NBS, ES and USCs as part of other models. Later, with the support of additional literature, it might be possible to model this NBS independently.

3.3.3.2. Potential NBS type 2 and 1, based on pre-selected NBS type 3.

Due to the lack of references to NBS type 2 and type 1 in the literature review, the NBS typology was used to identify potential NBS type 2 and 1 related to the selected NBS type 3. The easiness of their integration in the model, the existence of supporting literature, and the relation of the different NBS with the USCs were considered for their selection process.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Regarding NBS Type 2 related to biotic factors, phytoremediation was a solution that could be considered in combination with all the NBS Type 3 selected, except green roofs and green walls. Extensive literature on this NBS already exists for woodlands, wetlands and croplands, even if not framed within the ES assessment domain, which could be used as a support for system dynamic modeling (e.g. (Ouyang *et al.*, 2007; Rytter, 2012; Sacristan, Peñarroya and Recatala, 2015; Shi *et al.*, 2016). In addition, phytoremediation is usually related with the restoration of brownfields or contaminated waterbodies, being related to water and soil quality. For example, Heasman *et al.*, (2011) indicate that a 0.25-0.5% of the total land area in EU countries is classified as brownfield, being most of it artificial or urbanized land. Since a 4.6% of the EU land cover is classified as artificial land (Eurostat 2013), around a 5-10% of European urbanized areas could be assumed to be brownfield.

Other NBS type 2 related to the biotic factors include revegetation, removal of tree or scrub encroachment, sowing of grass or legume covers. Revegetation relates to all the selected NBS type 3, the others could be also applied to wetlands, and sowing of grass or legume covers to horticultural urban gardens and urban woodlands. These NBS could be included in an NBS system dynamics module by changing the conditions of initial inputs and testing different options or including discrete events that occur with a certain frequency. However, their contribution to specific USCs is not completely clear since it would depend on the specific context and NBS. For example, removal of tree encroachment could be positive for maintaining wetlands, but it might have negative consequences in terms of ES delivery.

With respect to NBS type 1, the enhancement of biocomplexity (urban woodland, green roofs and green walls), multiple cropping, and the enhancement of agricultural margins (urban horticultural gardens) could be done by testing different scenarios for the selected species, and the mix of sizes at planting or harvesting periods. However, despite the decline of diversity is usually associated with loss of ES (Isbell *et al.*, 2011), the relation with specific USCs (except loss of habitat) and their related ES is not entirely clear, and trade-offs could exist. This is also the case for low intensity grazing or frequent cutting or mowing. In the case of deadwood and old trees conservation (urban woodland), a positive relation with habitat enhancement for insects, birds and little mammals is already acknowledged in the literature (e.g. Corona *et al.*, 2011; Lindenmayer *et al.*, 2014; Morrison and Chapm, 2017).

Other NBS type 1 such as biomanipulation[8] might be difficult to be implemented in the model, since it requires in depth knowledge about the specific underpinning trophic web and the consequences are not comparable in different contexts. In addition, biomanipulation is an action that might not be relevant for an urbanized environment. This is also the case for the use of

[8] Biomanipulation is defined as a management practice in which populations of certain species are removed intentionally from standing waterbodies, restructuring the biological community to reduce algal biomass, increasing water quality and/or enhance ecological diversity in eutrophication (Perrow *et al.*, 1997).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

chemical additives (pesticides and fertilizers), for which it might be difficult to model the ES trade-offs, but also for people's actions on NBS, which also might not be relevant since people movement in urban open spaces is usually controlled by fencing or designated paths.

As a result, phytoremediation was selected as the preferred NBS type 2 to be considered in the modelling framework. Other NBS type 2 could also be considered by developing scenarios where different options for input variables are tested, or discrete events integrated. Conservation of deadwood and old trees, and biocomplexity were selected as the preferred NBS type 1 due to their contribution to habitat enhancement. Solutions such as low intensity grazing, and frequent cutting could also be considered by developing different scenarios.

3.3.3.3. Short comparison with the case studies at WP7.

The potential list of case studies for WP7 provided by the pilot cities includes a periurban edible forest (Alcala de Henares), quarry restorations as urban and periurban parks (Milan Metropolitan Area), regeneration of the waterfront of Tisza (Szeged), and conversion of a semi natural area into an urban park (Cankaya). Other case studies related to interventions in the built environment might be included in the future.

The four case studies all include the development of urban woodlands. The case studies of Milan Metropolitan Area also include naturalized standing waterbodies, and naturalized and constructed wetlands. Therefore, the selection of urban woodlands, naturalized standing waterbodies, wetlands (naturalized and constructed) to be developed in the modelling framework seems to be adequate for testing the integrated assessment during WP7. Retaining green roofs, green walls, and urban horticultural gardens could be adequate if interventions in the built environment are included in a later stage. The selected NBS, USCs and ES and their interrelation are summarized in Table 11. More details about the case studies are provided in Chapter 7.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 11. Relation of selected NBS-ES-UCs (& USCs). ES classes refer to the CICES system (Haines-Young and Potschin, 2018).

UC	USC	ES (Class)	Urban Woodland	Horticultural urban garden	Naturalised standing water	Naturalised Wetland	Constructed Wetland	Green Roofs & Green Walls	Phytoremediation	Biocomplexity	Conserving Deadwood	Conserving old trees
Climate issues	Climate mitigation/ Climate adaptation	Regulation of chemical composition of atmosphere	X	-	-	-	-	-	-	?	-	?
		Regulation of temperature and humidity	X	X	X	X	X	X	-	?	-	?
Water management	Storm water management	Hydrological cycle and water flow regulation	X	-	X	X	X	X		?	?	?
Physical Health	Air Quality	Filtration, sequestration, storage, accumulation by plants	X	-	-	-	-	X	-	?	-	?
	Water Quality			-	X	X	X	X	-	?	-	X
		Regulation of the chemical condition by living processes	X	-	X	X	X	-	-	?	-	?
		Bio-remediation by plants	-	-	-	-	X	-	X	?	-	-
	Soil Quality		-	-	-	-	X	-	X	?	-	-
		Filtration, sequestration, storage, accumulation by plants	X	-	-	-	-	-	-	?	-	-
Mental Health	Enhanced opportunities for outdoor activities	Characteristic of living systems enabling activities promoting health or enjoyment	X	X	X	X	X	X	-	?	-	-
	Psychological relaxation	Characteristic of living systems enabling aesthetic experiences	X	X	X	X	X	X	-	?	-	?
	Stress relief	Noise attenuation	X	X	-	-	-	-		?	-	-
Biodiversity	Loss of Habitat	Maintaining nursery populations and habitats	X	X	X	X	X	X	-	X	X	X
	Loss of Ecological Connectivity											
Resource efficiency	Energy Performance	Regulation of temperature and humidity	X	-	X	X	X	X	-	?	-	-
	Energy Production	Cultivated plants grown as source of energy	X	X	-	-	-	-	-	?	-	-
	Material Security	Materials from cultivated plants for direct use or processing	X	X	-	-	-	-	-	?	-	-
	Food Security	Cultivated plants grown for nutritional purposes	?	X	-	-	-	?	-	?	-	-

Notes:

X Indicates that positive relation was found between the NBS and the ES;

- Indicates that no relation was found between the NBS and the ES:

? Indicates that the relation is unclear and could depend on specific aspects of the NBS type and the urban context.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

4. Biophysical structures, socio-ecological processes, and the selection of ES Indicators

The following sections of this chapter describe: (i) the identification of the biophysical structures and ecological processes and social and ecological factors influencing the supply of ES; (ii) and the selection of ES indicators. The former is relevant for the definition of the main parameters to consider in the NBS modelling framework and to inform the selection of adequate ES parameter-proxy or indicators used as output in the models. The selection of ES indicators is also primordial for the definition of an economic impact assessment scale in Task 4.2.

4.1. Relation between biophysical structures, ecological processes, and social and ecological factors

The literature selected together with a review of existing environmental models (Table 12) can support the explicit identification of links between biophysical structures, ecological processes, and supply of specific ES. In some cases, papers also informed about the relevance of social factors influencing cultural ecosystem services (e.g. Schipperijn *et al.*, 2013). For some ES classes (e.g. characteristics of living systems enabling activities promoting health or enjoyment), a review of additional literature was necessary. The following sections describe the major factors and processes affecting the supply of specific ES.

Table 12. List of environmental models used to identify factors influencing ecological processes.

Name	Source	Purpose	Processes revised
i-Tree Eco carbon sequestration & storage model	(Nowak, 2000) https://www.itreetools.org/	Tree growth and carbon storage	Carbon storage
i-Tree Eco dry deposition model	(Hirabayashi, Kroll and Nowak, 2015) https://www.itreetools.org/	Deposition of pollutants in trees	Deposition of pollutants
i-Tree Eco precipitation interception model	(Hirabayashi, 2013) https://www.itreetools.org/	Interception of rainfall by trees	Interception, evaporation and infiltration
Yasso v 7, v.15	(Liski, Tuomi and Rasinmäki, 2009)el http://www.syke.fi/projects/yasso	Storage of carbon in soil	Storage and emission of carbon by soil
RothC, RothPC-1	(Jenkinson and Coleman, 2008; Coleman and Jenkinson, 2014) https://www.rothamsted.ac.uk/rothamsted-carbon-model-rothc	Storage of carbon in soil	Storage and emission of carbon by soil
ECOSSE	(Smith *et al.*, 2010) https://soil-modeling.org/resources-links/model-portal/ecosse	Storage of carbon in organic soils	Storage and emission of carbon by soil

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Name	Source	Purpose	Processes revised
BIOME	(Golinkoff, 2010) https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=805	State and fluxes of carbon, nitrogen, and water in ecosystems	Growth of vegetation, evapotranspiration
CO2fix	(Schelhaas *et al.*, 2004) http://dataservices.efi.int/casfor/models.htm	Sequestration of carbon and economic value of biomass	Growth of vegetation, storage and emission of carbon by soils
LANCA	(Bos *et al.*, 2016)	Characterisation factors of occupation and transformation of land for life cycle assessment	Erosion, physico-chemical filtration, mechanical filtration of soil pollutants
Soil & Water Assesment Tool (SWAT)	(Shekhar and Xiong, 2008) https://swat.tamu.edu/	Hydrological cycle and flux of sediment and pollutants	Infiltration, percolation, de/nitrification and immobilisation, erosion. plant uptake
Stormwater Management Model (SWMM)	(Rossman and Huber, 2016) https://www.epa.gov/water-research/storm-water-management-model-swmm	Hydrological cycle in urban areas	Interception, infiltration, percolation, and water run-off
Wetlands water quality model (WWQM)	(Chavan and Dennett, 2008)	Nitrogen, phosphorus and sediment retention in wetlands	De/nitrification, settling, immobilisation, plant uptake
Vertical Greenery System Model	(Marchi *et al.*, 2015)	Carbon sequestration by green walls	Storage and emission of carbon by vegetation

4.1.1. Regulation of chemical composition of atmosphere

The capacity of ozone (O_3), carbon dioxide (CO_2), and carbon monoxide (CO) uptake by vegetation and soils drives the regulation of chemicals composition in the atmosphere by NBS, even if in the literature this ES is usually related only to carbon sequestration and storage due to their major contribution (Vaccari *et al.*, 2013; Kim, Miller and Nowak, 2016; Reynolds *et al.*, 2017). In the case of plants, O_3 is absorbed as a by-product through the stomata during transpiration, being stomata resistance, cuticular resistance, and mesophyll resistance relevant factors driving its uptake by plants (Hirabayashi, Kroll and Nowak, 2015; Manes *et al.*, 2016; Selmi *et al.*, 2016). Absorption of CO_2 is not limited by the previous factors, since the amount of atmospheric concentration of CO_2 is one of the main variables modifying the previous resistances (Sanderson *et al.*, 2007; Flexas *et al.*, 2008) and CO is oxidised after absorption to become an additional source of CO_2.

In order to calculate CO_2 sequestration and storage by woody plants, scholars usually rely on standardized biomass growth rates and the calculation of biomass by making use of allometric equations (e.g. Nowak *et al.*, 2008; Vaccari *et al.*, 2013; Andersson, Dickin and Rosemarin, 2016). Several authors identify as factors influencing the growth rate the condition of the trees, the competition between cohorts and among cohorts (due to space limitation), the phenology, the limitation of nutrients due to water and soil conditions, and the differences between species (e.g.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

(Schelhaas *et al.*, 2004; Thornton, Running and Hunt, 2005; Nowak *et al.*, 2008). In addition, the amount of carbon stored in trees is usually calculated based on the proportion of biomass in stems, branches, roots, and foliage (and in some cases bark), the wood density, and the carbon fraction of dry biomass of specific species (Schelhaas *et al.*, 2004; Vaccari *et al.*, 2013). In the case of urban areas, differentiating the proportion of above-ground and below-ground biomass could be difficult, since specific soil conditions could make below-ground biomass very variable, changing from 16% to 41% of the total biomass (Strohbach and Haase, 2012).

In the case of non woody plants such as grasses, sedges and rushes, the carbon storage is usually calculated based on estimated annual growth rate or obtained through empirical sampling where individuals are harvested, their biomass dried, and their concentration in carbon and nitrogen analysed in the laboratory (e.g. (Schäfer *et al.*, 2014). However, the factors influencing their growth rate are equivalent to the ones of trees. This is the reason explaining why few carbon sequestration models used for urban forests (e.g. CO2FIX) are also adapted to model carbon sequestration of herbaceous communities, by assigning insignificant biomass to the stem and incorporating high turnovers of foliage and roots to acknowledge their different behaviour.

Regarding soils, CO_2 and CO are assimilated by the microbiota, but the main carbon uptake comes from organic compounds provided by different soil compartments (e.g. resistant plant material, decomposable plant material, humus) which is the major contribution to the soil organic matter. The soil organic matter is decomposed at different velocities depending on the degradability of the different compartments, the type of soil (texture affecting infiltration and aggregate stability), soil humidity, weather conditions, waterlogging, and soil management (Farina, Coleman and Whitmore, 2013; Coleman and Jenkinson, 2014). As a result, CO_2, CO, but also CH_4 (during waterlogged conditions) are released to the atmosphere, but part of the carbon is maintained in the humus, microbiota and inorganic matter compartments. In this sense, soil could act as a sink and source of carbon depending on the specific conditions.

The literature also discussed the role of water biophysical structures related to the carbon uptake. Similarly to plants, phytoplankton in the water uptakes CO_2, CO and O_3. However, like soil systems, constructed (or naturalised) wetlands and water standing bodies could act as a sink or source of carbon depending on their specific dynamics, although it is difficult to identify driving variables and processes adequate for all contexts and seasons (Schäfer *et al.*, 2014). In addition, for urban systems many scholars studying carbon sequestration did not consider the contribution of water biophysical structures to this ES (Strohbach and Haase, 2012; Nowak *et al.*, 2013). According to Grafius *et al.* (2016), this is due to the difficulty of urban authorities to manage those systems for the enhancement of carbon uptake.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

4.1.2. Regulation of temperature and humidity

The regulation of temperature and humidity is mainly driven by shading, evapotranspiration, and air heat exchange due to alteration of wind movement, as explicitly identified by several reviewed papers (Peters, Hiller and McFadden, 2011; Jim and Chan, 2016; Nocco, Rouse and Balster, 2016; Zölch *et al.*, 2016; Francis and Jensen, 2017; Zardo *et al.*, 2017). In the case of water and herbaceous plants such as the ones in grasslands, green roofs and green walls, evapotranspiration is considered the main process influencing this ES (Francis and Jensen, 2017).

Shading is mainly affected by the interception of solar radiation by woody plants coverage and leaf area density, being vegetation height also relevant in order to be effective for people (Jim, 2015; Zölch *et al.*, 2016; Zardo *et al.*, 2017). For evapotranspiration, several authors stressed on the relevance of canopy coverage, leaf area density, stomata behaviour (related to C3, C4, CAM vegetation functional groups), weather conditions, soil cover, soil types, soil substrate, soil moisture (dependent also on soil cover, soil types, and weather conditions), species (affecting capacity of evapotranspiration), and phenology or growing season length (Peters, Hiller and McFadden, 2011; Jim and Chan, 2016; Nocco, Rouse and Balster, 2016; Zölch *et al.*, 2016; Zardo *et al.*, 2017). Regarding wind, this is a process not typically controlled by NBS (although it can be argued that trees reduce wind speed, degrading comfort in warm seasons or circumstances), but rather driven by the environmental conditions as well as the urban form of the specific context (Zardo *et al.*, 2017), being in many cases difficult to acknowledge.

Additionally, Zardo *et al.* (2017) identified the size of green spaces as a factor affecting the relative importance of shading and evapotranspiration in regulation of temperature and humidity. For green spaces below two hectares shading has the major influence, but beyond this dimension evapotranspiration drives the supply of this ES. Moreover, Park and Cho (2016) acknowledged the relevance of certain NBS shape for the regulation of temperature and humidity, being linear features more effective than compact features of the same dimensions to regulate temperature and humidity for longer distances.

When this ES is considered in relation to energy saving the insulation thermal capacity of the material and the time of heat release seems to become also relevant for green roofs and green walls. In this sense, Jim (2015) acknowledged the relevance of considering substrate and their depth depending on the specific context, since deep substrates such as the ones of intensive roofs might become a heat sink delaying the heat release, but not impeding it. In some contexts, such as tropical ones, this could provoke increase of energy consumption with respect to shallow substrate solutions such as in the case of extensive green roofs (Jim (2015)).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

4.1.3. Hydrological factor and water flow regulation

The regulation of water flow is mainly driven by interception, evapotranspiration, infiltration, percolation (deep infiltration), water run-off, and duration and intensity of rainfall events (Hirabayashi, 2013; Rossman and Huber, 2016; Pappalardo *et al.*, 2017; Zölch *et al.*, 2017). In the case of NBS such as naturalised or constructed wetlands and naturalised standing waters, the capacity to store water in their basins is also relevant. Duration and intensity of rainfall events could affect the performance of run-off control significantly (Pappalardo *et al.*, 2017), affecting soil factors. However, some models such as SWMM do not consider the impact of rainfall intensity in soil factors when modelling NBS, apparently to avoid overcomplicated calculations.

Interception by vegetation and soil are mainly affected by the amount of vegetation cover, the capacity of vegetation to store water (depending on leaf area density), evapotranspiration, and depth of depression storage (Hirabayashi, 2013). Infiltration and percolation are influenced by the type of soil, soil humidity, soil evaporation, top and sub-soil water storage capacity (also dependent on the previous factors), plant uptake (which affects evapotranspiration), slope, and surface roughness (Rossman and Huber, 2016; Pappalardo *et al.*, 2017; Zölch *et al.*, 2017). In the case of green roofs, the type of drainage material and its thickness is also affecting infiltration (Rossman and Huber, 2016; Pappalardo *et al.*, 2017). Water run-off is affected by the previous processes, slope, the intensity of the rainfall, and the roughness coefficient of the surface (Pappalardo *et al.*, 2017)

4.1.4. Regulation of the chemical condition of freshwaters by living processes

For this ES, the processes and relevant biophysical factors depend on the specific pollutants considered. To evaluate the chemical conditions of freshwaters, the literature consulted stressed on the measurement of several variables such as: concentration of nitrogenous and phosphorous compounds (especially nitrates (NO_3^-), ammonium (NH_4^+), phosphates (PO_4^{3-}), total phosphorus, and total nitrogen), total dissolved solids, total suspended solids, chlorophyll-a, dissolved oxygen, biological oxygen demand, and electrical conductivity (Rooney *et al.*, 2015; De Troyer *et al.*, 2016; Jujnovsky *et al.*, 2017; Olguín *et al.*, 2017).

These variables are aligned with the physico-chemicals elements (e.g. thermal conditions, oxygenation conditions, salinity, acidification status, and nutrient conditions) identified in the EU Water Framework Directive 2000/60/EC (WFD) as a support to biological elements for the classification of the ecological status of freshwaters, including standing waters. In addition, the WFD provides an indicative list of main pollutants (Annex VIII) affecting conditions of freshwaters. Among these pollutants, materials in suspension, substances contributing to eutrophication (particularly nitrates and phosphates), and substances with an unfavourable influence in the oxygen demand are mentioned. Taking into account the information above and the purpose of

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

the deliverable (i.e. focus on a modelling framework for the supply of ES by NBS), nitrates, and phosphates are the specific pollutants considered for this ES. Hence, only their related processes and factors are taken into account.

For the regulation of nitrates uptake by plants, microbial immobilisation (microbial biological activity), denitrification, nitrification, mineralisation, volatilisation, atmospheric deposition, and erosion appear as the main processes mentioned in the literature (Lee, Mostaghimi and Wynn, 2002; Kazezyilmaz-Alhan, Medina and Richardson, 2007; Chavan and Dennett, 2008; Neitsch *et al.*, 2011; Hoang, van Griensven and Mynett, 2017; de Sosa *et al.*, 2018). Temperature, controlled by shading, is described as a main factor affecting biological activity of microorganisms, together with soil moisture before water in-flow into the waterbodies (Yevdokimov, Larionova and Blagodatskaya, 2016; de Sosa *et al.*, 2018). Both factors are also identified as key in mineralisation and nitrification processes (Chavan and Dennett, 2008). In the case of denitrification water saturation of the soil column (affecting oxic and anoxic conditions), dissolved organic carbon (complemented with particulate organic carbon), bulk density, pH, vegetation, soil depth, and temperature are identified as relevant factors (Hoang, van Griensven and Mynett, 2017; Sun *et al.*, 2017; de Sosa *et al.*, 2018). Soil erosion influences the water chemical condition due to the incorporation of sources of phosphates, nitrates and organic matter together with sediments into the system (Sosa et al 2018). As established in the universal soil loss equation (USLE) and its posterior modifications (e.g. RUSLE), the intensity of the rainfall, its erosivity, the erodibility of the soil, the slope, presence or not of soil cover and the soil management practices are the main factors affecting soil erosion processes by water (Renard *et al.*, 1991). For the case of plant uptake and deposition, factors affecting growth rate and the velocity of deposition on water surface for regulation of atmospheric chemical conditions are also relevant for this ES.

In the case of the regulation of phosphates, plant uptake, microbial immobilisation, erosion, and mineralisation soil sorption, degradation (organic matter decay), and settling are the main processes (Chavan and Dennett, 2008; Neitsch *et al.*, 2011; de Sosa *et al.*, 2018). Soil sorption is positively affected by the amount of organic matter (Hogan, Jordan and Walbridge, 2004; de Sosa *et al.*, 2018), and it is also dependent on the degradability of the pollutant, and on shifts in temperature and precipitation (de Sosa *et al.*, 2018). Several scholars indicated that settling is the most significant process when considering the long term storage of phosphates in a waterbody (Caraco, Cole and Likens, 1991; Chavan and Dennett, 2008). Plant uptake of soluble phosphorus (related to pollutant solubility) is important in the short term, although below-ground biomass storage of phosphorus could also contribute in the long-term storage (Ready *et al.*, 1999).

In both cases, in-flow (surface run-off and groundwater lateral flow) and out-flow (including infiltration, percolation) into waterbodies together with the concentration of phosphates and nutrients are also mentioned as factors to consider (Kazezyilmaz-Alhan, Medina and Richardson, 2007; Hoang, van Griensven and Mynett, 2017; Sun *et al.*, 2017). Then, surface water run-off

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

together with groundwater lateral flows, which depend on interception, infiltration (affected by evapotranspiration), and percolation, become processes affecting this ES.

4.1.5. Filtration, sequestration, storage and accumulation by plants

Similarly to the previous case, the processes and factors influencing this ES depend on the specific pollutants filtrated, sequestered, stored and accumulated. For air pollutants, the literature and models reviewed consider particulate matter ($PM_{2.5}$ and PM_{10}), sulphur dioxide (SO_2), CO, NO_2, and O_3. This list of pollutants is well-aligned with the traditional pollutants considered by the National Ambient Air Quality Standards of the Clean Air Act of United States (except for lead) and the EU Air Quality Directive 2008/50/EC (except for lead, benzene, arsenic, cadmium, nickel and polycyclic aromatic hydrocarbons).

For all these pollutants the rate of deposition is influenced by the velocity of deposition, the concentration of pollutants in the atmosphere, and the height of the boundary layer (Jim and Chen, 2008; Selmi *et al.*, 2016; Bottalico *et al.*, 2017). The former is also driven by wind velocity (mainly for $PM_{2.5}$), leaf area density, and canopy coverage. The condition of the trees (e.g. crown width, percentage of canopy missing) is also relevant since it affects the canopy coverage. In the case of SO_2, CO, NO_2, and O_3 the velocity of deposition and absorption is also controlled by aerodynamic resistance, quasi-laminar boundary layer resistance, and canopy resistance (Hirabayashi, 2013). Additionally, the canopy resistance for SO_2, NO_2, and O_3 is affected by the stomatal resistance, mesophyll resistance, cuticular resistance and soil resistance (Hirabayashi, 2013; Selmi *et al.*, 2016). Moreover, stomatal resistance is driven by the concentration of CO_2, solar irradiation, and soil humidity (Sanderson *et al.*, 2007).

For the case of herbaceous plants, the diversity of species, leaf morphology, leaf distribution, and mean height of the plant are also acknowledged factors (Weber, Kowarik and Säumel, 2014). Due to their morphological attributes, some species will be more suitable for capturing certain types of pollutants and the diversity of vegetation morphological types will ensure the removal of pollutants of different nature (Weber, Kowarik and Säumel, 2014).

4.1.6. Bio-remediation by plants

The literature usually identifies five types of bio-remediation by plants (phytoremediation): phytoextraction, phytodegradation, rhizofiltration, phytostabilisation, and phytovolatilisation (Pulford and Watson, 2003). The effectiveness of the type of phytoremediation depends on the specific plant species and pollutants. Similarly to previous ES, processes and factors are dependent on the studied pollutants. In this case, main heavy metals (Lead (Pb), Cadmium (Cd), Zinc (Zn), Nickel (Ni), Copper (Cu), Chromium (Cr(IV)), Mercurium (Hg), and Arsenic (As)) are selected due to their widespread presence in most urban brownfields, and their impact on human

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

and ecosystem health (Thornton *et al.*, 2008; Sacristan, Peñarroya and Recatala, 2015; Qian *et al.*, 2017).

Since phytovolatilisation could increase the human health risks due to air quality degradation (Limmer and Burken, 2016), it will not be considered as part of the NBS modelling, neither as a specific NBS Type 2 studied. In addition, phytodegradation only applies to organic compounds and therefore it will not be considered either as part of phytoremediation modelling.

For phytoextraction, uptake by plants, compartmentalisation in the biomass, and evapotranspiration (which affects uptake by plants) are identified as dominant processes (Pulford and Watson, 2003; Singh and Santal, 2015). Uptake by vegetation is highly dependent on the species selected, their hyperaccumulation capacity and/or high biomass, growth rate, deep root system, metal-resistance trait (Pulford and Watson, 2003). In addition, soil manipulation (mainly by soil amendments), soil aeration, presence of macronutrients, adequate soil waterholding, soil microbiological activity, and pH, are main factors affecting root uptake due to their effect on bioavailability of the heavy metals (Pulford and Watson, 2003; Gawronski, Greger and Gawronska, 2011; Singh and Santal, 2015). Pb, Cd, Zn, Ni, Cu, Hg and As bioavailability (or solubility) are increased for acidic soils (Marin, Masscheleyn and Patrick, 1993; Biester and Zimmer, 1998; Martínez and Motto, 2000; Houben, Evrard and Sonnet, 2013), while Cr(IV) bioavailability increases on basic conditions (Ertani *et al.*, 2017). Depending on the specific species and pollutants the compartmentalisation of pollutants in roots, stems, foliage or bark (for trees) can be different (Singh and Santal, 2015). In the case of phytoextraction, planting density, cropping period and the capacity of transfer pollutants to above-ground biomass are relevant since the removal of pollutants is done by harvesting the biomass (Gawronski, Greger and Gawronska, 2011; Singh and Santal, 2015).

For phytostabilisation and rizofiltration, leaching, immobilisation of contaminants by roots and soil microbiological activity are the main processes (Pulford and Watson, 2003; Ghosh and Singh, 2005; Singh and Santal, 2015). Rizofiltration is usually considered adequate for Ni, Zn, Cd, Cu, Pb, and Cr (Ghosh and Singh, 2005). Leaching is affected by plant uptake, infiltration processes and changes in the pH that increases solubility (Ghosh and Singh, 2005; Singh and Santal, 2015). Immobilisation and posterior uptake by roots is affected by roots growth rate and the exhudation of organic compounds, producing chemical reduction of metals, which in turn enhance absorption, precipitation or complexaction of metals to form insoluble compounds (Pulford and Watson, 2003; Ghosh and Singh, 2005; Singh and Santal, 2015).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

4.1.7. Characteristic of living systems enabling activities promoting health or enjoyment

In the case of this ES, relations with ecological and social processes were not found in the literature review. Additionally, regarding social and biophysical factors the current literature shows certain lack of consensus, which might be explained by context-specific social preferences, methodological variation, and a lack of detailed description of NBS characteristics (Giles-Corti *et al.*, 2005; Kaczynski, Potwarka and Saelens P, 2008; Schipperijn *et al.*, 2013).

Despite the certain lack of consensus, amount of green areas close to home, proximity, their size, presence of certain features, and adequate accessibility are usually shown relevant by different scholars by making use of social surveys, even if there is no agreement on their specific importance (Kaczynski, Potwarka and Saelens P, 2008; Kaczynski *et al.*, 2009; Schipperijn *et al.*, 2010, 2013; Lachowycz and Jones, 2011; Toftager *et al.*, 2011). With respect to specific features, Schipperijn *et al.*, (2013) found relevant the presence of walking/cycling routes, wooded areas, water features, lighting along trails, parking lots, and pleasant views (aesthetic), with a marked preference for wooded areas, water and lighting. In addition, Sikorska, Sikorski and Hopkins (2017) found that higher biodiversity adjacent to paths close to urban water features increases outdoor recreational activities, even if overall biodiversity of green spaces was not affecting recreation. For walking activities, feeling secure, lack of traffic, and availability of walking facilities increase outdoor recreation (Degenhardt *et al.*, 2011). Regarding social characteristics, age, health, and education are identified as factors influencing the use of green spaces for physical recreation, which are more used by young, healthy, and more educated people (Kaczynski *et al.*, 2009; Schipperijn *et al.*, 2013).

4.1.8. Characteristics of living systems enabling aesthetic experiences

Similarly to the previous ES, only biophysical factors and not processes were found in the literature review. This ES is highly subjective and dependent on individuals and cultures. Additionally, in urban areas there is a lack of studies on aesthetic values from an ES approach. Despite this, few common factors were identified in the literature review: diversity of landscape features (e.g. waterbodies, vegetation), amount of natural vegetation, amount of naturalised waterbodies, and shape diversity (Szücs, Anders and Bürger-Arndt, 2015; Brill, Anderson and O'Farrell, 2017; Andersson-Sköld *et al.*, 2018).

From the consulted literature, Ode, Tveit and Fry (2008) indicate that beyond cultural preferences there are certain abstract characteristics for which people have a common preference related to our common evolutionary history (Zube, 1984), which in many cases are linked to perception of good ecological status. In this regard, Ode, Tveit and Fry (2008) and Fry *et al.* (2009) developed an exhaustive literature review identifying factors affecting aesthetic preferences. This work was

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

supported by the framework of visual aesthetics developed by Tveit, Ode and Fry (2006), where several dimensions associated with visual perception were classified (i.e. imageability, stewardship, historicity, visual scale, coherence, complexity, naturalness, ephemera, and disturbance). From those, naturalness, complexity, coherence and ephemera are highly related to ecological aspects. The factors common to naturalness and complexity are related to patch and edge attributes, specifically size, shape (naturalness), density and heterogeneity (complexity). Moreover, similarly to the references from the literature review, the diversity of land covers is also identified as aesthetic factor related to complexity. In the case of ephemera dimension seasonal changes in vegetation and water features are identified as factors enhancing aesthetics.

4.1.9. Noise attenuation

The regulation of noise is driven by reflection (i.e. a change in direction of the noise waves), refraction (i.e. a change in direction accompanied by a change in speed and wavelength of the noise waves), scattering (dispersal of noise), reduction of wind speeds and absorption processes (Fang and Ling, 2003; Derkzen, van Teeffelen and Verburg, 2015). Independently of any obstacle, distance from the source, and frequency of noise are the most relevant factors influencing noise attenuation (Fang and Ling, 2003; Derkzen, van Teeffelen and Verburg, 2015). When obstacles are considered, distance also affects the effectiveness of noise attenuation, with a more adequate location of obstacles in closest distances to noise sources.

For reflection and refraction, density, height, length and width of vegetation are indicated as the dominant characteristics (Fang and Ling, 2003). Van Renterghem, Botteldooren and Verheyen, (2012) also indicate the role of stem diameters and the increased benefit of heterogeneity in these and in their location. In the adjacency of noise sources, the structure, especially spacing parallel to the axis of noise source, and foliage of vegetation are identified as dominant factors to ensure attenuation due to reflection and refraction (Fang and Ling, 2003; Van Renterghem, Botteldooren and Verheyen, 2012). Additionally, the structure orthogonal to the axis of noise source could be more relaxed without affecting significantly reflection and refraction (Van Renterghem, Botteldooren and Verheyen, 2012; Van Renterghem *et al.*, 2015). In the case of scattering, the density of the foliage and branches are the most influencing factors (Fang and Ling, 2003), and the ground roughening can also contribute to noise reduction (Van Renterghem *et al.*, 2015). However, Van Renterghem, Botteldooren and Verheyen (2012) demonstrated that canopy of trees could affect negatively noise reduction due to downward scattering. In the case of absorption, width of the vegetation, belt density, branches, height of trees, and absorptive capacity of soils (i.e. flow resistivity, porosity and structure factor) appear as highly relevant (Fang and Ling, 2003; Van Renterghem, Botteldooren and Verheyen, 2012; Derkzen, van Teeffelen and Verburg, 2015). In this sense, bare soils perform better than soils cover by grass since porosity and flow resistivity is reduced in the latter (Van Renterghem, Botteldooren and Verheyen, 2012).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Regarding specific types of vegetation, shrubs due to their dense foliage and branches are more adequate for scattering the noise, whilst tree belts for reflecting, refracting, and absorbing it (Fang and Ling, 2003). The contribution of green walls and green roofs is usually considered modest and related to absorption processes where the capacity of absorption of porous substrate (only green roofs) and the vegetation density are identified as the dominant factors (Van Renterghem *et al.*, 2015).

4.1.10. Maintaining nursery populations and habitats

The maintenance of populations and habitats depends on processes and factors in many cases species specific. However, habitat loss, physical fragmentation, and their influence on ecological connectivity are identified as common degradation processes of any type of habitats and nursery populations (Rayfield, Fortin and Fall, 2011; LaPoint *et al.*, 2015). In addition, it is difficult to relate changes on biophysical factors and processes to quantitative impacts on populations and habitats and, as a consequence, this ES.

Abundance of vegetation, its complexity (i.e. distribution and size), and compositional richness and diversity are common factors acknowledged in the literature review (Liquete *et al.*, 2016; Cabral *et al.*, 2017; Sikorska, Sikorski and Hopkins, 2017; Müller *et al.*, 2018). These factors relate to habitat enhancement or reduction of habitat loss. Regarding habitat fragmentation and connectivity, dimension of patches of habitats, their number, distances among them (their proximity and adjacency), the presence of barriers, and the suitability of the surrounding matrix for movement of species between habitats are common factors identified in urban and landscape ecology literature (Kindlmann and Burel, 2008; Gurrutxaga, Lozano and del Gabriel, 2010; Saura and Rubio, 2010).

4.1.11. Cultivated plants grown for nutrition, material, and energy purposes

These ES depend on the factors and processes explained in the section 4.1.1, since vegetation biomass is the physical output related to these ES. In some cases for cultivated plants grown for nutrition purposes, the role of pollinators is also acknowledged. In this case the abundance and distribution of pollinators is indicated by several authors as a relevant factor, which seems to be affected by the availability of forage areas, the reduction of mowing practices, and changes in land cover structure that affect availability of nesting habitats (Lowenstein, Matteson and Minor, 2015; Grafius *et al.*, 2016; Davies *et al.*, 2017). For cultivated plants grown for material purposes, depending on the specific plants the output of interest might be the stems, the roots, or the foliage, but in all the cases the factors and processes already identified become relevant. Additionally, in the case of cultivated plants for energy purposes together with the biomass, the energy yield of

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

the specific species is relevant for this ES (Ferrarini *et al.*, 2017), but this is an intrinsic factor of the biophysical structure related to the plant species selected.

4.2. Selection of ecosystem services indicators

An initial set of suitable ES indicators was selected from the list of D2.1. (Supplementary material, Table S4), based on their easiness to use, the availability of data to calculate them, and processes and factors identified in section 4.1. Those indicators were complemented with others extracted from the literature used in the previous section and the revision of MAES reports (Maes *et al.*, 2013; Maes, Zulian, *et al.*, 2016). The following sections provide a brief description of the ES indicators, summarised in Table 13, and the criteria adopted for their selection.

4.2.1. Regulation of chemical composition of atmosphere

Carbon Sequestration based on removal of CO_2 is selected as a suitable indicator from D2.1. It is split in carbon sequestration by soils and vegetation, to allow accounting for the different contribution of both types of biophysical structures. Following the assumptions of other scholars (Strohbach and Haase, 2012; Grafius *et al.*, 2016), the carbon stored in water is not budgeted. The emissions of CH_4 from waterlogged soils is acknowledged as part of soil carbon sequestration by converting CH_4 to equivalent CO_2 (1 kg CH_4 = 28 kg CO_2) based on its different global warming potential for a period of 100 years (IPCC, 2014). Continuous monitoring of CO_2 is done in urban air monitoring stations and available datasets should exist to characterise present and historic conditions. CO and O_3 are considered as part of filtration, sequestration, storage and accumulation by plants due to their relevance for air quality, what would create double counting issues if accounted also in this ES.

4.2.2. Regulation of temperature and humidity

Physiological equivalent temperature (PET) is selected due to its capacity to indicate the level of heat stress and the thermal perception of an average person among the actual thermal conditions as mentioned in D2.1. PET is measured in Celsius degrees, making it easy to understand by practitioners, is already recommended by German guidelines for urban and regional planners, and represents better future changes in thermal conditions than air temperature alone (Zölch *et al.*, 2016). Even if it requires more data (air temperature, vapour pressure, wind velocity, wind direction, mean radiant temperature) than just air temperature, it can be easily modelled since the equations are known and the data can be obtained from weather monitoring stations and solar irradiation data, supported with the use of existing tools (e.g. ENVI-met Biomet (Zölch *et al.*, 2016)) that can calculate it.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

For assessing the contribution of this ES to energy performance, energy saving in cooling or heating was identified as suitable indicator in the consulted literature (Jim, 2015; Coma *et al.*, 2017). This indicator would permit to calculate the energy saved in buildings adjacent to a NBS, based on the reduction or increase of energy necessary to guarantee the thermal comfort. To this end, data would also be necessary about internal thermal loads (depending on occupants activity and behaviour), heating, lighting, ventilation and air conditioning technologies (HVAC) of buildings surrounding NBS as well as building's construction materials, and the type of energy source used.

4.2.3. Regulation of hydrological cycle and water flow

Total run-off volume and variation of flooded area are selected as suitable indicators from D2.1. As indicated in D2.1, the former can be measured (or modelled) from the flowrate at the outlet of a considered catchment/neighbourhood, and can easily facilitate the identification of the impact pathways of an NBS in the regulation of water flow, requiring limited data. The latter is a measure of the variation in water accumulation during flooding events, which could facilitate the assessment of the impact of an NBS at neighbourhood and city levels during extreme events via the use of modelling techniques.

4.2.4. Filtration, sequestration, storage and accumulation by plants

Common air quality index (CO, SO_2, NO_2, O_3, $PM_{2.5}$, PM_{10}) is selected as a suitable indicator from D2.1 since it integrates concentration of air pollutants indicated in the EU Air Quality Directive 2008/50/EC and the revision of the US Clean Directive Act of 2003. It is also aligned with the selection of section 4.1.4. Similarly to CO_2, continuous monitoring of the other pollutants is usually done in European urban air monitoring stations, and available datasets should exist to characterise present and historic conditions.

4.2.5. Regulation of chemical conditions of freshwater by living processes

Load reduction of nitrogen and phosphorus are selected as suitable indicators, since these are adequate to measure the pollutants of interest selected in section 4.1.5. In addition, EU urban wastewater directive 91/271/EEC indicates as mandatory a maximum level of total nitrogen and total phosphorus for sewage treatment works discharging in water with eutrophication risk. In this sense, a continuous monitoring of nitrogen and phosphorus for urban wastewater should exist in EU municipalities. This data would permit to characterise current and historic conditions regarding nitrogenous and phosphorus levels, but also to understand if the impact of a specific NBS for the enhancement of water quality could be significant.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

4.2.6. Bio-remediation by plants

In the case of bio-remediation, no adequate indicator for a system dynamics modelling framework was found in the literature, since in most cases vegetation species are used as parameter proxy. The reduction in the concentration of the different heavy metals selected in section 4.1.6 were proposed as the indicators to model. The designation of a contaminated site, which is different than a potential contaminated site, in the EU is usually done after assessing its levels of pollutants. Hence, it was assumed that data on the concentration of heavy metals and characterisation of soil or waterbodies is available for these types of site, enabling to characterise existing conditions.

4.2.7. Characteristics of living systems enabling activities promoting health or enjoyment

Number of people visiting areas with NBS and the average amount of time spend on them were indicators identified during the literature review (Dennis and James, 2016; Liquete *et al.*, 2016; Lupp *et al.*, 2016; Moseley *et al.*, 2017). Moseley *et al.* (2017) also included intensity of physical activity together with the previous indicators to quantitatively assess the contribution of green spaces to promote physical exercise and as a consequence health enhancement. In addition, the factors identified in section 4.1.7 can inform about social preferences regarding outdoor activities. Since no other indicators were identified in the consulted literature that could aid to estimate this ES in a quantitative form, these were selected as the most suitable.

4.2.8. Characteristics of living systems enabling aesthetic experiences

Size, shape, and number of open land patches together with the Shannon diversity index of patch types and seasonal variation of vegetation were indicators identified during the literature review (Tveit, Ode and Fry, 2006; Ode, Tveit and Fry, 2008, 2010). These consider the main factors identified in section 4.1.8, even if they cannot provide a quantitative value of this ES. The first three indicators were defined in the European project Visulands (QLRT-2001- 01017) and have been already tested in rural areas, but could also be applicable for assessing combination of NBS Type 3 in urban and periurban areas. In addition, diversity of landscape features was identified in the consulted literature (Szücs, Anders and Bürger-Arndt, 2015; Brill, Anderson and O'Farrell, 2017; Andersson-Sköld *et al.*, 2018) and could be evaluated with Shannon diversity index, which was already selected in D2.1. Seasonal variability of vegetation (Ode, Tveit and Fry, 2008) permits to value the effect of short term changes in the aesthetic of the landscape, which could be easily measured by the amount of deciduous trees, annual herbaceous and crops present in NBS. All these indicators can be calculated making use of available landscaping documentation of NBS projects or high resolution land cover mapping of them.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

4.2.9. Noise attenuation

Night noise level and day-evening noise level are selected as suitable indicators from D2.1. Both of them are commonly used to assess noise impact in urban areas in European contexts, as mentioned in D2.1 and are already used by the European Environment Agency. As provided by D2.1 equations for calculating both indicators from measured or simulated noise, what makes them suitable to assess noise attenuation is already known, by NBS taking into account the processes and factors identified in section 4.1.9. If available data for noise does not exist, it can be modelled with land cover data and characterisation of noise within the environment using existing software such as CadnaA (http://www.datakustik.com/).

4.2.10. Maintaining nursery populations and habitats

Shannon diversity index of land covers (or patch classes) and biotope area factor, both extracted from D2.1, are selected as appropriate indicators related to habitat loss. The former is a simple index frequently used in ecology to account for diversity of land cover classes, vegetation communities or species in the NBS. The second, as indicated in D2.1, is a standard used in Berlin municipality (Germany) that considers the amount of area available for nature and vegetation with respect to the total area considered, weighting each type of land use to account for the potential of vegetation growth and nature implementation. Habitat loss indicators are complemented with two common landscape metrics to evaluate structural connectivity, mean patch size and mean patch density of natural or naturalised land covers that could inform in a semi-qualitative manner intra connectivity of NBS Type 3 or a combination of them. For all the indicators, availability of data is expected to occur since these only require detailed land cover maps or landscaping documentation of NBS projects.

4.2.11. Cultivated plants grown for nutrition, material, and energy purposes

These ES depend on the amount of biomass of cultivated plants grown for different purposes. Depending on the purpose, different parts of the biomass are relevant for this ES. In the case of nutrition, the agricultural yield allows to identify the amount of suitable biomass produced for different crops. For material manufacturing purposes, the wood or the stem (part of the above-ground biomass) is usually the product of interest. Both indicators are already used in urban pilot case studies of MAES (Maes, Zulian, *et al.*, 2016). To produce energy, not only the type of biomass itself is important, but also its calorific value and average yield per hectare which permits to estimate average energy yields, and is another indicator identified in the consulted literature (Van Meerbeek *et al.*, 2015; Ferrarini *et al.*, 2017).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 13. Set of ES indicators selected and their relation to ES (class) and USCs.

USC	ES (Class)	ES indicators	Source
Climate mitigation/ Climate adaptation	Regulation of chemical composition of atmosphere	Carbon sequestration by vegetation ([CO_2])	Modification of D 2.1
		Carbon sequestration by soil ([CO_2])	
	Regulation of temperature and humidity	Physiological equivalent temperature (PET) (°C)	Modification of D 2.1
	Regulation of hydrological cycle and water flow	Total run-off volume (mm)	D 2.1
		Variation of flooded area (ha)	D 2.1
Air Quality	Filtration, sequestration, storage, accumulation by plants	Removal of pollutants of common air quality index ([CO], [SO_2], [NO_2], [O_3], [$PM_{2.5}$], [PM_{10}])	D 2.1
Water Quality	Regulation of the chemical condition of freshwaters by living processes	Load reduction of nitrogen (t/ha year)	(Liquete *et al.*, 2016)
		Load reduction of phosphorus (t/ha year)	(Cabral *et al.*, 2016)
Soil Quality	Bio-remediation by plants	Removal of heavy metals ([Pb],[Cu],[Ni], [As], [Hg], [Cd], [Cr])	This report
Enhanced opportunities for outdoor activities	Characteristic of living systems enabling activities promoting health or enjoyment	Number of visitors	(Liquete *et al.*, 2016; Lupp *et al.*, 2016)
		Average amount of hours spent per visitor	(Dennis and James, 2017; Moseley *et al.*, 2017)
Psychological relaxation	Characteristic of living systems enabling aesthetic experiences	Ecological Habitat diversity (Shannon diversity index of patch types)	Modification of D 2.1
		Size of open land patches	Visulands Framework QLRT-2001-01017 (Ode, Tveit and Fry, 2010)
		Shape of open land patches	
		Number of patches of open land	
		Seasonal variability of vegetation (% of deciduous trees, annual herbaceous, and crops)	(Ode, Tveit and Fry, 2008; Fry *et al.*, 2009)
Stress relief	Noise attenuation	Reduction of Night noise level (Lnight) (DbA/m^2)	Modification of D 2.1
		Reduction of Day-evening-night noise level (Lden) ((DbA/m^2)	Modification of D 2.1
Loss of Habitat	Maintaining nursery populations and habitats	Ecological Habitat diversity (Shannon diversity index of patch classes)	Modification of D 2.1
		Biotope Area Factor	D 2.1
Loss of Ecological Connectivity		Mean patch size	(Tian *et al.*, 2011; Li, Chen and He, 2015)
		Mean Patch density	
Energy Performance	Regulation of temperature and humidity	Reduction in energy consumption for cooling and/or heating (kWh/ m^2year)	Modification of (Li, Chen and He, 2015; Coma *et al.*, 2017)
Energy Production	Cultivated plants grown as source of energy	Average energy yield (GJ/ha)	(Van Meerbeek *et al.*, 2015; Ferrarini *et al.*, 2017)
Material Security	Materials from cultivated plants for direct use or processing	Average aboveground biomass growth (ton/ha yr)	(Maes, Zulian, *et al.*, 2016)
Food Security	Cultivated plants grown for nutritional purposes	Average agricultural yield (kg/ha yr)	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

5. Establishment of the pillars for the modelling and characterization of urban systems for NBS assessment

The following sections of this chapter describe: (i) the approach for assessing urban NBS as part of urban systems (ii) the representation of urban systems, their sub-systems and main flows; (iii) spatial levels for assessing NBS as part of urban systems; (iv) definition of urban system boundaries, urban typologies and their indicators.

5.1. Urban NBS and urban systems under a combined approach

As introduced in Chapter 3, urban NBS have the potential to address societal challenges in an effective and adaptive form providing economic, social, and environmental benefits (IUCN 2016; EC 2015), which could remediate part of the negative impacts of urban systems, increasing their adaptive capacity (resilience), reducing their dependency on external sources, and better distributing them to different stakeholders. This statement is aligned with the vision of several scholars, who consider that urban areas should: first, enhance their ES supply (Pataki *et al.*, 2011; Pincetl, 2012; Elmqvist *et al.*, 2015); second, make a better use of their own and external resources, optimising the urban metabolism (Kennedy, Pincetl and Bunje, 2011; Pincetl, 2012); third, and understand how the network of socio-political structures (urban political ecology) influence the use of nature and distribution of flows (Coelho and Ruth, 2006; Pincetl, 2012).

For the enhancement of urban ES supply, an urban ecology (UE) approach could provide a better understanding of the urban ecosystems (biophysical structures), their distribution, diversity, and changes (Wu, 2014; McPhearson *et al.*, 2016; Zhou, Wang and Cadenasso, 2017) and how socio-economic and environmental components affect each other (Coelho and Ruth, 2006; Pickett *et al.*, 2008), helping to identify providing, benefiting and connecting areas of ES (as defined by Syrbe and Walz, 2012). Understanding where different urban ES are demanded, supplied, and how eventually conveyed could help to optimise the urban metabolism (UM), the quantitative flows of materials, water, nutrients, waste, and energy that occur in urban areas (Kennedy, 2012). For example, this could be done by identifying hotspots where NBS are required or by planning the land uses demanding ES together with the networks of NBS. In addition, the use of an urban political ecology (UPE) perspective can help to show how interacting economic and socio-political processes and structures influencing UM affect the access to resources and services or could make it uneven (Heynen, Kaika and Swyngedouw, 2006; Cornea, Véron and Zimmer, 2017; Pincetl and Newell, 2017). This knowledge about socio-political structures and processes would be valuable to inform the implementation of urban NBS, ensuring better distribution of their benefits.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

UE, UM, and UPE approaches use a systems perspective and usually are supported by system dynamics tools (Lifset and Graedel, 2002; Pincetl, 2012; Alberti, 2016). Their combination could provide a more holistic assessment of urban systems (Coelho and Ruth, 2006; Kennedy, Pincetl and Bunje, 2011; Pincetl, 2012; Pincetl, Bunje and Holmes, 2012; Newell and Cousins, 2014; Pincetl and Newell, 2017), better considering ecological, economic and social aspects. To assess the potential of NBS to address UCs, the system dynamics modelling framework developed in the Task 4.1 builds on these combined approaches, stressing on the potential of adopting a combined UE and UM thinking perspective, and further considering UPE during the assessment of NBS implementation models in the Task 5.4.

For the development of the framework, an explicit formulation of urban system boundaries is necessary as well as an adequate representation of urban systems, their ES flows of demand and supply. This implies the implementation of data of increased granularity, the use of sociodemographic (and environmental) variables when characterising urban structure patterns, and the connection of spatial data analysis to the governance of urban areas, as anticipated by Pincetl and Newell (2017).

5.2. Representation of urban systems

An adequate representation of urban systems should consider that urban areas are systems under continuous evolution with dynamics defined, firstly, by multi-scalar, non-linear, heterogeneous interactions; secondly, by emergent properties result of human, natural and technological patterns, processes and feedbacks; thirdly, by capacity of innovation; and, finally, by multiple equilibria or regime shift (Wu, 2014; Alberti, 2016). As a consequence of urban multi-scalar interactions, contextual (adjacent or not) socio-economic and ecological factors influence changes in the urban structure, which later re-affect contextual processes in a feedback loop due to pattern-process co-dependency (Wu, 2013, 2014). In this sense, the urban structure and their changes are usually considered key to understand how an urban system relates to its surrounding rural area (Grimm *et al.*, 2008; Schwarz, 2010b), but also how changes in their own dynamics impact the urban and surrounding rural environment (Alberti, 2005; Schwarz, 2010b). In addition, not only the urban structure is relevant, but also its built infrastructure and distribution as well as the consumption preferences of inhabitants, a result of their behaviour (Liu *et al.*, 2017). As a consequence, not only the structure shall be necessarily represented in the modelling framework but also the processes of urban systems and their sub-systems, in order to understand their spatio-temporal interactions and the opportunity to assess the impact of urban NBS in the UM.

Regarding urban subsystems representation, Pickett, Cadenasso and Grove (2005) identify three interrelated urban sub-systems: social (from individuals to entire societies and their governance structures), ecological (from patches to landscape level), and hydrological (from single

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

waterbodies to entire catchments). City Protocol (2015) also defines three interrelated sub-systems, divided in interconnected components: structure (environment, infrastructure, and built domain), interactions (functions, economy, culture, and information), and society (person, family, organisation, business, and governments). In addition, this protocol further divides the infrastructure sub-system in: communication, water, energy, matter, mobility, and urban nature. Similarly, Meerow, Newell and Stults (2016) propose four interrelated sub-systems with linked inner components: governance networks (states, labour, industry, consumers and Non-Governmental Organisations), networked material and energy flows (waste, energy, material, food, water, and consumer goods), urban infrastructure and form (buildings, utilities, ecological greenspace, and transportation), and socio-economic dynamics (demographics, mobility, equity and justice, public health, capital, and education).

Building on the above three guideline schemes, five main interconnected and overlapping urban sub-systems relevant for the modelling framework were identified (Figure 8): social, buildings, infrastructure, urban nature, and governance. The social sub-system incorporates the inhabitants, private organisations, and labour or business (e.g. industries, commerce). The built domain sub-system integrates the static human artefacts built by people, represented as static artificial land use types (e.g. housing, health care facilities, offices), where modules corresponding to some NBS Type -1 are accommodated. The infrastructure sub-system includes dynamic artificial land use types represented by transport and utilities responsible for supporting the movement of people and part of the resources (water, energy, matter) inside the built domain, and urban nature sub-systems (where modules corresponding to the rest of the NBS Type -1 are accommodated).

More specifically, modules for air, land, water, and green built structures are integrated in the urban nature sub-systems with the aim to host NBS Type 3 and Type 0, where the ES are produced and part of the resources generated/transformed/consumed. While the governance sub-system includes the public and private institutions defining norms and rules affecting the function and organisation of the other sub-systems. The internal spatial composition and configuration of these sub-systems as well as their internal components affect the spatio-temporal interactions and therefore the flows of information, water, energy, matter (materials, food, and waste), and people in the urban system.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

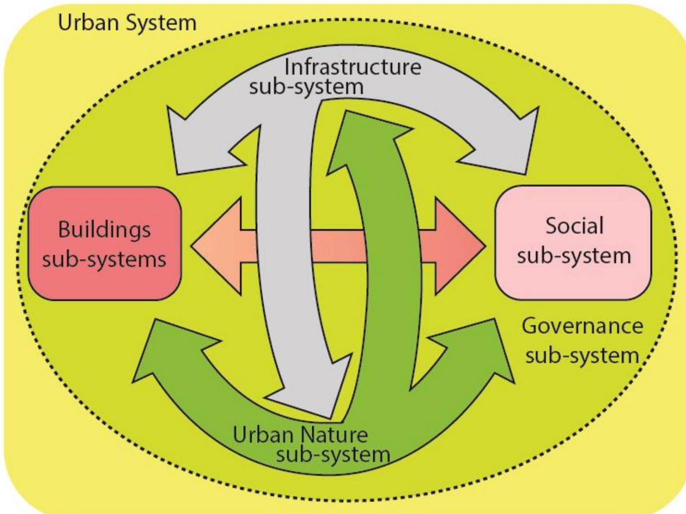


Figure 8. Scheme of urban sub-systems

5.3. Spatial and temporal levels

The spatial levels for assessing NBS as part of urban systems correspond to the ones of the third hierarchy of the NBS typology (object, neighbourhood/district, city/metropolitan, and urban region). As indicated in D2.1, the spatial extension of the three first levels can be defined as follows (Barbano et al. 2015):

- Object level: from few meters to several hundred meters.
- Neighbourhood/District level: from few hundred meters to few kilometers.
- City/metropolitan level: from few kilometers to several kilometers.

An *urban region* corresponds to the area of active human and ecological interactions between a city or metropolis and its surroundings (Forman, 2014). In other words, it is the area socially, environmentally, and economically influenced by the urban core and its growth (Hoffmann *et al.*, 2017). In this sense, its spatial extent could go from several kilometres to more than one hundred kilometres (Figure 9).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

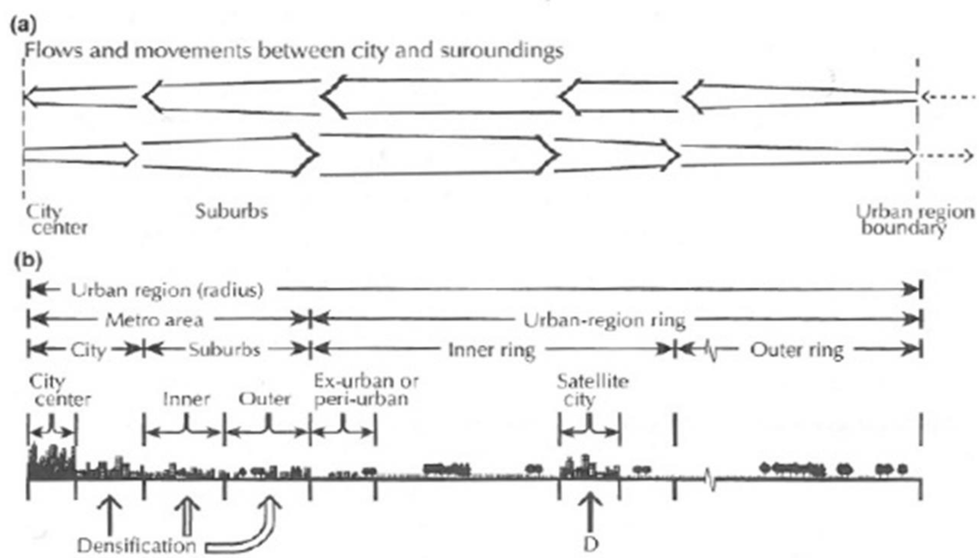


Figure 9. Scheme of an urban region and its main components (Forman, 2014).

The identification of temporal levels should instead consider the time frames of different socio-ecological processes and the demand and supply of ES, but also the time-frames of urban management and planning that should be informed by the NBS assessment. This could permit avoiding temporal mismatches between the environmental issues and their related decision making processes (Bai *et al.*, 2010; Ernstson, Barthel and Andersson, 2010). For example, decision making for hydrological cycle and water flow regulation has usually a time frame of 5 years (e.g. EU river basin management plans), whilst some of the events for which this ES is more demanded (e.g. flooding events) might occur in much shorter timespans (hours or days). In addition, considering more than one time frame could aid taking into account the complexity of temporal interactions (direct/indirect, the influence of legacy or past dynamics, and time lagged interactions) in socio-ecological systems like urban areas (Pickett, Cadenasso and Grove, 2005). As a result, the following temporal levels should be considered:

- Short-time frames: from day to few weeks.
- Medium-time frames: from few weeks to several months.
- Long-time frames: from one to several years.

Additionally, a maximum temporal horizon should be defined for the long-time frame. This horizon should be aligned with the temporal scope of the decision making informed by the NBS assessment. Moreover, the definition of the maximum time frame should take into account the level of reliability required for the NBS assessment based on the needs of the decision making process.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

5.4. Definition of urban system boundaries, urban types, and initial selection of indicators

5.4.1. Urban system boundaries

In many cases urban systems expand beyond the administrative limits of individual municipalities (Dijlkstra and Poelman, 2012). These could be imaginary boundaries that do not represent the real extension of urban areas and which could lead to mistakes when quantifying their components. As an example, (Angel *et al.*, 2011) identified an underestimation for the population of the urbanised area of Castellon de la Plana (Spain). There the urban system overcomes the limits of the municipality without being supported by any official definition of a metropolitan level or urban agglomeration. This simply suggests that municipal limits are inadequate for the definition of spatial system boundaries or spatial scope of urban studies. However, at the same time local statistics on social, economic variables, and in some cases environmental ones, are recorded based on administrative limits (Kennedy *et al.*, 2014), what could make difficult an adequate integration of them in urban assessments when municipal limits are not considered as system boundaries. In addition, urban systems are also composed by urban nature sub-systems, for which the scale of their ecological patterns and processes influencing ES might goes beyond the scales of their management (Borgström *et al.*, 2006; Cumming, Cumming and Redman, 2006), which usually match administrative limits. In turn, this could lead to inadequate delimitation of urban nature sub-systems that might neglect certain spatio-temporal interactions relevant for ES supply, especially in transitional rural-urban areas. Moreover, as stated in the previous section urban systems evolve along the time, increasing (or reducing) their population and size. Hence, considering fixed system boundaries may also result in a limitation when developing medium or long-term assessments.

In order to inform the urban system boundaries for the modelling framework in Task 4.1, the previous arguments needed to be balanced with the easiness of replicability and to rely on existing available data. As a solution for the SDM, two system boundaries were proposed related to the spatial levels defined above:

1) a principal system boundary (city/metropolitan level), focused on the urbanised areas;
2) an (optional) secondary system boundary (urban region level), ensuring a coherent delimitation of transitional natural areas sharing strong spatio-temporal interactions with the urbanised areas.

For both system boundaries, potential spatial indicators were selected that could represent adequately the built domain (urbanised area) and urban nature, and that the values of which could be easily updated in a long-time frame (e.g. annually). For this selection, key literature (Bengs

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

and Schmidt-Thomé, 2005; Dijlkstra and Poelman, 2012; Hoffmann *et al.*, 2017) was complemented with a systematic literature review (Supplementary Material, Table S5a-c) as indicated in Chapter 1.

Despite the fact that the period considered for the literature review was 20 years, half of the papers were published in the last 5 years and almost all in the last 10 years, indicating how recently this issue was considered in the literature. The selected potential indicators (Table 14) were related to the variables population, commuting population, artificial or impervious land cover, natural land covers, and distances to urbanised land. In most of the papers selected, the indicators were related to spatial/landscape metrics (e.g. Benza et al 2016; Gonçalves et al 2017). Several of the indicators related to complexity and heterogeneity of the land cover (Benza et al 2016; Salvati et al 2016; Gonçalves et al 2017). This type of indicators permits differentiation of periurban areas where there are higher values of fragmentation and diversity of land cover (Weng 2007) from rural ones, which is composed of less heterogeneous patterns. On top of this collection, the municipal administrative limit was further added as an indicator to keep the coherence with the areas for which statistical data is usually collected.

Table 14. Potential system boundary indicators.

System boundaries	Indicators/Index	Original Description & Thresholds	References
Principal urban system boundary	Population density	Amount of population per 1 km^2 (>1500 inhabitants/km^2 (1))	(1) Dijkstra and Poelman 2012; Bengs & Schmidt-Thomé 2005; Salvati et al 2015
	Population	Clustered cells of 1km^2 (>1500 inhabitants) with more than 50.000 inhabitants	Dijkstra and Poelman 2012; Qureshi et al 2014; Kennedy et al 2014
	Housing/building density	Density of built footprint(m^2/m^2) per area	Gonçalves et al 2017; Voulgaris et al 2017
	Percentage of imperviousness	Amount of sealed area	Benza et al 2016; Qureshi et al 2014 ;
	Patch density of impervious or urban land	Density of patches of sealed area in the context of study	Benza et al 2016; Gonçalves et al 2017
	Area weighted mean Fractal dimension (impervious patches)	Defines the shape complexity of the area focusing on impervious surfaces	Benza et al 2016
	Standard deviation of the urban patch size	How much the sizes of the urban land cover patches differ from the average size	Gonçalves et al 2017
	Municipal administrative limits	Municipal boundaries including the clustered cells of population	Dijkstra and Poelman 2012

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

System boundaries	Indicators/Index	Original Description & Thresholds	References
Secondary urban system boundary	Percentage of people commuting from surrounding municipalities	Amount of residents of a surrounding municipality working in the principal urban system boundary (>15%)	Dijkstra and Poelman 2012
	Density of road and rail network	Amount of roads and railways	Qureshi et al 2014; Bengs & Schmidt-Thomé 2005
	Survey Stratification Index	The geometric mean of the normalised values of distance to main built area and percentage of non-built up area	Hoffmann et al 2017
	Largest patch index of natural land cover	Largest patch classified as natural land cover with respect to the total area	Gonçalves et al 2017
	Land Use Information Entropy Model (index)	Based of Shannon entropy informs about the heterogeneity of the land covers (impervious, water, vegetation, others) for a specific grid of pixels to identify periurban areas (highest entropy)	Hu et al 2015
	Municipal administrative limits	Municipal boundaries including the clustered cells of population	Dijkstra and Poelman 2012

The indicators of Table 14 intend to inform about the current state of the art in the definition of urban system boundaries at an early stage of development of the modelling framework. However, a revision of system boundaries is also considered through consultation with external advisors (see section 7.2 for further details). In future stages of Nature4Cities, further revisions might be carried out through a comparison with the indicators of Task 3.1 and an additional assessment of available data.

5.4.2. Urban Types

The definition of urban types, similarly to landscape character types (e.g. Brunet-Vinck, 2004; Sala, 2009; Tudor, 2014), can be described as a characterisation of urban contexts by a distinct and consistent combination of natural and anthropic patterns able to differentiate types of urban areas and their subset in a spatially explicit manner. In this sense, natural and anthropic spatial variables representative of the patterns of interest should be selected in order to define and delimitate urban types. For the purpose of the NBS modelling framework, the urban types should be based on a characterisation of urban resource consumption types (related to the demand of ES in the context of UM) and ecological functioning types (related to UE). This can facilitate a better comprehension of urban systems or their subsets by optimising the initial selection of NBS, by providing an initial understanding of the current status of ES provision and demand and the potential for enhancement and, finally, by informing if the relevance of variables (e.g. temperature, humidity) driving the ecological process of NBS or UM flows is different depending on specific urban types.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Urban types were defined at three out of four different spatial levels of study (urban region, city/metropolis, and neighbourhood/district), for which indicators representative of each of the urban sub-systems were selected (Table 15, 16 and 17). Similarly to the case of urban system boundaries, the selection was done making use of key literature (Bengs and Schmidt-Thomé, 2005; Alberti, 2008; Schwarz, 2010b; Dijlkstra and Poelman, 2012; Stewart and Oke, 2012; Ferrão and Fernández, 2013; Larondelle *et al.*, 2014; Qureshi, Haase and Coles, 2014; Zhou *et al.*, 2014; Zhou, Pickett and Cadenasso, 2016) complemented with a systematic literature review, and indicators from the Geocluster4NBS tool (supplementary material, Table S6). A narrowed set of indicators was then obtained with items defined based on easiness of calculation and data availability.

In the literature review, the typologies were either made explicit (e.g. Benza et al., 2016; Dumas et al., 2008; Herold et al., 2005, 2003, 2002; Lowry and Lowry, 2014; Van de Voorde et al., 2011; Vanderhaegen and Canters, 2017) or clusters were identified (e.g. Huang et al., 2007; Salvati et al., 2016; Schwarz, 2010) based on the indicators selected. For most papers, as occurred with urban system boundaries, the indicators relied on spatial/landscape metrics which can be easily obtained based on land cover maps and GIS processing, particularly using the *FRAGSTATS* software (McGarigal and Marks, 1994). Those metrics are then combined with other indicators such as socio-economic, built environment or mobility indicators to define urban typologies (e.g. Gil, 2016; Lowry & Lowry, 2014; Song et al., 2013; Schwarz, 2010), being the socio-economic indicators the most common ones. In some cases, the papers aimed to evaluate how urban forms (usually defined making use of spatial metrics) influence environmental factors, e.g. biodiversity aspects (e.g. species richness (Sandström, Angelstam and Mikusiński, 2006; Godefroid and Koedam, 2007), air quality variables (Cárdenas Rodríguez, Dupont-Courtade and Oueslati, 2016; She *et al.*, 2017) or surface temperature (Tratalos *et al.*, 2007; Larondelle *et al.*, 2014a; Hamstead *et al.*, 2016).

In this sense, spatial metrics that demonstrated a correlation with environmental factors could be valuable indicators to define urban typologies that inform about environmental conditions affecting ecological functions or the resource consumption. Additionally, few articles characterised city/metropolitan levels based on material flows/storage indicators, which could be useful from an UM perspective (Kennedy et al 2014; Rosado et al 2017). However, these indicators are not easily available for initial characterisation of urban typologies before an UM assessment is developed. Also, none of the papers explored the link between UM flows and urban typologies at neighbourhood/district level. In addition, only a few papers characterised urban typologies taking into account infrastructure (Gonçalves et al 2017; Solecki et al., 2015; Zeng et al., 2014; da Costa et al.,2013; Manaugh et al 2010; del Valle et al 2009), energy (Solecki et al., 2015; Huang et al., 2001) and governance aspects (Solecki et al., 2015; da Costa et al.,2013).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Similarly to the case of system boundaries, the indicators of the urban typology are informative for the SDM framework. A possible revision could be done in future stages of the project once the framework is applied, thus to integrate the contributions from other tasks (e.g. Task 2.2).

Table 15. Potential system boundary indicators.

Indicators/Index	Original Description	UC	References
Average Heating Seasonal External Air Temperature	Air floating average temperature of the last 15 days under 19°C).	Climate issues and Resource efficiency	Geocluster4NBS (Eurostat NUTS 3)
Average Cooling Seasonal External Air temperature	Air floating average temperature of the last 15 days above 26°C).		Geocluster4NBS (Eurostat NUTS 3)
Maximum Air temperature	Maximum annual external temperature		Geocluster4NBS (Eurostat NUTS 3)
Average ambient wet bulb temperature over cooling season	Average ambient wet bulb temperature over cooling season.		Geocluster4NBS (Eurostat NUTS 3)
Housing density	Amount of houses per area (According to (2) related with temperature)	Resource efficiency	Lowry and Lowry 2014; Tratalos et al 2007 (2)
Age of Construction	Number of buildings constructed during the reference period.		Geocluster4NBS (Eurostat NUTS 3)
Use Residential – Proportion of single house vs apartment flats	Use – Percentage or residential singles houses		Modification of Geocluster4NBS (Eurostat NUTS 3)
Electricity consumption of households	Quantity of electricity consumed by households for all use of electricity		Geocluster4NBS (Eurostat NUTS 3)
Disposable income of households	Disposable income of households		Geocluster4NBS (Eurostat NUTS 3)
Share of industry	Percentage of industrial land cover (related to PM10)	Resource efficiency, Public health	Cardenas et al 2016
Total urban area (CA)	Amount of urban land cover types (related to PM2.5, PM 10 and CO)	Resource efficiency, Public health, Stormwater management	She et al 2017
Number of urban patches (NP)	Density of urban land cover types ((1) related to PM2.5, PM 10, SO2, and CO) ((2) Related to NO2)		She et al 2017 (1); Cardenas et al 2016 (2)
Share of forest area	Percentage of forest land cover	Biodiversity	Bengs & Schmidt-Thomé 2005
Share of agriculture	Percentage of agricultural land cover (related to NO2, SO2, PM10)		Cardenas et al 2016
Mesh effective size	Amount of natural area than an organism is connected to in a landscape starting from a randomly chosen point		Deslauriers et al 2017

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 16. Potential indicators for the city/metropolitan level.

Indicators/Index	Original Description		References
Population	Number of population in the urban area	Resource efficiency	Schwarz 2011
Housing density	Amount of houses per area ((2) related with temperature)		Lowry and Lowry 2014; Tratalos et al 2007 (2)
Period of construction of the building	Permits characterisation of the type of building based on its year of construction		Wu et al 2017; Geocluster4NBS; Manaugh et al 2010
Electricity consumption	Quantity of electricity consumed by households for all use of electricity		Huang et al 2001; Geocluster4NBS
Average (or median) income per household	Average income of population in the area		Réquia Junior et al 2015 ; Manaugh et al 2010
Mean distance to public transport stop	Average distance of urban type cells to a public transport stop		Lowry and Lowry 2014
Mean distance to public parks	Average distance of urban type cells to green spaces	Resource efficiency, Public Health	Lowry and Lowry 2014
Percentage of imperviousness	Amount of sealed area in the context of study (related to NO2, PM10)	Resource efficiency, Public Health, Biodiversity, Stormwater management	Benza et al 2016; Qureshi et al 2014 ; Cardenas et al 2016
Number of patches of sealed urban area	Measures compactness of the urban form		Schwarz 2011
Share of industry	Amount of industrial land cover (related to PM10)	Resource efficiency, Public Health	Cardenas et al 2016
Edge density	Accounts for the length of the edge relative to the total area	Biodiversity and Energy	Schwarz 2011
Compactness index of the largest patch	Measures compactness of the largest patch in the city		Schwarz 2011
Share of agriculture	Amount of agricultural land cover (related to NO2, SO2, PM10)	Biodiversity	Cardenas et al 2016
Share of forest area	Percentage of forest land cover		Bengs & Schmidt-Thomé 2005
Mesh effective size	Amount of natural area than an organism is connected to in a landscape starting from a randomly chosen point		Deslauriers et al 2017

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 17. Potential indicators for the neighborhood/district level.

Indicators/Index	Original Description		References
Age structure	Percent of population per range of ages	Resource efficiency, Public Health	Solecki et al 2015
Level of education	Percent of population by level of education		Adaptation of Manaugh et al 2010; del Valle et al 2009
Population density	Amount of population per area	Resource efficiency (Energy)	Wu et al 2017; Budiyantini and Pratiwi 2016 ; Solecki et al 2015
Housing density	Amount of houses per area ((2) related with temperature)		Lowry and Lowry 2014; Tratalos et al 2007 (2), Voulgaris et al 2017
Average household size	The floor dimension of the residential buildings		Manaugh et al 2010
Period of construction of the building	Permits characterisation of the type of building based on its year of construction		Wu et al 2017; Geocluster4NBS; Manaugh et al 2010
Electricity consumption	quantity of electricity consumed by households for all use of electricity		Huang et al 2001; Geocluster4NBS
Average (or median) income per household	Average income of population in the area		Réquia Junior et al 2015 ; Manaugh et al 2010
Mean distance to public parks	Average distance of urban type cells to green spaces	Publich Health, Resource effciency	Lowry and Lowry 2014
Mean distance to public transport stop	Average distance of urban type cells to a public transport stop	Resource efficiency (Energy)	Lowry and Lowry 2014; Voulgaris et al 2017
Percentage of imperviousness	The amount of impervious surfaces in the study area (related to temperature; (2) explains 54% of land surface temperature at Beijing (China))	Resource efficiency, Public Health, Biodiversity, Stormwater management	Bechtel et al 2015; Benza et al 2016; Qureshi et al 2014 ; Chen et al 2014 (2)
Number of patches of sealed urban area	Measures compactness of the urban form		Schwarz 2011
Structure of Urban Landscape	Combination of land cover (tree canopy, grass/shrub, bare soil, water, paved, low rise building, mid-rise building, high rise building) per cell informs about temperature	Resource efficiency, Biodiversity	Hamstead et al 2016; Larondelle et al 2014
Mesh effective size	Amount of natural area than an organism is connected to in a landscape starting from a randomly chosen point	Biodiversity	Deslauriers et al 2017

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

6. Representation of NBS and urban systems in the system dynamics modelling framework of WP4

The following sections of this chapter describe: (i) the adaptation of MIMES to the study or urban systems and NBS; (ii) the representation of NBS and urban systems in the modelling framework, the main compartments and processes; (iii) the strategy for integrating the modelling framework in the Nature4Cities platform.

6.1. Introduction to system dynamics models, MIMES and its adaptation to the study of urban systems

Quantitative models can be grouped in two macro-categories: deterministic and stochastic models. The former produces a specific outcome for a specific set of parameters and initial conditions, while the latter includes uncertainty associated with the simulation (Basso, Cammarano and Carfagna, 2013). In addition, models can represent systems in an equilibrium state (steady-state) or take into account spatio-temporal variations, and therefore dynamic conditions. Dynamic models are particularly suitable for modelling socio-ecological systems in continuous evolution, as urban systems, where it is important to understand and circumscribe the complexity of social, economic, cultural and environmental factors (e.g. Chen *et al.*, 2014; Liu *et al.*, 2014; Feng and Burian, 2016; Omer and Kaplan, 2017).

Among dynamic models, system dynamics models (SDMs) are becoming more and more popular to model ecological systems and to inform decision support systems (Aguirre-Gutierrez *et al.*, 2017; Du *et al.*, 2018). In recent years, SDMs have been used to represent the supply of specific ES by NBS, such as bioremediation by plants (Ouyang *et al.*, 2007; Mohammed and Babatunde, 2017), carbon sequestration by green walls (Marchi *et al.*, 2015) and carbon sequestration by woodland plantations (Jerez, Quevedo and Moret, 2015). While these models provided a clear representation of the relevant ecological systems, they have not been able to capture the socio-economic impacts, which are important components of urban systems.

In response to these needs, the Multiscale Integrated Model of Ecosystem Services (MIMES) framework (Figure 10) has been developed in recent years to assess ES provision taking into account the biophysical and socio-economic dynamics at different spatial scales (e.g. Boumans *et al.*, 2014, 2015). MIMES models are also based on a system dynamics rationale and are designed to simulate over time and space the interactions between human and ecological systems. In this regard, MIMES is one of the most effective examples of integrated modelling framework generated to reduce the variability and increase the comparability between different management/land-use options (Turner et al 2016). The rationale of MIMES is that any system, human or ecological, holds

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

certain capitals and is (multi-)functional. Four types of capital are typically distinguished in MIMES: natural, built, human and social. Through their multi-functionality, systems interact using some capitals to produce other capitals, and this interaction induces exchanges of resources, wastes, goods and services among systems and over time and space. In the 'system dynamics' language, such a perspective is typically what it is meant through stocks & flows modelling. For instance, a forest has a growing function (i.e. photosynthesis made by trees) that uses CO_2 as "atmospheric resource's capital" to increase its own "biomass capital" and releases O_2 stocked in the "atmosphere's capital". Carbon and oxygen are thus exchanged between the atmosphere and the biosphere. Similarly, a region may have an industrial production function that consumes natural resources (e.g. timber from a "forest's capital") to produce goods (own "capital") and emits wastes and pollutants (increasing the "natural systems pollution's capital"). Carbon is thus exchanged between the biosphere and the anthroposphere in this case.

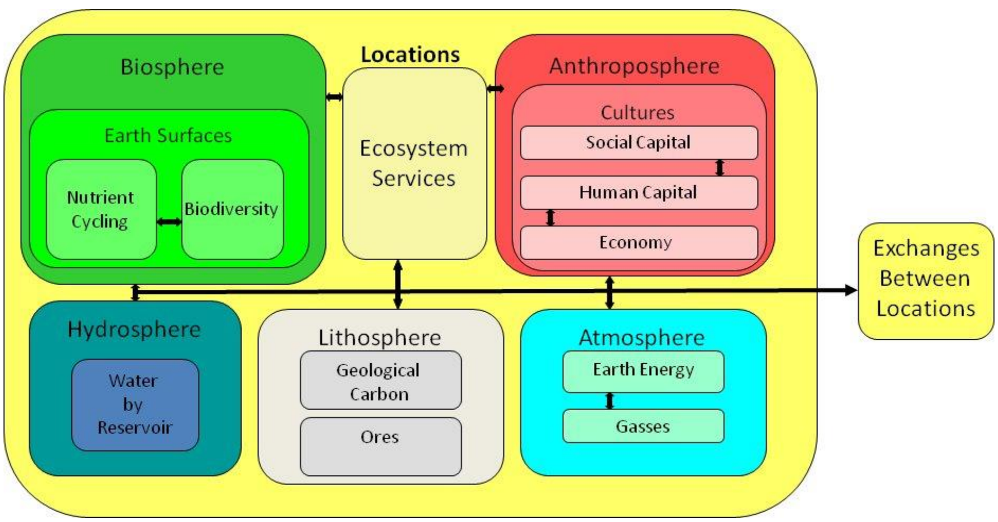


Figure 10. MIMES framework (Boumans et al 2015).

By modelling the processes that rule these interactions, and the feedbacks and synergies among them, MIMES allows to track the ES flowing from the ecosphere to the society and test the impact of different development scenarios on their values, thus highlighting potential trade-offs that might arise from different management strategies. These features make MIMES a very powerful tool for assessing the impact of NBS on ES within urban systems. However, the modelling of these processes is a complex task since much is unknown about most of ecosystem functions at the basis of ecosystem services' supply and maintenance.

To palliate this lack of knowledge, MIMES relies on a deductive modelling approach. Accordingly, processes are formulated a priori, as functions of diverse parameters. Some of these parameters are well-known (i.e. data is available), while others are not, although the *a priori* description of the processes assumes that they exist and are meaningful. Therefore, the MIMES framework relies on

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

a calibration phase to retrieve values for unknown parameters (according to a “business as usual” scenario). This calibration phase will be based on the data collection and literature review done in the different tasks of WP4, which started in Task 4.1 (see Chapter 3, 4 and 7) and will continue in Task 4.2 and Task 4.4. It is then worth remarking that the structure of the model (concepts and equations a priori formulated) must be consistently validated, showing its effectiveness in reproducing past behaviours of the system.

MIMES modules are implemented in SIMILE (www.simulistics com), which is a proprietary software built on visual declarative modelling to combine system dynamics, differential equations and disaggregated modelling approaches. Flexible to use, Simile allows transcribing, coupling and running different existing models under a unique dynamic spatially-explicit and time-dependent frame.

Overall, the MIMES conceptual framework, via SIMILE, is a very flexible platform to model the complex interaction between NBS, urban systems and the provision of ES. More specifically, the modelling framework suggested in WP4 is composed of two types of MIMES based modules which are connected to each other: the urban system module and the NBS module.

6.2. Representation of NBS in the modelling framework

The NBS module adapts MIMES defining four main compartments: NBS, anthroposphere, atmosphere, ES, and implementation compartment. Each compartment comprises several submodels and its spatial scope is limited to the neighbourhood level (Figure 11). In the remaining part of this section, compartments are described in details. Please refer to Table 12 in Section 4.1 for more information on the submodels used in each compartment.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

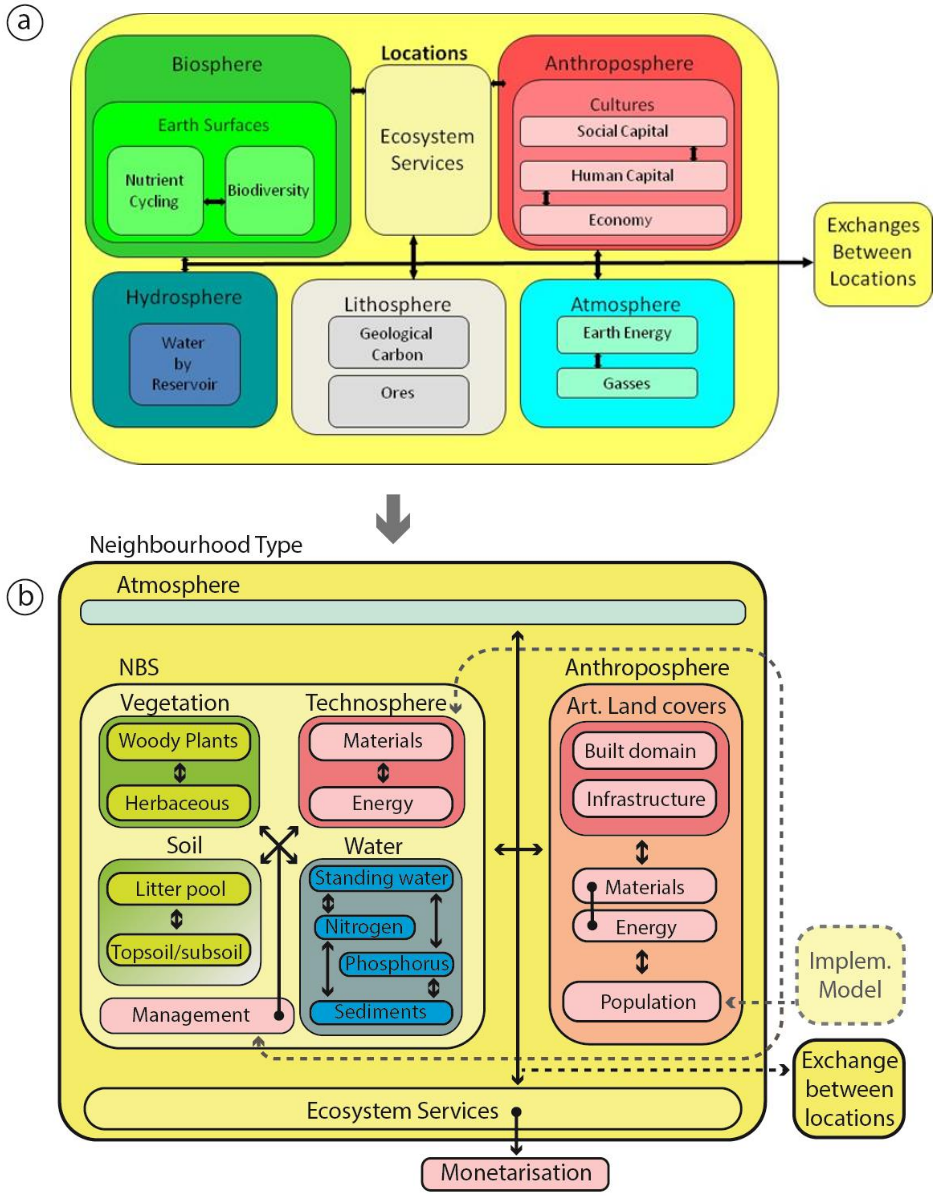


Figure 11. Adaptation of the (a) MIMES framework to represent a generic (b) NBS module, composed by four main compartments: NBS, anthroposphere, atmosphere, ES, and implementation compartment.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

6.2.1. NBS compartment

The NBS compartment of the NBS module (Figure 12) is composed by five subcompartments: vegetation, soil, water, technosphere, and management, which represent the potential main structures that could be present in the selected NBS Type 3. The submodels of each subcompartment are linked between them and with the ones of other compartments, since many processes depend on several submodels and outputs in one submodel are inputs in others. For example, as stated in Chapter 4, the amount of water run-off depends on several processes (i.e. interception, evapotranspiration, infiltration, and percolation) related to factors of vegetation and soil.

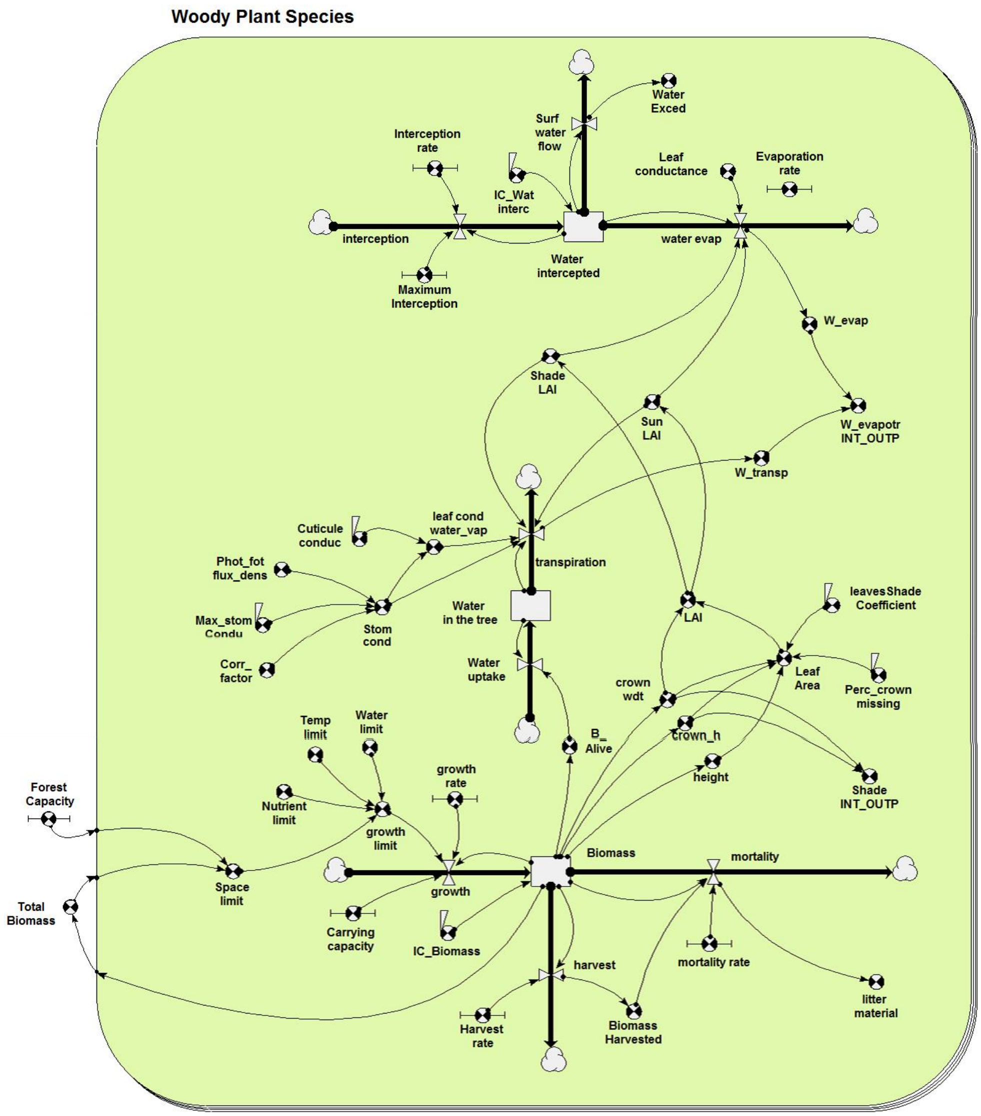


Figure 12. Current representation of the woody plants submodel in SIMILE.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

Vegetation is divided in the submodels between woody plants and herbaceous plants due to differences in their growth and role of their structures in different processes. Figure 12 shows the submodel woody plants that is based on CO2fix and i-Tree Eco models (refer to Table 12 for further information). The submodel herbaceous plants uses as reference an adaptation of CO2fix. If both structures are present in an NBS these submodels are linked. For simplicity, it is assumed that leaf area is only dependent on canopy's growth, and could be modified by known management actions, even if in reality it also changes due to seasonal temperature, vapour pressure deficit, light, water and nutrients availability, phenology, and plant maturity (Hunter et al., 2014).

Soil is divided in the submodels between litter pools and soil (top soil and subsoil). The former is formed by the stocks of decomposable plant material, resistant plant material, humus, microbiomes, and inorganic carbon (Figure 13). The latter is composed by top soil and subsoil storage and relates mainly to the processes of infiltration and percolation. Currently, the litter pools submodel is based in ECOSSE and RothPC-1 models and incorporates attributes of SWAT (refer to Table 12 for further information). The soil submodel uses the modelling of Low Impact Development (SUDS) in SWMM as the main reference.

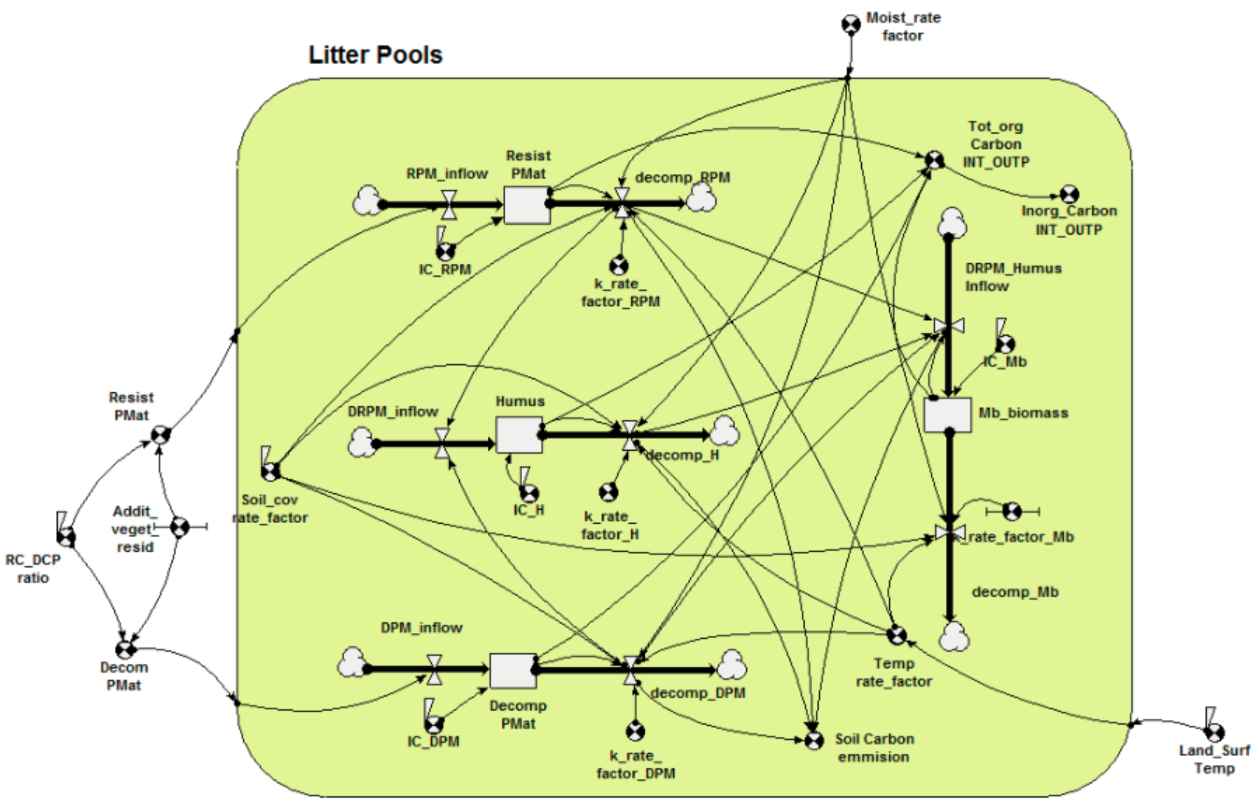


Figure 13.Current representation of the litter submodel in SIMILE.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Water is divided in the submodels between free standing water, nitrogen, phosphorus, and sediments (settling of suspended solid). The first is a water balance model of the waterbody. The second takes into account the processes of mineralisation/nitrification, denitrification, and volatilisation. The phosphorus submodel and the sediment submodel are linked since the main process for the removal of phosphorus is settling. Phosphorus and nitrogen models interact with the vegetation compartment through plant uptake. The four submodels are currently based in WWQM which was developed specifically for constructed wetlands. In addition, three main assumptions have been undertaken: first, there is no carbon sequestration, then particulate organic carbon and dissolved organic carbon only inform processes related to nitrogen and phosphorus; second, resuspension is negligible; third, there is no seasonal or permanent water stratification (epilimnion, thermocline, hypolimnion) independently of the water depth. As a consequence, water flow and nutrients (phosphorus and nitrogen) are evenly mixed through the waterbody. The first assumption is a consequence of not accounting for carbon storage in urban wetlands or ponds as stated in Section 4.1.1. The last two assumptions are common in wetland models (e.g. Lee, Mostaghimi and Wynn, 2002; Chavan and Dennett, 2008; Neitsch *et al.*, 2011), preventing overcomplicated calculations that in most cases might not apply to urban wetlands or ponds due to their shallow depth.

The management compartment includes the input variables representing the management actions applied on vegetation, soil, and water. Initially, these are mainly related to harvesting, trimming, mowing, replacement, and replanting. This permits the incorporation of NBS Type 1 in the module. Since these actions require an input of material and energy, the NBS compartment also interacts with the technosphere.

The technosphere accounts for the known stocks of materials and energy used along the life-cycle of the NBS, simplified as construction and planting, operational life, and end of life stages. For the construction and planting phase, the amount of materials and energy are calculated from the bill of quantities of the different projects, acting as the initial stock. For the operational life, additional materials and energy are added to the stock based on the management tasks. The end of life incorporates the removal of products and transport to landfill/industry or reutilisation (only vegetal material) on site, increasing the stock of energy used. The stock of materials are aggregated in vegetable products, construction mineral (e.g. stone, gravels), metals, chemical products and fertilisers, plastic, wood, rubber, glass, and other products.

6.2.2. Anthroposphere compartment

The anthroposphere compartment is composed by the artificial land covers surrounding the NBS and its population, which are defined as input variables. Its spatial extent is defined by the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

boundaries of the neighbourhood type/s surrounding the NBS (or sites of NBS intervention). In this sense, the extent of the anthroposphere defines the secondary system boundary of this module, and the limits of the NBS the extent of the principal system boundary (see section 5.4.1 for further details on the boundary definitions).

The artificial land cover and basic population characteristics (density, age structure, average education, and average income) influence the demand of materials and energy stocks of the neighbourhood. On one hand, the NBS compartment also affects this demand through the supply of provisioning and regulation services (e.g. changes in PET). On the other hand, the artificial land cover and the population affect variables related to cultural and regulation services (e.g. sealed surfaces affect run-off and air temperature) in the NBS and atmosphere compartment. For simplicity, this compartment is assumed as being “exogenous”. Therefore, NBS are not expected to influence the dynamics of the population and the land cover during the modelling time. This assumption might be relaxed in other tasks, for instance Task 3.2 will offer insights on the interrelationships between NBS project and citizens’ socio-economic behaviour.

6.2.3. Atmosphere compartment

The atmosphere is the only compartment conceived without spatial attributes. It contains the climatic variables (e.g. precipitation, irradiation, air temperature, concentration of air pollutants) affecting processes in the NBS compartment and the stocks of material and energy in the anthroposphere compartment.

6.2.4. ES compartment

This compartment is conceived for clarity of exposition and contains the indicators representing the ES classes, which are the final outputs of the processes occurring in the module.

6.2.5. Implementation compartment

To pave the road for follow-up activities in the Task 5.4, an implementation compartment is foreseen. As stated in D1.2, the NBS implementation models are defined by the combination of the financial, business, and governance theoretical implementation models, which mainly affect the use of resources, ownership, financial mechanisms, planning approach, and participation of stakeholders. Based on this information, it may be initially assumed that the implementation model will influence the perception of the population regarding the NBS (e.g. by assuming predefined scenarios of interaction over time representing different levels of acceptability), the stocks of the technosphere compartment, and the management actions, but not directly other submodels.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

6.3. Representation of urban systems in the modelling framework

Based on the information of section 5.2, the urban system module in the MIMES framework is built using an urban metabolism (UM) approach. Six compartments (water, land cover, consumption of energy and materials, population, transport, carbon, and atmosphere) are represented in each cell of the urban system (Figure 14). In this sense, the urban system is converted in a grid of regular cells, whose spatial resolution is determined based on the availability of data and the decision makers' needs. An additional compartment (information) is included for the entire urban system. This compartment defines the characteristics of land cover, transport, material preferences, and governance that could occur in any cell.

As introduced in Chapter 5, two system boundaries are considered in the urban system modelling framework: i) the secondary system boundary, which matches the urban region level, and ii) the principal system boundary that matches the city/metropolitan level (Figure 14). In principle, for each case study the definition of the spatial limits of both boundaries should derive from the use of the indicators pre-selected in section 5.4.1. However, as mentioned in section 5.4.1 these could be modified based on the outputs of Task 3.1 and the consultation with external advisors (see section 7.2 for further details).

Additionally, an initial characterisation of urban typologies at urban region and city/metropolitan level per each case study should be done before the application of the urban system module. This would provide an initial understanding of the potential dynamics of each urban area and if they should be comparable between each other. Moreover, it might inform the future application of the model to similar urban typologies already evaluated. For example, previous calibrations of the model done for urban areas of the same typology might already be adequate for future case studies of the same typology. As another example, minor adaptations required in the structure of the model or some internal relations might also apply to future case studies of the same urban typology. Hence, the development of a database of urban typologies based on previous applications of the models could be beneficial for faster and easier adaptation of the urban system model to future case studies. Similarly to system boundaries, the descriptive indicators defined in section 5.4.2 would inform the definition of urban typologies, which might be further modified after initial applications of the model.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

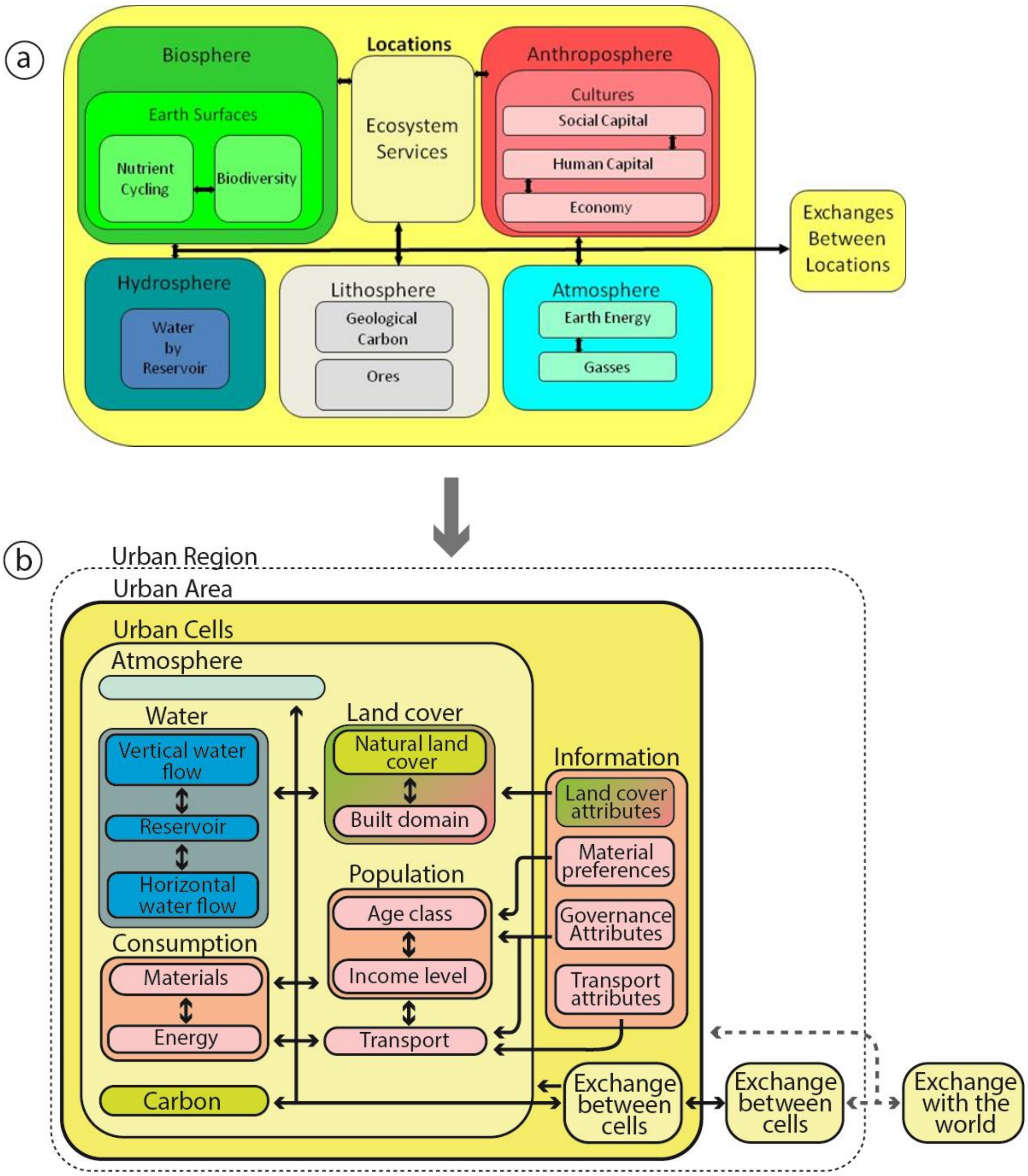


Figure 14. Adaptation of the (a) MIMES framework to depict (b) an urban system module.

6.3.1. Differences and similitudes with the NBS module

Differently from the NBS module, the urban system focuses on assessing the stock and flows of resources of the urban environment which are also (partially) sourced by the NBS module. In addition, the cells of the urban system (their compartments) interact with each other (e.g. transfer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

of water flow, population, carbon), affecting the internal processes of each cell and therefore the consumption of materials and energy.

In the urban system module, the atmosphere compartment works like in the NBS module. Instead, the population and transport compartments are dynamic and –together with the land cover and water compartments– influence the consumption of materials and energy. The population compartment is currently defined by the different age classes (children, youths, adults, and elder people) and levels of income (high, upper-middle, middle, and low) which evolve during the modelling and whose combinations influence the material preferences and type of mobility. The water compartment includes the vertical flow (evapotranspiration, infiltration and percolation processes) and horizontal flow (run-off) that affects the water reservoirs of the city. Concurrently, these are also affected by the characteristics the built domain and natural land cover (distribution, permeability, slope) as well as the temperature, and the intensity and duration of the precipitation. Finally, all the compartments of the cell influence the emission and sequestration of carbon in each urban cell, which is used as a simple indicator to illustrate changes in the impact of the UM.

6.4. Relationship between NBS and urban systems in the modelling framework

In the proposed modelling framework, the NBS and urban system modules are interconnected (Figure 15). As introduced before, the NBS module focuses on the calculation of ES as final outputs, also considering changes in the consumption of materials and energy to inform the impact of certain ES (e.g. the impact of the regulation of temperature and humidity in the consumption of energy). On the other hand, the urban system module aims to understand how the supply of ES by NBS could affect the UM by modifying the demand of materials and energy.

To inform the urban system module, ES outputs from the NBS module will be calculated using as inputs the environmental and anthroposphere factors generated from the urban system module. The ES values for different conditions will then be integrated in the attributes of land cover classes representing NBS in the urban system module. As a result, the urban system module will be able to consider changes in ES results with land cover modifications and assess how those impact the flows of matter, energy, waste and water, together with the impacts derived from changes in the population dynamics. These will be reused as inputs in the NBS module iteratively.

NBS and urban system modules are very complex (dynamic and spatial explicit) and there is a certain risk that the integration would not be feasible due to computational limitations. In this case, the mitigation strategy would be to generate different urban system scenarios representing a range of possible impacts of NBS at the urban level: e.g. from “low impact scenario” in which the

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

dynamics of key environmental and anthroposphere factors (e.g. increase of population, increase of temperature) are similar to the business as usual trends; up to "high impact scenario" in which, based on previous literature and expert's opinion on NBS, these dynamics are largely affected. These scenarios will be used as inputs in the NBS module to analyse the ES provision at the neighbourhood level.

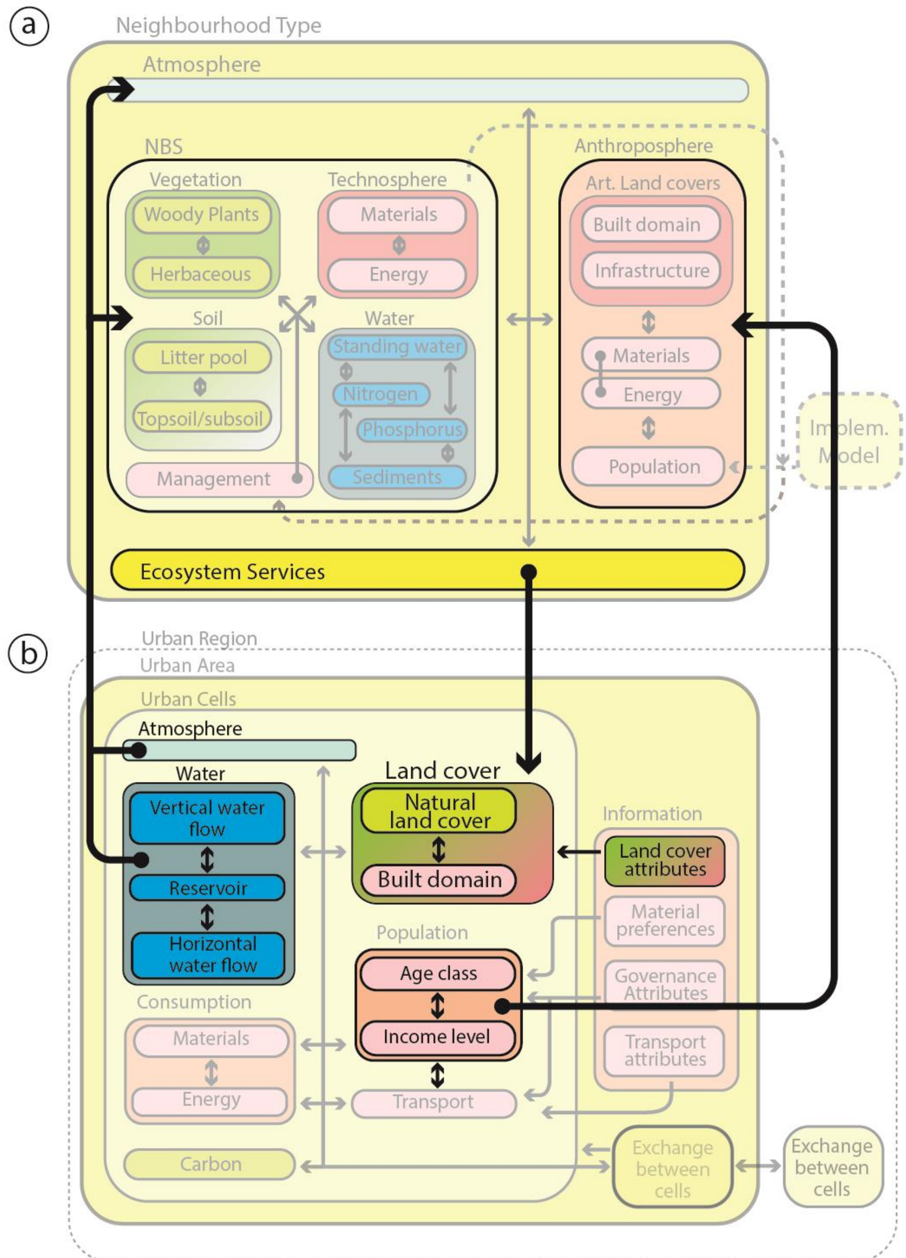


Figure 15. Exchanges between (a) the NBS module and (b) the urban system module within the whole SDM.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

6.5. Outlook on the SDM interoperability with the platform

The whole SDM will be integrated into the Nature4Cities platform in the form of archetypal outputs obtained after running the model in SIMILE (Figure 16). In parallel, this knowledge will also be embedded in an independent web-based tool that is aimed to be developed by LIST in the Task 4.4 ("Web-based tool development for NBS trade-offs and synergies forecast").

In order to run the model, inputs in the form of georeferenced spatial data, survey data, and statistical data collected for the case studies of WP7 will be necessary. In the platform, the SDM outputs can be visualized by first defining NBS selection criteria, then filtering UCs and/or ES and then plotting changes in key environmental and anthroposphere factors (e.g. increase of population, increase of temperature) that will inform about a set of future plausible conditions in which to evaluate the NBS impacts on the provision of ES. Hence, it will be primordial to share a common set of scenarios by the assessment tools of WP2, WP3, and WP4 as well as a common set of NBS types studied to ensure that a holistic assessment in the WP7 will be possible. The different archetypal outputs will be obtained in the form of spreadsheets with spatial data associated that would be integrated into the platform of Nature4Cities.

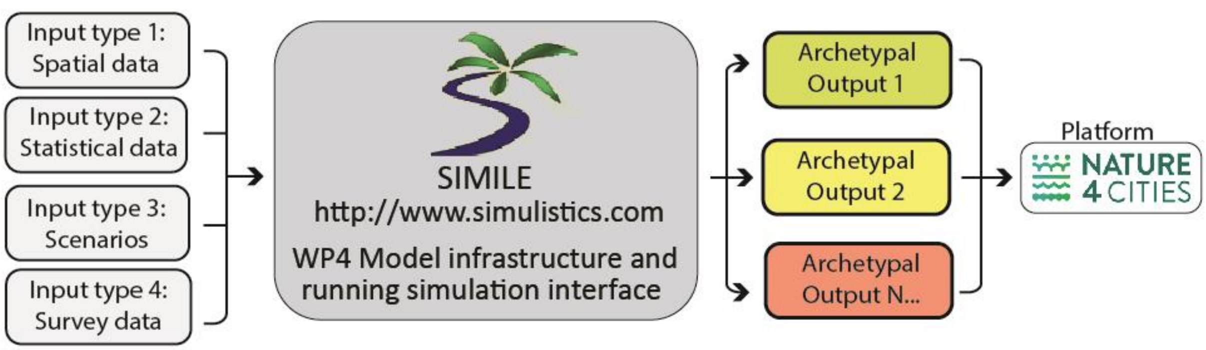


Figure 16. Procedure for the integration of MIMES tool into the platform.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

7. Collection of data and initial evaluation of the modelling framework

The following sections of this chapter describe: (i) the collection of data from case studies provided by pilot cities, G4C and P&C; (ii) data limitations for the urban systems and NBS modules based on the information gathered from the proposed case studies and public sources; (iii) an initial evaluation of the modelling framework through a workshop with external consultants.

7.1. Case studies

The pilot cities (AH, CAN, SZEG, CMM) provided environmental, social, and economic data in historic time series from the inventories and databases of their municipalities, regional authorities, and public companies in charge of public services. This allowed to understand the availability of data of typical European cities and to compare it with the expected input data required by the urban system module in order to calculate outputs based on the processes identified. Similarly, the pilot cities were asked to provide available environmental and economic data from sites of intervention (Figure 17) that could constitute potential NBS case studies for the calibration and testing phase of the NBS module.

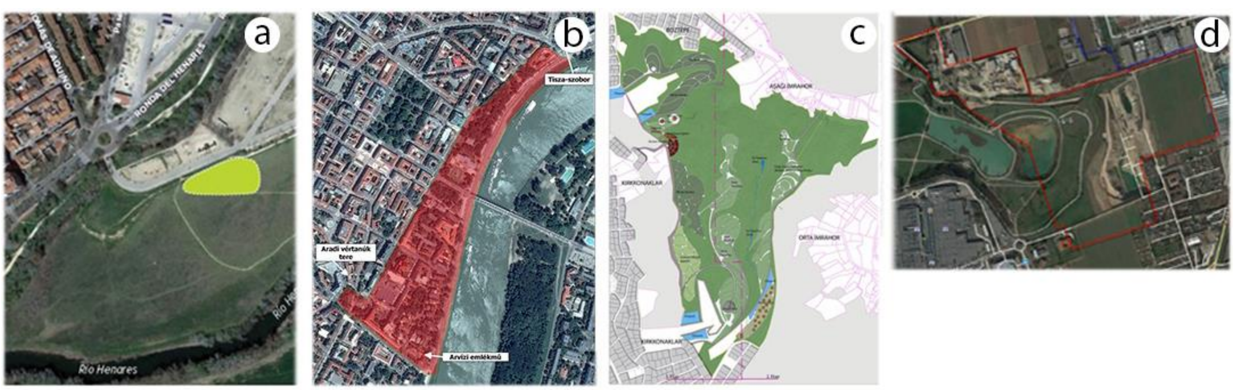


Figure 17. (a) Edible forest, Alcala de Henares (b) Urban park, Cankaya (c) Waterfront, Szeged (d) Quarry restoration, Metropolitan City of Milan.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

7.1.1. Alcala de Henares

The municipality of Alcala de Henares, located adjacent to the river Henares in the south-eastern part of the Region of Madrid, and with a population of 200.000 inhabitants, is a good example of European medium city to inform the development and testing of the urban system module. Given that about 34.5% of the municipality is already urbanised, a main concern of the planning authorities is the provision of zones for recreation, but also natural conservation in the periurban area. The municipality has developed a landscape plan for the south-eastern part of the city close to the river, where an edible forest was developed. This could be a potential case study for calibrating and testing the NBS model for urban woodlands. However, so far environmental or economic data for the NBS case study have not been delivered by the local authorities. Only some datasets related to the urban system could be collected which are presented in Table 18.

Table 18. Social, economic, and environmental datasets collected for Alcala de Henares.

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Land	Percentage of urban land use	N	%	-	Unknown
Land	Percentage of land approved for urbanisation	N	%	2012-2014	AH
Land	Percentage of land urbanised	N	%	2012-2014	AH
Land	Digital Elevation Model – 5m resolution	Y	meters	2017	Centre of Geographic Information
Land	Urban Land Use/Land Cover	Y	Meters	2012,2016	Copernicus land monitoring service
Social	Population by neighbourhood	Y	persons	Unknown	AH
Social	Age Structure (by gender)	N	-	2011	National institute of Statistics
Social	Average age by district	N	-	2011	AH
Social	No. people per household	N	persons	2011	AH
Social	Family structure per household	N	-	2011	AH
Social	Number of siblings per household	N	No.	2011	AH
Social	Professional sector per employed person	M	persons	2011	AH
Social	Natural Movement of Population	N	persons	2015	Unknown
Social	No. of unemployed people by district		Persons	2011	AH
Social	No. of unemployed people (by gender, below 25 y, above 45 y)	N	persons	2012-2016	Minister of Employment and Social Security
Transport	No. of vehicles	N	persons	2012-2016	National Directorate General for Traffic
Transport	No. of inhabitants with driving licence (by gender)	N	persons	2012-2016	
Transport	Bus stops by bus route	Y	Bus stop	Unknown	AH
Resources	Electric energy consumed per capita	N	MWh	2015	Iberdrola
Air	Hourly concentration of air pollutants (SO_2, NO_2, CO, NO, NOx, O_3, PM_{10})	N	μg/m^3	1990-2018	Regional Directorate General of Environment
Air	Hourly Wind velocity	N	m/s	1990-2018	
Air	Hourly Air temperature	N	°C	1990-2018	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Air	Hourly Relative Humidity	N	%	1990-2018	
Air	Hourly Air Pressure	N	Atm	1990-2018	
Air	Hourly Solar radiation	N	W/m^2	1990-2018	Regional Directorate General of Environment
Air	Hourly Precipitation	N	mm	1990-2018	
Water	Biological Demand of Oxygen 5days (Discrete monitoring from effluent of 4 sewage treatment plants)	N	mg/l	2017	Canal Isabel II
Water	Chemical Demand of Oxygen (Discrete monitoring from effluent of 4 sewage treatment plants)	N	mg/l	2017	Canal Isabel II
Water	Total Suspended Solids (Discrete monitoring from effluent of 4 sewage treatment plants)	N	mg/l	2017	Canal Isabel II
Water	Total Phosphorus (Discrete monitoring from effluent of 3 sewage treatment plants)	N	mg/l	2017	Canal Isabel II

7.1.2. Szeged

The municipality of Szeged is located in the Southern Great Plain of Hungary and crossed by the Tisza River. It owns a population of around 160.000 inhabitants, which makes it another example of European medium size city to inform the modelling of the urban system. The municipality suggested a plan for the rehabilitation of the waterfront of the Tisza River to offer green recreational areas and mitigate the urban heat island effect. As part of this plan, a section in the downtown is proposed here as a potential case study for calibrating and testing the model for urban woodlands. However, as for Alcala de Henares, so far the municipality of Szeged was not able to provide environmental or economic data for the NBS case study. Only data for the urban system could be collected (Table 19).

Table 19. Social, economic, and environmental datasets collected for Szeged.

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Land	Administrative boundaries	Y	-	Unknown	
Land	Footprint of building in the city centre	Y	-	Unknown	SZEG
Land	Digital Elevation Model of the city centre	Y	meters	unknown	
Land	Urban Land Use/Land Cover	Y	Meters	2012,2016	Copernicus land monitoring service
Land	National map of soil-geoenvironmental classes	Y	-	Unknown	SZEG
Land	No. of dwellings (by age of construction, occupants, height and size, rooms) in the municipality	N	No.	1946-2011	Hungarian Central Statistics Office

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Resources	Regional agricultural production (cattle, chicken, pig, sheep, cereals, viticulture)	N	tonnes	2000-2016	
Resources	Regional industrial production	N	$	2002-2016	
Resources	Regional output of construction by residence	N	$	2002-2016	
Resources	Regional per capita GDP	N	$	2002-2016	
Land	National household consumption per capita	N	$	2000-2016	
Resources	National electricity energy balance	N		1990-2015	
Resources	National primary energy balance	N		1995-2015	
Resources	National production of renewable energy and waste	N	Million - KwH	2005-2015	
Resources	National share of renewable resources and waste in energy	N		2005-2015	
Resources	Regional waste removed	N	Thousand tons	1990-2015	
Resources	Regional waste removed by group and type of treatment	N	Thousand tons	1990-2015	
Resources	Regional Regularly cleaned areas	N	Thousand m^2	1990-2015	
Resources	Regional Waste water treatment	N	Thousand m^3	1990-2015	
Health	County deficiencies and long lasting diseases (by disease	N	Persons	2011	Hungarian Central Statistics Office
Health	National psychiatric disorders	N	Persons	1990-2016	
Health	National pulmonary diseases	N	Persons	1990-2016	
Health	National expenses on health	N	Persons	2003-2015	
Social	No. persons per household at Szeged	N	Persons	1980-2011	
Social	Household composition (type of family) at Szeged	N	-	2011	
Social	Family by children and type at Szeged	N	Children	2011	
Social	No. of inhabitants at Szeged	N	Persons	1870-2011	
Social	Population (by gender,marital status, nationality, religion, economic activity, education) at Szeged	N	Persons	2011	
Transport	National No. of interurban passengers	N	Persons	2001-2016	
Transport	National No. of intraurban passengers	N	Persons	2001-2016	
Transport	National stock of passengers by car	N	Persons	2002-2016	
Transport	Regional stock of road motor vehicles	N	vehicles	2000-2016	
Environmental	National logging (by tree species)	N	Thousandm^2	1996-2016	
Environmental	National forest area (by tree species and age)	N	Thousand m^3	1996-2016	
Air	Daily concentration of air pollutants (SO_2, NO_2, CO, NO, NOx, O_3, PM_{10}, $PM_{2.5}$) of Szeged	N	$\mu g/m^3$	2011-2017	Hungarian Air Quality Network
Air	Monthly sunny hours of Szeged	N	hours	2013-2017	Hungarian Centre of Meteorological Data

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Air	Monthly air temperature (mean, maximum, minimum) of Szeged	N	°C	2013-2017	Hungarian Centre of Meteorological Data
Air	Monthly precipitation	N	mm	2013-2017	
Air	Annual sunshine hours of Szeged	N	Hours	1985-2016	
Air	Annual mean air temperature of Szeged	N	°C	1985-2016	
Air	Annual rainy days of Szeged	N	Days	1985-2016	
Air	Annual precipitation of Szeged	N	mm	1985-2016	
Air	Daily air Temperature of Szeged (average, maximum, minimum)	N	°C	1901-2010	
Air	Daily precipitation	N	mm	1901-2010	

7.1.3. Cankaya

The municipality of Cankaya is located inside the urban area of Ankara. This represents a valuable example of a subset of a metropolitan area to inform the development and testing of the urban system model. The municipality is concerned about the lack of natural recreational space and proposed the regeneration of a vacant land of 68 ha integrated in the urban area as a park. The project will include conservation and planting of trees and creation of urban gardens. As such it represents a potential case study for calibrating and testing the NBS model for urban woodlands and horticultural urban gardens. However, as for the previous cities the municipality of Cankaya has so far not released environmental or economic data for the NBS case study, and therefore only data for the urban system is presented (Table 20).

Table 20. Social, economic, and environmental datasets collected for Cankaya.

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Land	Urban land use-land cover	Y	-	2012	Copernicus land monitoring service
Soil	Monthly average soil temperature at 50 and 100 cm (mean, minimum) for a 55 year period for Ankara	N	°C	1960-2015	General Directorate of Meteorology
Air	Average, minimum and maximum pressure per month for a 55 year period for Ankara	N	Atm.	1960-2015	
Air	Average, minimum and maximum air temperature per month for a 55 year period for Ankara	N	°C	1960-2015	
Air	Average number of days above 30°C, 25°C, 20°C, 0.1°C per month for a 55 year period for Ankara	N	Days	1960-2015	
Air	Average number of days below -20°C, -10°C, -3°C, 5°C, 10°C, 15°C, 20°C per month for a 55 year period for Ankara	N	Days	1960-2015	
Air	Number of snowy days per month for a 55 year period for Ankara	N	Days	1960-2015	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Air	Average steam pressure per month for a 55 year period for Ankara	N	Atm	1960-2015	General Directorate of Meteorology
Air	Average relative humidity per month for a 55 year period for Ankara	N	%	1960-2015	
Air	Average number of cloudy days per month for a 55 year period for Ankara	N	Days	1960-2015	
Air	Precipitation per month for a 55 year period for Ankara	N	mm	1960-2015	
Air	Average wind speed (per orientation) per month for a 55 year period for Ankara	N	m/s	1960-2015	
Air	Average daily total solar time for a 55 year period for Ankara	N	Hours	1960-2015	
Air	Average surface evaporation for a 55 year period for Ankara	N	mm	1960-2015	
Air	Annual Intensity of precipitation by duration for Ankara	N	Mm	1940-2010	
Air	Daily average wind speed	N	m/s	2015	
Air	Daily maximum wind speed and direction per month	N	m/s	2015	
Air	Daily maximum and minimum temperature per month	N	°C	2015	

7.1.4. Metropolitan City of Milan

The Metropolitan City of Milan (CMM) is composed by the city of Milan and other 133 municipalities, and with a population of around 3.200.000 inhabitants is another example of European metropolitan area that could inform the modelling of the urban system. CMM is developing a new territorial planning tool for the existing and future quarries in the periurban area, which should be valid for the next 10 years. The plan defines the location of quarries, the extraction volumes, the environmental restoration and the final fruition of the area. In relation to the environmental restoration, CMM proposed the 4 restored quarries as sites of intervention, and for two of them the process of restoration is nearly finished. One of the last two quarries is proposed as potential case study for calibrating and testing the NBS model for constructed wetlands and urban woodlands. The data collected for the urban system (Table 21), the NBS case study and the other three quarries (Table 22) is presented.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 21. Social, economic, and environmental datasets collected for the Metropolitan City of Milan.

Topic	Variable/parameter/data	Spatial data	Unit	Period	Source
Land	Acoustic regulation maps	Y	dBA	2017	Geoportal Lombardia
Land	Types of Agricultural land cover	Y	-	2013	Geoportal Lombardia
Land	Hydrogeological protected areas	Y	Ha	2013	Geoportal Lombardia
Land	Brownfield areas	Y	Ha	2017	Geoportal Lombardia
Land	Areas of forest	Y	Ha	2012	Geoportal Lombardia
Land	Geological units	Y	-	2017	Geoportal Lombardia
Land	Geomorphological units	Y	-	2007	Geoportal Lombardia
Land	Land use classification	Y	-	1954,1980, 1999,	Geoportal Lombardia
Land	Presence of Hedgerows	Y	m	2000,2000, 2007,2015	Geoportal Lombardia
Land	Quarries	Y	Ha	2015	Geoportal Lombardia
Land	Soil classes	Y	-	2013	Geoportal Lombardia
Land	Cycle network	Y	m	2014	Geoportal Lombardia
Land	Waterbodies	Y	Ha	2006	Geoportal Lombardia
Land	No of trees inside Milan municipality	Y	No	2017	Geoportal City of Milan
Air	Regional air pollutant emissions by economic sector (SO_2, NO_2, CO, CH4, N_2O, NH_3, COV, NO, NOx, O_3, PM_{10}, $PM_{2.5}$)	N	μg/m³	2012,2014	ARPA Lombardia
Air	Daily concentration of air pollutants (SO_2, NO_2, CO, NO, NOx, O_3, PM_{10}, $PM_{2.5}$)	N	μg/m³	2003-2014	ARPA Lombardia
Air	Precipitation	N	mm	1990-2018	ARPA Lombardia
Air	Average temperature	N	°C	1990-2018	ARPA Lombardia
Air	Relative humidity	N	%	1990-2018	ARPA Lombardia
Air	Solar radiation	N	W/m²	1990-2018	ARPA Lombardia
Air	Wind speed and orientation	N	m/s	1990-2018	ARPA Lombardia
Air	Accumulated snow	N	M	1990-2018	ARPA Lombardia
Social	No. of inhabitants (total, by age)	N	person s	2017	National Statistical Institute
Social	Regional- No. of foreign residents	N	person s	2017	National Statistical Institute
Social	Regional – Percentage of unemployed people (by age structure)	N	person s	2017	National Statistical Institute

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 22. NBS case studies of Metropolitan City of Milan.

Data	Spatial data	Unit	Source
Limits of the site of intervention	Y	-	Restoration plans provided by CMM
Areas for the different restoration actions	Y	m^2	
Number of trees and shrubs of each species	N	No	
Age of trees planted	N	years	
Dimension of trees planted		m (height)	
Percentage of tree and shrub species per each zone	N	%	
Scheme of planting density	Y	-	
Scheme of planting distribution	Y	-	
Density of herbaceous seed in the seedbeds	N	No. seeds/m^2	
List of potential animal species that could host the restored area	N	-	
Length and width of waterbodies	Y	m	
Depth of waterbodies		m	
Periodical management of actions	N	-	
Chronogram of the works	N	-	
Disaggregated cost of restoration works and management works	N	Euro	
Plans, sections of the landscaping works	Y	-	

7.1.5. NBS case studies provided by G4C

G4C collected environmental data from NBS case studies of urban woodlands, green roofs, green walls, plantainers with climbers, and Sustainable Urban Drainage Systems (SUDS) from their own real projects (Table 23). Since the environmental data was intended to be used for testing and calibrating the model, G4C tried to increase the range of case studies and amount of data contacting the following institutions:

- EFB – European Federation of Green Roofs and Walls
- VfB – Austrian green roof and wall association
- FBB – German Professional Green Roof Association
- SFG – Swiss Professional Association for Building greening
- BOKU – University of Natural resources and life science Vienna
- Optigrün Gmbh – Green roof producer
- Garten Haas – Green roof distributor
- several Architects, NBS distributors and Landscape gardeners

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 23. List of G4C case studies.

No.	City	Country	NBS Type
1	Milano	Italy	Forest
2	Vienna	Austria	Green wall / Green roof extensive
3	Baden	Austria	Green wall
4	Vienna	Austria	Green wall
5	Vienna	Austria	Plantainer with climbers
6	St. Pölten	Austria	SUDS
7	Melk	Austria	Green roof extensive
8	Berlin	Germany	Plantainer with climbers
9	Zürich	Switzerland	Park with climbers
10	Vienna	Austria	Plantainer with climbers

However, G4C informed about difficulties in the collection of monitored environmental data that could be used for the calibration of the model. In many cases these data is collected in pioneer research projects where special conditions are negotiated and the data is not easily available. In any case, the environmental data collected (Table 24) could inform the works on the NBS model and be used for calibration or validation purposes.

Table 24. Environmental data of the NBS case studies of G4C

Case study	Variable/parameter	Unit	Period	Original Source
1	Average Sun hours	Hours/day	May-October	Breathe.Austria (2015)
1	Average Precipitation per month	mm/month	-	Breathe.Austria (2015)
1	Amount of soil	m^3	-	G4C
1,7	Number of shrubs, grasses and flowers	Pieces	-	G4C
1	Trees	Pieces	-	G4C
1	Total leaf area	m^2	-	G4C
1,4	AverageCO_2 absorption	Kg/day	-	Breathe.Austria (2015); Krieger (2014)
1	O_2 production	Kg/day	-	Breathe.Austria (2015)
1	Universal Thermal Climax Index of a hot summer day (Pathway Shade & Vegetation Shade)	°C	-	Kessling et al (2015)
1	Air temperature of a hot summer day (Pathway Shade & Vegetation Shade)	°C	-	Kessling et al (2015)
1	Relative Humidity of a hot summer day (Pathway Shade & Vegetation Shade)	°C	-	Kessling et al (2015)
1	Mean Radiant Temperature of a hot summer day (Pathway Shade & Vegetation Shade)	°C	-	Kessling et al (2015)
1	Air velocity of a hot summer day (Pathway Shade & Vegetation Shade)	m/s	-	Kessling et al (2015)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Case study	Variable/parameter	Unit	Period	Original Source
2	Improvement of U-value (green wall)	W/m^2K	-	Korjenic et al (2016)
3	Improvement of U-value (green wall)	W/m2K	-	Korjenic et al (2016)
4,8	Evapotranspiration performance	l/day, l/m2	-	Scharf et al (2013); Köhler (2008), SenStadt (2010)
4	Reduction of surface temperature	°C	-	Scharf et al (2013)
4	Change in annual transmission losses	kwH to kwH/m2	-	Korjenic et al (2016)
4	Water demand (till)	l/day	-	Krieger, B. (2014)
4,6	Water retention (app 8l/lfm)	l, l/m3, l/bus station	-	Krieger, B. (2014); Beinlich, L. (nA); Dachgrün (2015)
6	Flow rate	m/s	-	Beinlich, L. (nA)
6	Heavy metal backing (Pb, Cu, Zn)	µg/l, %	-	Beinlich, L. (nA)
7	Cooling effect	kWh/façade/day	-	Köhler (2008); SenStadt (2010)
8	Water efficiency	kWh/l	-	SenStadt (2010
8	Primary energy need	kWh/m2/a	-	Dettmar et al (2016)

7.1.6. NBS case studies provided by P&C

P&C collected environmental data from NBS case studies composed by constructed wetlands, green roofs, and urban woodlands (Table 25) from projects to which they were related to.

Table 25. List of P&C case studies.

No.	Name / ID	City	Country	NBS type
1	Zone libellule + projet ZHART *Dragonfly zone'*	Saint Just (Hérault)	France	Constructed wetland of superficial flow
2	SUDS in Bézannes ZAC	Reims	France	Constructed wetland of superficial flow
3	A schools' green roof : Aimé Césaire	Nantes	France	Green Roof
4	Urban silviculture	Lorient	France	Mixed Urban Woodland
5	Florilèges green roofs	-	France	Green Roof
6	Fresque végétalisée	Irigny	France	green wall
7	IME Les Papillons Blancs	Roppe	France	green wall
8	Meaux	Paris	France	green wall
9	Mur du square Vinet	Bordeaux	France	green wall
10	Mur Gabriel Perri	-	France	green wall
11	Mur Raimu	Nantes	France	green wall
12	Muséum d'Histoire Naturelle	Toulouse	France	green wall
13	Résidence du château à Toulouse	Toulouse	France	green wall
14	Centre IRD France Sud	Montpellier	France	green wall
15	Darius Milhaud	Paris	France	green wall
16	Mur AMAEVA	Andigné	France	green wall
17	Mur d'Anthos	Boulogne Billiancourt	France	green wall
18	Mur de Carrefour	Labege	France	green wall

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

No.	Name / ID	City	Country	NBS type
19	Mur de la Mairie	Blagnac	France	green wall
20	Mur INH	Angers	France	green wall
21	Paprec	Paris	France	green wall
22	Centre d'échanges de Lyon Perrache, pilier sud-ouest CELP 1	Lyon	France	green wall
23	Local technique de la place Jenner	Le Havre	France	green wall
24	Mur de la place Mésirard	Dreux	France	green wall
25	Mur végétal du tramway	Pessac	France	green wall
26	Pont Raynal	Toulouse	France	green wall
27	Mur Carrefour de la BUISSIERE	-	France	green wall
28	Mur CASTELLANE	Rillieux La Pape	France	green wall
29	Square Félix Jacquier	Lyon	France	green wall
30	Jardin des géants	Lille	France	green wall
31	mur végétal de l'aquapol	Montrouge	France	green wall
32	Totems végétalisés	Bagnolet	France	green wall
33	La Fontaine du Campo Marengo	Toulouse	France	green wall
34	Le mur végétal à la résidence Adoma du Dôme	Boulogne Billancourt	France	green wall
35	Mur de la rue de la préfecture	Cergy Pontoise	France	green wall
36	Mur végétal Voie Nouvelle	Paris	France	green wall
37	Mur végétalisé du CFPPA	Antibes	France	green wall
38	Parking PAIXHANS	Metz	France	green wall
39	Parking Vallier	Marseille	France	green wall
40	Phonifleur	Beautiran	France	green wall
41	René Fonck	-	France	green wall
42	Parking des Halles d'Avignon	Avignon	France	green wall

Similar to G4C, it was not possible to collect time series data from environmental monitoring. However, the datasets provided (Table 26) can be accommodated in the NBS module for calibration and validation purposes.

Table 26. Environmental datasets for the NBS case studies of P&C

Case Study	Variable/parameter	Unit	Source
1,3,4	Soil		P&C
1-4	Landscape plan		P&C
1-42	Type of vegetation	-	P&C
6-42	Surface	m^2	P&C
6-42	Orientation		P&C
6-42	Number of species	-	P&C
6-42	Plant density (implementation)	$plant/m^2$	P&C
6-42	Plant density (present)	-	P&C
6-42	Changes in vegetation since implementation (reason)	-	P&C
6-42	Maintenance frequency	No. interventions/ year	P&C

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Case Study	Variable/parameter	Unit	Source
6-42	Maintenance operation types	-	P&C
6-42	Irrigation type	-	P&C
6-42	Annual consumption of water	m3	P&C
6-42	Fertilisation	Yes/No/Unknown	P&C
6-42	Herbicides	Yes/No/Unknown	P&C
6-42	Insecticides	Yes/No/Unknown	P&C
6-42	Fungicides	Yes/No/Unknown	P&C
6-42	Waste	No/Unknown/Type	P&C

7.2. Initial evaluation of the modelling framework

A revision of the data received by the pilot cities shows that so far there is a substantial lack of data for many topics. A relevant lack of spatial disaggregated data at municipal level occurs across all the pilot cities, except for the case of the Metropolitan City of Milan. This includes lack of data regarding waterbodies, soil, land cover and land use, buildings, vegetation, and infrastructures. As far as Szeged is concerned, partial information exist for buildings, but only for their footprint in the city centre. Spatial data extracted from the OS map of Szeged containing roads, rivers, buildings and green area was shared in the last phases of T4.1, but for some attributes this information is still incomplete and therefore it was not included in the list of available data.

In this regard, the lack of LULC data, vegetation and soil could be problematic for the calibration of both models. The lack of LULC data could be partially compensated by making use of information from the Urban Atlas of the Copernicus programme. However, these spatial data only covers two periods (2006, 2012), with the exception of Cankaya, for which only 2012 data is available. The lack of the vegetation data, instead, could impede to acknowledge the role of existing vegetation before NBS interventions and later on in the modelling. Eventually, the lack of soil data could also be problematic for modelling infiltration and the processes related to retention of pollutants and the influence of soil on vegetation growth.

Regarding social and economic datasets, these are not disaggregated beyond municipal level, except for population data provided by Alcala de Henares. In fact, in some cases, the data is aggregated at regional and national levels and in the specific case of Cankaya this information seems to not be available. This makes difficult to account for different social and economic factors and assess their influence in the processes dependent upon the anthroposphere. Such a situation could be partially compensated with the dataset *population estimation data by polygon* provided in the Urban Atlas database. However, this information is not available for Turkish municipalities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

As an alternative, it can be assumed that the historic values provided at regional and national level are a proxy for the ones of the municipality and its neighbourhoods. However, this is likely to affect the quality of the model outcomes.

With respect to data on consumption of resources (materials, waste, water, and energy) and water quality, data was not available at municipal level. Szeged has provided data on resources at regional level. Similarly, Alcala de Henares has provided data on water quality for 2017 obtained from the monitoring of the effluents from EDARs (Spanish wastewater treatment plants) associated with the municipality. This lack of data creates additional constraints for the urban system module, which in the case of the NBS module might instead be overcome based on assumptions.

For weather and air pollutants data, historic time series information is available at municipal level, monitored on a daily and hourly basis. However, in the case of Alcala de Henares there is no data monitored for $PM_{2.5}$. In this sense, changes for this pollutant might not be possible to be modelled.

Finally, no continuous monitoring environmental data was available in the case of G4C and P&C and related NBS case studies, which would constraint the calibration of the NBS module. In addition, only Milano Metropolitan Area was able to provide environmental and economic data about its case studies. As introduced before, the data from G4C and P&C, in most cases measured outputs, could inform the development of the model. For example output data from green roofs provided by G4C could be compared to outputs calculated by the model for similar conditions, helping to assess the reliability of the results. As another example, some data (e.g. average enhancement of insulation performance) – together with additional information extracted from the literature – could be used to define the value of some input variables of the model.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

8. Evaluation based on expert knowledge

On mid-march 2018, a workshop was held in Luxembourg for another research project of LIST (ESTIMUM: https://www.list.lu/en/research/project/estimum/) where the modelling and assessment of urban ecosystem services is also a subject of investigation. Since some common aspects are shared by WP4 in Nature4Cities and ESTIMUM, the feedback from the advisory board of ESTIMUM (composed by both scientific experts and public authority officers) was informative for an initial evaluation of the following aspects of the system dynamics modelling framework: priority urban ES, urban system boundaries, temporal levels, and definition of urban typologies.

8.1. Priority urban ESs

Despite there was non-unanimous agreement between the members of the advisory board several common ES were considered with a highest or medium priority by most of them. These results were compared with our previous prioritisation (Table 27).

This exercise resulted informative since in many cases the prioritisation already developed has a good correspondence with the one done initially in the Task 4.1 based on the literature review and on the information inferred from the questionnaires about the sites of interventions and the UCS of interest filled-out by pilot cities municipalities (WP7). The major difference was related to the priority given to the regulation of chemical condition of atmosphere and materials from cultivated plants for direct use or processing. Interestingly, the priority given to cultivated plants grown as a source of energy, bio-remediation by plants, and noise attenuations remained also low or medium-low compared to other ES.

The advisory board was also asked to mark additional ES classes (CICES v5.1) not present among the selected ones (Table 27), but worth to be considered. As a result, there were no additional urban ES proposed by the members.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table 27. Comparison of the priority ES to be investigated.

UC	USC	ES (Class)	Advisory board priority	Task 4.1 Modelling priority
Climate issues	Climate mitigation/ Climate adaptation	Regulation of chemical composition of atmosphere	Medium-Low	High
		Regulation of temperature and humidity	High-Medium	High
Water management	Storm water management	Hydrological cycle and water flow regulation	High-Medium	High
Physical Health	Air Quality	Filtration, sequestration, storage, accumulation by plants	High-Medium	High
	Water Quality	Regulation of the chemical condition of freshwaters by living processes	Medium-Low	Medium
		Bio-remediation by plants	Medium-Low	Low
	Soil Quality	Filtration, sequestration, storage, accumulation by plants	Medium-Low	Medium
	Enhanced opportunities for outdoor activities	Characteristic of living systems enabling activities promoting health or enjoyment	High-Medium	High
Mental Health	Psychological relaxation	Characteristic of living systems enabling aesthetic experiences	High-Medium	Medium
	Stress relief	Noise attenuation	Medium-Low	Low
Biodiversity	Loss of Habitat Loss of Ecological Connectivity	Maintaining nursery populations and habitats	High-Medium	Medium
Resource efficiency	Energy Performance	Regulation of temperature and humidity	High-Medium	High
	Energy Production	Cultivated plants grown as source of energy	Low	Low
	Material Security	Materials from cultivated plants for direct use or processing	Medium-Low	Medium
	Food Security	Cultivated plants grown for nutritional purposes	High-Medium	High

8.2. Urban system boundaries

The use of two spatial system boundaries was almost agreed by all members of the advisory board as adequate. However, the use of dynamic spatial system boundaries was not considered adequate by the advisory board due to its complexity and due to a disagreement on what informs the limits of an urban system. It was suggested to work with fixed system boundaries.

For the principal system boundary, it was also suggested to start using the administrative limits as the spatial system boundary, instead of using indicators to define them. For medium and small urban areas the municipal administrative limits were proposed as adequate. While for large urban areas the limits of the defined urban metropolitan areas were recommended.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Similarly, for the secondary system boundary, it was proposed to use the valuation scope of ES classes. In this sense, biophysical limits related to the supply of ES overpassing urban areas were proposed. For example, in the case of hydrological cycle and water regulation the limits of the subcatchments surrounding the urban areas should be used, which could be also adequate for other ES (e.g. regulation of the chemical condition of freshwaters by living processes). The final secondary system boundary should be obtained by overlapping the different ES limits. However, for certain ES the spatial limits cannot be defined clearly, such as in the case of chemical condition of atmosphere. Therefore, further research might be required and some indicators previously selected might still be relevant for the definition of biophysical limits. For example, the indicator *land use information entropy model* could define which cultivated areas (due to their more fragmented pattern typical of periurban area) are in the area influenced by urban dynamics, being part of the urban system. As another example, density of road and rail network could be used to define noise attenuation boundaries, since this is a major source of noise in urban areas.

8.3. Temporal levels

Workshop participants discussed the length of the maximum temporal horizon to be simulated (already introduced in section 5.3) and agreed on a maximum of 10-15 years as the adequate length for obtaining results that are reliable enough for quantitative purposes. In this sense, it was proposed that at least 15 years of historic data were required to calibrate the urban system module. It was suggested that the end of the modelling should match 2030, to be aligned with the current deadline for the sustainable development goals. This can allow to understand the contribution of NBS to the expected sustainability objectives proposed for urban areas. A simulation horizon beyond 15 years was also suggested as a rationale to discuss long term trends of different scenarios. These outputs will only be adequate as qualitative information due to the high level of uncertainty underpinning such simulation exercise.

8.4. Urban typologies

Several members of the advisory board considered relevant identifying different urban typologies for understanding comparable urban regions, cities and neighbourhoods. Moreover, it was also agreed that urban typologies could be relevant to understand the adaptability of NBS on different urban systems. As initially proposed in Task 4.1, it was indicated that urban typologies need to relate to parameters of ES (their processes and structures) and UM (resource consumption and demand). These confirmed the adequacy of the previous works, even if further refinement and research might be required.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

9. Conclusions and outlook

Deliverable 4.1 has defined a system dynamic modelling framework for assessing ecosystem services (ES) supply by urban NBS to understand their effectiveness for addressing main challenges of urban systems.

As part of the framework, relationships between urban challenges (UC), ES, and NBS have been established supported by a literature review. Specifically, this review firstly allowed the identification of UC directly related to NBS based on the works of D2.1; secondly, supported the selection of an ES classification (CICES) and ES classes that could address the UC selected and for which enough information already exists; thirdly informed the adaptation of the NBS typology of D1.1 for modelling purposes; and finally assisted the selection of NBS types able to provide the ES classes selected and relevant for the integrated assessment (WP7) of the case studies proposed by the pilot cities.

Making use of the ES cascade model, the main processes and biophysical and social factors influencing the supply of ES have been defined supported by scientific literature and review of existing system dynamics models for assessing ES. This helped to define parameter proxies for the ES classes selected, but also to define the main compartments, submodels, relations, and assumptions of a system dynamics NBS module based on Multiscale Integrated Model of Ecosystem Services (MIMES).

Additionally, urban systems and their main subsets were defined under an integrated urban ecology (UE) and urban metabolism (UM) perspective. This was the basis for the identification of main urban subsystems and their flows as well as indicators for defining a double system boundary and urban typologies (urban region, metropolis/city, and neighborhood). The double urban system boundary (principal and secondary) was defined making use of a literature review and supported by expert knowledge, which takes into account the dependency of the urban systems on their surrounding environment and the potential burden shifting. As a result, and similarly to the NBS module, the main compartments, submodels, relations, and assumptions of an urban system model based on MIMES that assesses the effects of ES on the UM were also defined.

Finally, a revision of this preliminary work was done by comparing the expected data requirements of the models with the availability of data from municipalities and public sources, on the one hand,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

and taking into account expert knowledge feedback, on the other hand. The former permitted to understand that there is a lack of data available for the urban systems of the pilot cities and their sites of intervention, which could jeopardise the development of the models, their testing, and calibration. The latter aid in the refinement of the urban system boundaries, tested the interest of the definition of urban typologies at different spatial levels and allowed the definition of a modelling temporal scope for the models. This revision will permit the refinement and further enhancement of the models guiding the future research.

Future work will require the development of a strategy to minimise the impact that the lack of data could have in the development of the model. As an alternative, existing models identified in this deliverable could be applied to the case studies and their outputs along time could be used for calibrating and testing the model. In addition, new data collected from the works of partners in other tasks of Nature4Cities (e.g. task 1.7) might also contribute to minimise the impact of data scarcity.

Additionally, the modelling framework, the selected ES classes and their parameter proxies provide a basis for the current development of an economic assessment scale (Task 4.2) to monetarise the values of ES provided by NBS comparing it with the costs along their life cycle. The calculation of the costs will be based on real case studies and collection of data from the literature. In this sense, as part of the collection of environmental data, G4C and P&C provided economic data for the case studies presented in the present deliverable as part of their specific works in Task 4.2.

In the near future, the team will make greater effort and put more guidance to incentive partners' cities on data collection. Since the NBS modelling and assessment framework will act as a support tool to inform them on how to assess and evaluate their NBS, municipalities shall in turn put more determination on data collection, since data are often not available. Should their scope be to aligning with some smart cities projects (e.g. the lighthouse and follower cities), the information provided in this report could allow cities better investigate any opportunity to enhance measurement and data collection strategies, such as by using sensors and easy data collection solutions. Such opportunities might be additionally discussed within the Urban Agenda partnership (https://ec.europa.eu/futurium/en/urban-agenda) as a key and critical finding, important for the future roll out market uptake of NBS.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

10. References

Adhikari, A. R. *et al.* (2011) 'Removal of nutrients and metals by constructed and naturally created wetlands in the Las Vegas Valley, Nevada', *Environmental Monitoring and Assessment*, 180(1–4), pp. 97–113. doi: 10.1007/s10661-010-1775-y.

Aguirre-Gutierrez, J. *et al.* (2017) 'Butterflies show different functional and species diversity in relationship to vegetation structure and land use', *GLOBAL ECOLOGY AND BIOGEOGRAPHY*, 26(10), pp. 1126–1137. doi: 10.1111/geb.12622.

Alberti, M. (2005) 'The Effects of Urban Patterns on Ecosystem Function', *International Regional Science Review*, 28(2), pp. 168–192. doi: 10.1177/0160017605275160.

Alberti, M. (2008) *Advances in Urban Ecology*.

Alberti, M. (2016) *Cities that think like planets: complexity, resilience, and innovation in hybrid ecosystems*. University of Washington Press.

van Andel, J. and Aronson, J. (2012) *Restoration ecology: the new frontier*. John Wiley & Sons.

Andersson-Sköld, Y. *et al.* (2018) 'A framework for assessing urban greenery's effects and valuing its ecosystem services', *Journal of Environmental Management*, 205, pp. 274–285. doi: 10.1016/j.jenvman.2017.09.071.

Andersson, K., Dickin, S. and Rosemarin, A. (2016) 'Towards ``Sustainable{''} Sanitation: Challenges and Opportunities in Urban Areas', *SUSTAINABILITY*, 8(12). doi: 10.3390/su8121289.

Angel, S. *et al.* (2011) 'The dimensions of global urban expansion: Estimates and projections for all countries, 2000-2050', *Progress in Planning*, 75(2), pp. 53–107. doi: 10.1016/j.progress.2011.04.001.

Arnaiz-Schmitz, C. *et al.* (2018) 'Identifying socio-ecological networks in rural-urban gradients: Diagnosis of a changing cultural landscape', *Science of the Total Environment*. Elsevier B.V., 612, pp. 625–635. doi: 10.1016/j.scitotenv.2017.08.215.

Babí Almenar, J. (no date) *Nature based solutions for sustainable and resilient urban development. expected submission:* Luxembourg Institute of Science and Technology (Luxembourg), University of Bordeaux (France), University of Trento (Italy.

Bai, X. *et al.* (2010) 'Urban policy and governance in a global environment: complex systems, scale mismatches and public participation', *Current Opinion in Environmental Sustainability*, 2(3), pp. 129–135. doi: 10.1016/j.cosust.2010.05.008.

Baro, F. *et al.* (2014) 'Contribution of ecosystem services to air quality and climate change mitigation policies: the case of urban forests in Barcelona, Spain', *Ambio*, 43(4), pp. 466–479. doi: 10.1007/s13280-014-0507-x.

Basso, B., Cammarano, D. and Carfagna, E. (2013) 'Review of Crop Yield Forecasting Methods and Early Warning Systems', *The First Meeting of the Scientific Advisory Committee of the Global Strategy to Improve Agricultural and Rural Statistics*, pp. 1–56. doi: 10.1017/CBO9781107415324.004.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Bauduceau, N. *et al.* (2015) 'Towards an EU Research and Innovation Policy Agenda for Nature-based Solutions & Re-naturing Cities: Final Report of the Horizon 2020 Expert Group on'Nature-based Solutions and Re-naturing Cities''. Publications Office of the European Union.

Bengs, C. and Schmidt-Thomé, K. (2005) *Urban-rural relations in Europe: ESPON 1.1.2*.

Benza, M. *et al.* (2016) 'A pattern-based definition of urban context using remote sensing and GIS', *Remote Sensing of Environment*. Elsevier Inc., 183, pp. 250–264. doi: 10.1016/j.rse.2016.06.011.

Berland, A. *et al.* (2017) 'The role of trees in urban stormwater management', *Landscape and Urban Planning*, 162, pp. 167–177. doi: 10.1016/j.landurbplan.2017.02.017.

Biester, H. and Zimmer, H. (1998) 'Solubility and changes of mercury binding forms in contaminated soils after immobilization treatment', *Environmental Science and Technology*, 32(18), pp. 2755–2762. doi: 10.1021/es9709379.

Borgström, S. T. *et al.* (2006) 'Scale mismatches in management of urban landscapes', *Ecology and Society*, 11(2). doi: 10.1097/MCC.0b013e32807f2aa5.

Bos, U. *et al.* (2016) 'LANCA ® Characterization Factors for Life Cycle Impact Assessment', p. 166.

Bottalico, F. *et al.* (2017) 'A spatially-explicit method to assess the dry deposition of air pollution by urban forests in the city of Florence, Italy', *URBAN FORESTRY & URBAN GREENING*, 27, pp. 221–234. doi: 10.1016/j.ufug.2017.08.013.

Boumans, R. *et al.* (2015) 'The Multiscale Integrated Model of Ecosystem Services (MIMES): Simulating the interactions of coupled human and natural systems', *Ecosystem Services*, 12, pp. 30–41. doi: 10.1016/j.ecoser.2015.01.004.

Boumans, R. J. M. *et al.* (2014) 'Developing a model for effects of climate change on human health and health–environment interactions: Heat stress in Austin, Texas', *Urban Climate*, 8, pp. 78–99. doi: 10.1016/j.uclim.2014.03.001.

Brill, G., Anderson, P. and O'Farrell, P. (2017) 'Methodological and empirical considerations when assessing freshwater ecosystem service provision in a developing city context: Making the best of what we have', *ECOLOGICAL INDICATORS*, 76, pp. 256–274. doi: 10.1016/j.ecolind.2017.01.006.

Brink, E. *et al.* (2016) 'Cascades of green: A review of ecosystem-based adaptation in urban areas', *Global Environmental Change*. Elsevier Ltd, 36, pp. 111–123. doi: 10.1016/j.gloenvcha.2015.11.003.

Brunet-Vinck, V. (2004) *Méthode pour les atlas de paysages: enseignements méthodologiques de 10 ans de travaux*. Ministère de l'écologie et du développement durable, Direction de la nature et des paysages, Sous direction des sites et paysages, Bureau des paysages.

Buck-Sorlin, G. (2013) 'Process-based Model', in Dubitzky, W. et al. (eds) *Encyclopedia of Systems Biology*. New York, NY: Springer New York, p. 1755. doi: 10.1007/978-1-4419-9863-7_1545.

Budiyantini, Y. and Pratiwi, V. (2016) 'Peri-urban typology of Bandung Metropolitan Area', *Procedia - Social and Behavioral Sciences*. Elsevier B.V., 227(November 2015), pp. 833–837. doi: 10.1016/j.sbspro.2016.06.152.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Cabral, I. *et al.* (2017) ‘Ecosystem services of allotment and community gardens: A Leipzig, Germany case study’, *Urban Forestry and Urban Greening*. Elsevier GmbH., 23, pp. 44–53. doi: 10.1016/j.ufug.2017.02.008.

Cabral, P. *et al.* (2016) ‘Assessing the impact of land-cover changes on ecosystem services: A first step toward integrative planning in Bordeaux, France’, *ECOSYSTEM SERVICES*, 22(B), pp. 318–327. doi: 10.1016/j.ecoser.2016.08.005.

Calderon-Contreras, R. and Quiroz-Rosas, L. E. (2017) ‘Analysing scale, quality and diversity of green infrastructure and the provision of Urban Ecosystem Services: A case from Mexico City’, *ECOSYSTEM SERVICES*, 23, pp. 127–137. doi: 10.1016/j.ecoser.2016.12.004.

Cameron, R. W. F., Taylor, J. and Emmett, M. (2015) ‘A Hedera green façade – Energy performance and saving under different maritime-temperate, winter weather conditions’, *Building and Environment*, 92, pp. 111–121. doi: 10.1016/j.buildenv.2015.04.011.

Camps-calvet, M. *et al.* (2016) ‘Ecosystem services provided by urban gardens in Barcelona , Spain : Insights for policy and planning’, *Environmental Science and Policy*. Elsevier Ltd, 62, pp. 14–23. doi: 10.1016/j.envsci.2016.01.007.

Caraco, N., Cole, J. J. and Likens, G. E. (1991) ‘A Cross-System Study of Phosphorus Release from Lake Sediments BT - Comparative Analyses of Ecosystems: Patterns, Mechanisms, and Theories’, in Cole, J., Lovett, G., and Findlay, S. (eds). New York, NY: Springer New York, pp. 241–258. doi: 10.1007/978-1-4612-3122-6_12.

Cárdenas Rodríguez, M., Dupont-Courtade, L. and Oueslati, W. (2016) ‘Air pollution and urban structure linkages: Evidence from European cities’, *Renewable and Sustainable Energy Reviews*. Elsevier, 53, pp. 1–9. doi: 10.1016/j.rser.2015.07.190.

Cash, D. W. *et al.* (2003) ‘Knowledge systems for sustainable development.’, *Proceedings of the National Academy of Sciences of the United States of America*, 100(14), pp. 8086–8091. doi: 10.1073/pnas.1231332100.

Chavan, P. V. and Dennett, K. E. (2008) ‘Wetland simulation model for nitrogen, phosphorus, and sediments retention in constructed wetlands’, *Water, Air, and Soil Pollution*, 187(1–4), pp. 109–118. doi: 10.1007/s11270-007-9501-2.

Chen, W. Y. and Jim, C. Y. (2011) ‘Resident valuation and expectation of the urban greening project in Zhuhai, China’, *Journal of Environmental Planning and Management*, 54(7), pp. 851–869. doi: 10.1080/09640568.2010.537552.

Chen, Y. *et al.* (2014) ‘Modeling urban land-use dynamics in a fast developing city using the modified logistic cellular automaton with a patch-based simulation strategy’, *International Journal of Geographical Information Science*. Taylor & Francis, 28(2), pp. 234–255. doi: 10.1080/13658816.2013.831868.

City Protocol (2015) *City Anatomy: A framework to support City Governance, Evaluation and Transformation*.

Cochran, F. V and Brunsell, N. A. (2017) ‘Biophysical metrics for detecting more sustainable urban forms at the global scale’, *International Journal of Sustainable Built Environment*. The Gulf Organisation for Research and Development, 6(2), pp. 372–388. doi: 10.1016/j.ijsbe.2017.05.004.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

Coelho, D. and Ruth, M. (2006) ‘Seeking a unified urban systems theory’, 1, pp. 179–188. doi: 10.2495/sc060171.

Cohen-Shacham, E. *et al.* (2016) ‘Nature-based Solutions to address global societal challenges’, *IUCN, Gland, Switzerland. doi*, 10.

Coleman, K. and Jenkinson, D. S. (2014) ‘RothC - A Model for the Turnover of Carbon in Soil: Model description and Users guide (DOS version; updated June 2014)’, *Rothamsted Research*, Rothamsted(June), p. 26pp. doi: 10.1007/978-3-642-61094-3_17.

Collins, R., Schaafsma, M. and Hudson, M. D. (2017) ‘The value of green walls to urban biodiversity’, *Land Use Policy*, 64, pp. 114–123. doi: 10.1016/j.landusepol.2017.02.025.

Coma, J. *et al.* (2017) ‘Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades’, *Building and Environment*, 111, pp. 228–237. doi: 10.1016/j.buildenv.2016.11.014.

Connors, J. P., Galletti, C. S. and Chow, W. T. L. (2013) ‘Landscape configuration and urban heat island effects: Assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona’, *Landscape Ecology*, 28(2), pp. 271–283. doi: 10.1007/s10980-012-9833-1.

Cornea, N. L., Véron, R. and Zimmer, A. (2017) ‘Everyday governance and urban environments: Towards a more interdisciplinary urban political ecology’, *Geography Compass*, 11(4), pp. 1–12. doi: 10.1111/gec3.12310.

Corona, P. *et al.* (2011) ‘Contribution of large-scale forest inventories to biodiversity assessment and monitoring’, *Forest Ecology and Management*. Elsevier B.V., 262(11), pp. 2061–2069. doi: 10.1016/j.foreco.2011.08.044.

da Costa, E. M., Fumega, J. and Louro, A. I. (2013) ‘Academic papers: Defining sustainable communities: The development of a toolkit for urban policy’, *Journal of Urban Regeneration and Renewal*, 6(3), pp. 278–292. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84876096622&partnerID=40&md5=9d570106f181986a6909b67b19c6da74.

Croci, S. *et al.* (2008) ‘Small urban woodlands as biodiversity conservation hot-spot: A multi-taxon approach’, *Landscape Ecology*, 23(10), pp. 1171–1186. doi: 10.1007/s10980-008-9257-0.

Cuce, E. (2017) ‘Thermal regulation impact of green walls: An experimental and numerical investigation’, *Applied Energy*. Elsevier Ltd, 194, pp. 247–254. doi: 10.1016/j.apenergy.2016.09.079.

Cumming, G. S., Cumming, D. H. M. and Redman, C. L. (2006) ‘Scale Mismatches in Social-Ecological Systems : Causes , Consequences , and Solutions’, 11(1). doi: 10.5751/ES-01569-110114.

Davies, H. J. *et al.* (2017) ‘Challenges for tree officers to enhance the provision of regulating ecosystem services from urban forests’, *Environ Res*, 156, pp. 97–107. doi: 10.1016/j.envres.2017.03.020.

Degenhardt, B. *et al.* (2011) ‘Influences of personal, social, and environmental factors on workday use frequency of the nearby outdoor recreation areas by working people’, *Leisure Sciences*, 33(5), pp. 420–440. doi: 10.1080/01490400.2011.606780.

Dennis, M. and James, P. (2016) ‘User participation in urban green commons: Exploring the links

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

between access, voluntarism, biodiversity and well being', *URBAN FORESTRY & URBAN GREENING*, 15, pp. 22–31. doi: 10.1016/j.ufug.2015.11.009.

Dennis, M. and James, P. (2017) 'Ecosystem services of collectively managed urban gardens: Exploring factors affecting synergies and trade-offs at the site level', *ECOSYSTEM SERVICES*, 26(A), pp. 17–26. doi: 10.1016/j.ecoser.2017.05.009.

Derkzen, M. L., van Teeffelen, A. J. A. and Verburg, P. H. (2015) 'REVIEW Quantifying urban ecosystem services based on high-resolution data of urban green space: an assessment for Rotterdam, the Netherlands', *JOURNAL OF APPLIED ECOLOGY*, 52(4), pp. 1020–1032. doi: 10.1111/1365-2664.12469.

Deslauriers, M. R. *et al.* (2016) 'Implementing the connectivity of natural areas in cities as an indicator in the City Biodiversity Index (CBI)', *Ecological Indicators*. Elsevier Ltd, 2011, pp. 1–15. doi: 10.1016/j.ecolind.2017.02.028.

Dijlkstra, L. and Poelman, H. (2012) *Cities in Europe. The new OCED-EC Definition*.

Dou, Y. *et al.* (2017) 'Assessing the importance of cultural ecosystem services in urban areas of Beijing municipality', *ECOSYSTEM SERVICES*, 24, pp. 79–90. doi: 10.1016/j.ecoser.2017.02.011.

Du, Y. *et al.* (2018) 'Plant diversity decreases net global warming potential integrating multiple functions in microcosms of constructed wetlands', *Journal of Cleaner Production*. Elsevier B.V. doi: 10.1016/j.jclepro.2018.02.273.

Dumas, E., Jappiot, M. and Tatoni, T. (2008) 'Mediterranean urban-forest interface classification (MUFIC): A quantitative method combining SPOT5 imagery and landscape ecology indices', *Landscape and Urban Planning*, 84(3–4), pp. 183–190. doi: 10.1016/j.landurbplan.2007.12.002.

Dumenu, W. K. (2013) 'What are we missing? Economic value of an urban forest in Ghana', *Ecosystem Services*. Elsevier, 5, pp. 137–142. doi: 10.1016/j.ecoser.2013.07.001.

Dusza, Y. *et al.* (2017) 'Multifunctionality is affected by interactions between green roof plant species, substrate depth, and substrate type', *ECOLOGY AND EVOLUTION*, 7(7), pp. 2357–2369. doi: 10.1002/ece3.2691.

Eggermont, H. *et al.* (2015) 'Nature-based Solutions: New Influence for Environmental Management and Research in Europe', *GAIA - Ecological Perspectives for Science and Society*, 24(4), pp. 243–248. doi: 10.14512/gaia.24.4.9.

Elmqvist, T. *et al.* (2015) 'Benefits of restoring ecosystem services in urban areas', *Current Opinion in Environmental Sustainability*, 14, pp. 101–108. doi: 10.1016/j.cosust.2015.05.001.

Elsawah, S. *et al.* (2017) 'An overview of the system dynamics process for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies', *Environmental Modelling & Software*, 93, pp. 127–145. doi: 10.1016/j.envsoft.2017.03.001.

Ernstson, H., Barthel, S. and Andersson, E. (2010) 'Scale-Crossing Brokers and Network Governance of Urban Ecosystem Services : The Case of Stockholm', 15(4).

Ertani, A. *et al.* (2017) 'Chromium in Agricultural Soils and Crops: A Review', *Water, Air, and Soil Pollution*. Water, Air, & Soil Pollution, 228(5). doi: 10.1007/s11270-017-3356-y.

Fan, P. *et al.* (2017) 'Nature-based solutions for urban landscapes under post-industrialization

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

and globalization: Barcelona versus Shanghai', *Environmental Research*. Elsevier Inc., 156(March), pp. 272–283. doi: 10.1016/j.envres.2017.03.043.

Fang, C. F. and Ling, D. L. (2003) 'Guidance for noise reduction provided by tree belts', *Landscape and Urban Planning*, 71(1), pp. 29–34. doi: 10.1016/j.landurbplan.2004.01.005.

Farina, R., Coleman, K. and Whitmore, A. P. (2013) 'Modification of the RothC model for simulations of soil organic C dynamics in dryland regions', *Geoderma*. Elsevier B.V., 200–201, pp. 18–30. doi: 10.1016/j.geoderma.2013.01.021.

Feng, Y. and Burian, S. (2016) 'Improving Evapotranspiration Mechanisms in the US Environmental Protection Agency's Storm Water Management Model', *JOURNAL OF HYDROLOGIC ENGINEERING*, 21(10). doi: 10.1061/(ASCE)HE.1943-5584.0001419.

Feng, Z. *et al.* (2015) 'Environmental Policy Simulation and Assessment under Rapid Urbanization: Case Study of Essential Area Policy in Shenzhen, China', *JOURNAL OF URBAN PLANNING AND DEVELOPMENT*, 141(4). doi: 10.1061/(ASCE)UP.1943-5444.0000259.

Ferrão, P. and Fernández, J. E. (2013) *Sustainable urban metabolism*. MIT press.

Ferrarini, A. *et al.* (2017) 'Multiple ecosystem services provision and biomass logistics management in bioenergy buffers: A state-of-the-art review', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 73(January 2016), pp. 277–290. doi: 10.1016/j.rser.2017.01.052.

Flexas, J. *et al.* (2008) 'Mesophyll conductance to CO2: Current knowledge and future prospects', *Plant, Cell and Environment*, 31(5), pp. 602–621. doi: 10.1111/j.1365-3040.2007.01757.x.

Forman, R. T. T. (2014) *Urban Ecology: Science of Cities*. Cambridge University Press. Available at: https://books.google.it/books?id=gQSuAgAAQBAJ.

Francis, L. F. M. and Jensen, M. B. (2017) 'Benefits of green roofs: A systematic review of the evidence for three ecosystem services', *URBAN FORESTRY & URBAN GREENING*, 28, pp. 167–176. doi: 10.1016/j.ufug.2017.10.015.

Francis, L. F. M. and Jensen, M. B. (2017) 'Benefits of green roofs: A systematic review of the evidence for three ecosystem services', *Urban Forestry and Urban Greening*, 28(April), pp. 167–176. doi: 10.1016/j.ufug.2017.10.015.

Fry, G. *et al.* (2009) 'The ecology of visual landscapes: Exploring the conceptual common ground of visual and ecological landscape indicators', *Ecological Indicators*, 9(5), pp. 933–947. doi: 10.1016/j.ecolind.2008.11.008.

Fusaro, L. *et al.* (2015) 'Researches in Castelporziano test site: ecophysiological studies on Mediterranean vegetation in a changing environment', *RENDICONTI LINCEI-SCIENZE FISICHE E NATURALI*, 26(3), pp. S473–S481. doi: 10.1007/s12210-014-0374-1.

Fusaro, L. *et al.* (2017) 'Modeling ozone uptake by urban and peri-urban forest : a case study in the Metropolitan City of Rome'. Environmental Science and Pollution Research.

Fusco, G. (2016) 'Beyond the built-up form/mobility relationship: Spatial affordance and lifestyles', *Computers, Environment and Urban Systems*, 60, pp. 50–66. doi: 10.1016/j.compenvurbsys.2016.07.011.

Gao, J. *et al.* (2015) 'Application of BMP to urban runoff control using SUSTAIN model: Case study in an industrial area', *ECOLOGICAL MODELLING*, 318(SI), pp. 177–183. doi:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

10.1016/j.ecolmodel.2015.06.018.

Garcia, X. *et al.* (2016) 'Is river rehabilitation economically viable in water-scarce basins?', *ENVIRONMENTAL SCIENCE & POLICY*, 61, pp. 154–164. doi: 10.1016/j.envsci.2016.04.011.

Gawronski, S. W., Greger, M. and Gawronska, H. (2011) 'Detoxification of Heavy Metals', 30, pp. 91–109. doi: 10.1007/978-3-642-21408-0.

Ghosh, M. and Singh, S. P. (2005) 'Asian Journal on Energy and Environment A Review on Phytoremediation of Heavy Metals and Utilization of It's by Products', *As. J. Energy Env*, 6(604), pp. 214–231. doi: 10.1007/s10681-014-1088-2.

Gil, J. (2016) 'Urban modality: Modelling and evaluating the sustainable mobility of urban areas in the city-region', *A+BE Architecture and the Built Environment*, pp. 1–436. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84988649140&partnerID=40&md5=8034fbaf35f17b3d878855c1fc2f8d7d.

Giles-Corti, B. *et al.* (2005) 'Increasing walking: How important is distance to, attractiveness, and size of public open space?', *American Journal of Preventive Medicine*, 28(2 SUPPL. 2), pp. 169–176. doi: 10.1016/j.amepre.2004.10.018.

Godefroid, S. and Koedam, N. (2007) 'Urban plant species patterns are highly driven by density and function of built-up areas', *Landscape Ecology*, 22(8), pp. 1227–1239. doi: 10.1007/s10980-007-9102-x.

Golinkoff, J. (2010) 'Biome BGC version 4.2: Theoretical framework of Biome-BGC', *Respiration*, (Thornton 1998), pp. 1–71.

Gonçalves, J. *et al.* (2017) 'Differentiating peri-urban areas: A transdisciplinary approach towards a typology', *Land Use Policy*, 63, pp. 331–341. doi: 10.1016/j.landusepol.2017.01.041.

Grafius, D. R. *et al.* (2016) 'The impact of land use/land cover scale on modelling urban ecosystem services', *LANDSCAPE ECOLOGY*, 31(7), pp. 1509–1522. doi: 10.1007/s10980-015-0337-7.

Grimm, N. B. *et al.* (2008) 'The changing landscape: Ecosystem responses to urbanization and pollution across climatic and societal gradients', *Frontiers in Ecology and the Environment*, 6(5), pp. 264–272. doi: 10.1890/070147.

Grunwald, L., Heusinger, J. and Weber, S. (2017) 'A GIS-based mapping methodology of urban green roof ecosystem services applied to a Central European city', *Urban Forestry and Urban Greening*. Elsevier GmbH., 22, pp. 54–63. doi: 10.1016/j.ufug.2017.01.001.

Gurrutxaga, M., Lozano, P. J. and del Gabriel, B. (2010) 'Assessing highway permeability for the restoration of landscape connectivity between protected areas in the Basque country, Northern Spain', *Landscape Research*, 35(5), pp. 529–550. doi: 10.1080/01426397.2010.504915.

Haase, D. *et al.* (2012a) 'Synergies, trade-offs, and losses of ecosystem services in urban regions: An integrated multiscale framework applied to the leipzig-halle region, Germany', *Ecology and Society*, 17(3). doi: 10.5751/ES-04853-170322.

Haase, D. *et al.* (2012b) 'Synergies, Trade-offs, and Losses of Ecosystem Services in Urban Regions: an Integrated Multiscale Framework Applied to the Leipzig-Halle Region, Germany', *Ecology and Society*, 17(3). doi: 10.5751/es-04853-170322.

Haase, D., Frantzeskaki, N. and Elmqvist, T. (2014) 'Ecosystem services in urban landscapes:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

practical applications and governance implications', *Ambio*, 43(4), pp. 407–412. doi: 10.1007/s13280-014-0503-1.

Haines-Young, R. and Potschin, M. (2010) 'The links between biodiversity, ecosystem services and human well-being', *Ecosystem Ecology: a new synthesis*. Cambridge University Press Cambridge, pp. 110–139.

Haines-Young, R. and Potschin, M. (2014) 'Typology / Classification of Ecosystem Services', *OpenNESS Ecosystem Services Reference Book*, (2), pp. 1–8. Available at: http://www.xn--opennessproject-7s9h.eu/library/reference?book.

Haines-Young, R. and Potschin, M. (2017) '2.4. Categorisation systems: The classification challenge', *Mapping Ecosystem Services*. Pensoft Publishers, Sofia, p. 42.

Haines-Young, R. and Potschin, M. B. (2018) *Ecosystem, Common International Classification of Structu, Services (CICES) V5.1 and Guidance on the Application of the Revised Structure*. Available at: www.cices.eu.

Hamstead, Z. A. *et al.* (2016) 'Classification of the heterogeneous structure of urban landscapes (STURLA) as an indicator of landscape function applied to surface temperature in New York City', *Ecological Indicators*. Elsevier Ltd, 70, pp. 574–585. doi: 10.1016/j.ecolind.2015.10.014.

Heasman, F. *et al.* (2011) 'Environmental liability transfer in Europe: Divestment of contaminated land for brownfield regeneration', *NICOLE Brownfield Working Group*, 57.

Hermosilla, T. *et al.* (2014) 'Using street based metrics to characterize urban typologies', *Computers, Environment and Urban Systems*, 44, pp. 68–79. doi: 10.1016/j.compenvurbsys.2013.12.002.

Herold, M., Couclelis, H. and Clarke, K. C. (2005) 'The role of spatial metrics in the analysis and modeling of urban land use change', 29, pp. 369–399. doi: 10.1016/j.compenvurbsys.2003.12.001.

Herold, M., Liu, X. and Clark, K. C. (2003) 'Spatial Metrics and Image Texture for Mapping Urban Land Use', *Photogrammetric Engineering and Remote Sensing*, 69(9), pp. 991–1001. doi: 10.14358/PERS.69.9.991.

Herold, M., Scepan, J. and Clarke, K. C. (2002a) 'The use of remote sensing and landscape metrics to describe structures and changes in urban land uses', 34, pp. 1443–1458. doi: 10.1068/a3496.

Herold, M., Scepan, J. and Clarke, K. C. (2002b) 'The use of remote sensing and landscape metrics to describe structures and changes in urban land uses', *Environment and Planning A*, 34(8), pp. 1443–1458. doi: 10.1068/a3496.

Heynen, N., Kaika, M. and Swyngedouw, E. (2006) *In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism*, *Urban Geography*. doi: 10.2747/0272-3638.28.2.206.

Hirabayashi, S. (2013) 'i-Tree Eco Precipitation Interception Model Descriptions', p. 21. Available at: https://www.itreetools.org/eco/resources/iTree_Eco_Precipitation_Interception_Model_Descriptions.pdf.

Hirabayashi, S., Kroll, C. N. and Nowak, D. J. (2015) 'i-Tree Eco Dry Deposition Model Descriptions', p. 35. Available at:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

http://www.itreetools.org/eco/resources/iTree_Eco_Dry_Deposition_Model_Descriptions.pdf.

Hoang, L., van Griensven, A. and Mynett, A. (2017) 'Enhancing the SWAT model for simulating denitrification in riparian zones at the river basin scale', *Environmental Modelling and Software*. Elsevier Ltd, 93, pp. 163–179. doi: 10.1016/j.envsoft.2017.03.017.

Hobbs, R. J., Higgs, E. and Harris, J. A. (2009) 'Novel ecosystems: implications for conservation and restoration', *Trends in Ecology and Evolution*, 24(11), pp. 599–605. doi: 10.1016/j.tree.2009.05.012.

Hoffmann, E. M. *et al.* (2017) 'Construction and Use of a Simple Index of Urbanisation in the Rural-Urban Interface of Bangalore, India', *SUSTAINABILITY*, 9(11). doi: 10.3390/su9112146.

Hogan, D. M., Jordan, T. E. and Walbridge, M. R. (2004) 'Phosphorus retention and soil organic carbon in restored and natural freshwater wetlands', *Wetlands*, 24(3), pp. 573–585. doi: 10.1672/0277-5212(2004)024[0573:PRASOC]2.0.CO;2.

Houben, D., Evrard, L. and Sonnet, P. (2013) 'Mobility, bioavailability and pH-dependent leaching of cadmium, zinc and lead in a contaminated soil amended with biochar', *Chemosphere*. Elsevier Ltd, 92(11), pp. 1450–1457. doi: 10.1016/j.chemosphere.2013.03.055.

Howes, G. (1998) 'Urban problems and policy: An Anglican case study', *SOCIAL COMPASS*, 45(1), pp. 43–55. doi: 10.1177/003776898045001004.

Hoyle, H. *et al.* (2017) '"Not in their front yard" The opportunities and challenges of introducing perennial urban meadows: A local authority stakeholder perspective', *Urban Forestry & Urban Greening*. Elsevier, 25(May), pp. 139–149. doi: 10.1016/j.ufug.2017.05.009.

Hu, S. *et al.* (2015) 'Urban boundary extraction and sprawl analysis using Landsat images: A case study in Wuhan, China', *Habitat International*. Elsevier Ltd, 47, pp. 183–195. doi: 10.1016/j.habitatint.2015.01.017.

Huang, J., Lu, X. X. and Sellers, J. M. (2007) 'A global comparative analysis of urban form: Applying spatial metrics and remote sensing', *Landscape and Urban Planning*, 82(4), pp. 184–197. doi: 10.1016/j.landurbplan.2007.02.010.

Huang, S. L., Lai, H. Y. and Lee, C. L. (2001) 'Energy hierarchy and urban landscape system', *Landscape and Urban Planning*, 53(1–4), pp. 145–161. doi: 10.1016/S0169-2046(00)00150-X.

Hui, S. C. M. (2011) 'Green roof urban farming for buildings in high-density urban cities'.

Hurley, P. T. and Emery, M. R. (2018) 'Locating provisioning ecosystem services in urban forests: Forageable woody species in New York City, USA', *Landscape and Urban Planning*. Elsevier, 170(August 2016), pp. 266–275. doi: 10.1016/j.landurbplan.2017.09.025.

IPCC [Core Writing Team, R. K. P. and L. A. M. (eds.). (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, *IPCC, Geneva, Switzerland,*. doi: 10.1017/CBO9781107415324.

Isbell, F. *et al.* (2011) 'High plant diversity is needed to maintain ecosystem services', *Nature*. Nature Publishing Group, 477(7363), pp. 199–202. doi: 10.1038/nature10282.

Jenkinson, D. S. and Coleman, K. (2008) 'The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover', *European Journal of Soil Science*, 59(2), pp. 400–413. doi:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

10.1111/j.1365-2389.2008.01026.x.

Jerez, M., Quevedo, A. and Moret, A. (2015) 'Simulador de crecimiento y secuestro de carbono para plantaciones de teca en Venezuela : una aplicación en SIMILE Growth and carbon sequestration simulator for teak plantations in Venezuela : An application in SIMILE', *Bosque*, 36(3), pp. 519–530. doi: 10.4067/S0717-92002015000300018.

Jim, C. Y. (2015) 'Assessing climate-adaptation effect of extensive tropical green roofs in cities', *Landscape and Urban Planning*, 138, pp. 54–70. doi: http://dx.doi.org/10.1016/j.landurbplan.2015.02.014.

Jim, C. Y. and Chan, M. W. H. (2016) 'Urban greenspace delivery in Hong Kong: Spatial-institutional limitations and solutions', *URBAN FORESTRY & URBAN GREENING*, 18, pp. 65–85. doi: 10.1016/j.ufug.2016.03.015.

Jim, C. Y. and Chen, W. Y. (2008) 'Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China)', *Journal of Environmental Management*, 88(4), pp. 665–676. doi: 10.1016/j.jenvman.2007.03.035.

Jujnovsky, J. *et al.* (2017) 'Water assessment in a peri-urban watershed in Mexico City: A focus on an ecosystem services approach', *ECOSYSTEM SERVICES*, 24, pp. 91–100. doi: 10.1016/j.ecoser.2017.02.005.

Kabisch, N. *et al.* (2016) 'Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action', *ECOLOGY AND SOCIETY*, 21(2). doi: 10.5751/ES-08373-210239.

Kaczynski, A. T. *et al.* (2009) 'Association of Parkland proximity with neighborhood and park-based physical activity: Variations by gender and age', *Leisure Sciences*, 31(2), pp. 174–191. doi: 10.1080/01490400802686045.

Kaczynski, A. T., Potwarka, L. R. and Saelens P, B. E. (2008) 'Association of park size, distance, and features with physical activity in neighborhood parks', *American Journal of Public Health*, 98(8), pp. 1451–1456. doi: 10.2105/AJPH.2007.129064.

Kain, J.-H. *et al.* (2016) 'Exploring local consequences of two land-use alternatives for the supply of urban ecosystem services in Stockholm year 2050', *ECOLOGICAL INDICATORS*, 70(SI), pp. 615–629. doi: 10.1016/j.ecolind.2016.02.062.

Kain, J. H. *et al.* (2016) 'Exploring local consequences of two land-use alternatives for the supply of urban ecosystem services in Stockholm year 2050', *Ecological Indicators*. Elsevier Ltd, 70, pp. 615–629. doi: 10.1016/j.ecolind.2016.02.062.

Kazezyilmaz-Alhan, C. M., Medina, M. A. and Richardson, C. J. (2007) 'A wetland hydrology and water quality model incorporating surface water/groundwater interactions', *Water Resources Research*, 43(4), pp. 1–16. doi: 10.1029/2006WR005003.

Kelly, R. A. *et al.* (2013) 'Environmental Modelling & Software Selecting among fi ve common modelling approaches for integrated environmental assessment and management q', *Environmental Modelling and Software*, 47, pp. 159–181. doi: 10.1016/j.envsoft.2013.05.005.

Kennedy, C. (2012) 'A Mathematical Description of Urban Metabolism', pp. 275–291. doi: 10.1007/978-1-4614-3188-6_13.

Kennedy, C. *et al.* (2014) 'Developing a multi-layered indicator set for urban metabolism studies

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

in megacities', *Ecological Indicators*. Elsevier Ltd, 47, pp. 7–15. doi: 10.1016/j.ecolind.2014.07.039.

Kennedy, C., Pincetl, S. and Bunje, P. (2011) 'The study of urban metabolism and its applications to urban planning and design', *Environmental Pollution*. Elsevier Ltd, 159(8–9), pp. 1965–1973. doi: 10.1016/j.envpol.2010.10.022.

Kim, G., Miller, P. and Nowak, D. (2016) 'The Value of Green Infrastructure on Vacant and Residential Land in Roanoke, Virginia', *SUSTAINABILITY*, 8(4). doi: 10.3390/su8040296.

Kim, J. and Zhou, X. (2012) 'Landscape structure, zoning ordinance, and topography in hillside residential neighborhoods: A case study of Morgantown, WV', *Landscape and Urban Planning*. Elsevier B.V., 108(1), pp. 28–38. doi: 10.1016/j.landurbplan.2012.07.011.

Kindlmann, P. and Burel, F. (2008) 'Connectivity measures: A review', *Landscape Ecology*, 23(8), pp. 879–890. doi: 10.1007/s10980-008-9245-4.

Korpela, K. M. *et al.* (2010) 'Favorite green, waterside and urban environments, restorative experiences and perceived health in Finland', *Health Promotion International*, 25(2), pp. 200–209. doi: 10.1093/heapro/daq007.

Kremer, P. *et al.* (2016) 'Key insights for the future of urban ecosystem services research', *ECOLOGY AND SOCIETY*, 21(2). doi: 10.5751/ES-08445-210229.

Lachowycz, K. and Jones, A. P. (2011) 'Greenspace and obesity: A systematic review of the evidence', *Obesity Reviews*, 12(501), pp. 183–189. doi: 10.1111/j.1467-789X.2010.00827.x.

Langemeyer, J. *et al.* (2018) 'Stewardship of urban ecosystem services: understanding the value(s) of urban gardens in Barcelona', *Landscape and Urban Planning*. Elsevier, 170(May 2016), pp. 79–89. doi: 10.1016/j.landurbplan.2017.09.013.

LaPoint, S. *et al.* (2015) 'Ecological connectivity research in urban areas', *Functional Ecology*, 29(7), pp. 868–878. doi: 10.1111/1365-2435.12489.

Larondelle, N. *et al.* (2014a) 'Applying a novel urban structure classification to compare the relationships of urban structure and surface temperature in Berlin and New York City', *Applied Geography*, 53, pp. 427–437. doi: 10.1016/j.apgeog.2014.07.004.

Larondelle, N. *et al.* (2014b) 'Applying a novel urban structure classification to compare the relationships of urban structure and surface temperature in Berlin and New York City', *Applied Geography*, 53, pp. 427–437. doi: 10.1016/j.apgeog.2014.07.004.

Lee, E. R., Mostaghimi, S. and Wynn, T. M. (2002) 'a Model To Enhance Wetland Design and Optimize Nonpoint Source Pollution Control', *Journal of the American Water Resources Association*, 38(1), pp. 17–32. doi: 10.1111/j.1752-1688.2002.tb01531.x.

Li, H., Chen, W. and He, W. (2015) 'Planning of green space ecological network in urban areas: An example of Nanchang, China', *International Journal of Environmental Research and Public Health*, 12(10), pp. 12889–12904. doi: 10.3390/ijerph121012889.

Lifset, R. and Graedel, T. E. (2002) 'Industrial ecology: goals and definitions', *A handbook of industrial ecology*, pp. 3–15.

Limmer, M. and Burken, J. (2016) 'Phytovolatilization of Organic Contaminants', *Environmental Science and Technology*, 50(13), pp. 6632–6643. doi: 10.1021/acs.est.5b04113.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Lin, L. *et al.* (2017) ‘Characterization of particulate matter deposited on urban tree foliage: A landscape analysis approach’, *Atmospheric Environment*. Elsevier Ltd. doi: 10.1016/j.atmosenv.2017.09.012.

Lindenmayer, D. B. *et al.* (2014) ‘New policies for old trees: Averting a global crisis in a keystone ecological structure’, *Conservation Letters*, 7(1), pp. 61–69. doi: 10.1111/conl.12013.

Liquete, C. *et al.* (2016) ‘Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits’, *Ecosystem Services*. Elsevier, 22(June), pp. 392–401. doi: 10.1016/j.ecoser.2016.09.011.

Liski, J., Tuomi, M. and Rasinmäki, J. (2009) ‘Yasso07 user-interface manual’, *University of Helsinki*, (March). Available at: www.environment.fi/syke/yasso.

Liu, C., Zhang, Y. and Weschler, C. J. (2014) ‘Science of the Total Environment The impact of mass transfer limitations on size distributions of particle associated SVOCs in outdoor and indoor environments’, *Science of the Total Environment, The*. Elsevier B.V., 497–498, pp. 401–411. doi: 10.1016/j.scitotenv.2014.07.095.

Liu, W. *et al.* (2017) ‘A framework for the urban eco-metabolism model - Linking metabolic processes to spatial patterns’, *Journal of Cleaner Production*. Elsevier Ltd, 165, pp. 168–176. doi: 10.1016/j.jclepro.2017.07.055.

Liu, X. *et al.* (2014) ‘Simulating urban growth by integrating landscape expansion index (LEI) and cellular automata’, *International Journal of Geographical Information Science*, 28(1), pp. 148–163. doi: 10.1080/13658816.2013.831097.

Lowenstein, D. M., Matteson, K. C. and Minor, E. S. (2015) ‘Diversity of wild bees supports pollination services in an urbanized landscape’, *Oecologia*. Springer Berlin Heidelberg, 179(3), pp. 811–821. doi: 10.1007/s00442-015-3389-0.

Lowry, J. H. and Lowry, M. B. (2014) ‘Comparing spatial metrics that quantify urban form’, *Computers, Environment and Urban Systems*. Elsevier Ltd, 44, pp. 59–67. doi: 10.1016/j.compenvurbsys.2013.11.005.

Lowry, J. H. and Lowry, M. B. (2014) ‘Computers , Environment and Urban Systems Comparing spatial metrics that quantify urban form’, *COMPUTERS, ENVIRONMENT AND URBAN SYSTEMS*. Elsevier Ltd, 44, pp. 59–67. doi: 10.1016/j.compenvurbsys.2013.11.005.

Luederitz, C. *et al.* (2015) ‘A review of urban ecosystem services: six key challenges for future research’, *Ecosystem Services*, 14, pp. 98–112. doi: 10.1016/j.ecoser.2015.05.001.

Luna-Reyes, L. F. and Andersen, D. L. (2003) ‘Collecting and analyzing qualitative data for system dynamics: Methods and models’, *System Dynamics Review*, 19(4), pp. 271–296. doi: 10.1002/sdr.280.

Lundy, L. and Wade, R. (2011) ‘Integrating sciences to sustain urban ecosystem services’, *Progress in Physical Geography*, 35(5), pp. 653–669. doi: 10.1177/0309133311422464.

Lupp, G. *et al.* (2016) ‘Assessing the Recreation Value of Urban Woodland Using the Ecosystem Service Approach in Two Forests in the Munich Metropolitan Region’, *SUSTAINABILITY*, 8(11). doi: 10.3390/su8111156.

MA (Millennium Ecosystem Assessment) (2005) *Millennium ecosystem assessment synthesis report.*, *Millennium Ecosystem Assessment*.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730468

Maes, J. *et al.* (2013) *Mapping and assessment of ecosystems and their services*. doi: 10.2779/75203.

Maes, J., Liquete, C., *et al.* (2016) 'An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020', *Ecosystem Services*, 17, pp. 14–23. doi: 10.1016/j.ecoser.2015.10.023.

Maes, J., Zulian, G., *et al.* (2016) *Mapping and Assessment of Ecosystems and their Services. Urban Ecosystems*. doi: 10.2779/625242.

Maes, J. and Jacobs, S. (2017) 'Nature-Based Solutions for Europe's Sustainable Development', *Conservation Letters*, 10(1), pp. 121–124. doi: 10.1111/conl.12216.

Mak, C., Scholz, M. and James, P. (2017) 'Sustainable drainage system site assessment method using urban ecosystem services', *URBAN ECOSYSTEMS*, 20(2), pp. 293–307. doi: 10.1007/s11252-016-0593-6.

Manaugh, K., Miranda-Moreno, L. F. and El-Geneidy, A. M. (2010) 'The effect of neighbourhood characteristics, accessibility, home-work location, and demographics on commuting distances', *Transportation*, 37(4), pp. 627–646. doi: 10.1007/s11116-010-9275-z.

Manes, F. *et al.* (2016) 'Regulating Ecosystem Services of forests in ten Italian Metropolitan Cities: Air quality improvement by PM10 and O-3 removal', *ECOLOGICAL INDICATORS*, 67, pp. 425–440. doi: 10.1016/j.ecolind.2016.03.009.

Manolaki, P. and Vogiatzakis, I. N. (2017) 'Ecosystem services in a peri-urban protected area in Cyprus: a rapid appraisal', *NATURE CONSERVATION-BULGARIA*, (22), pp. 129–146. doi: 10.3897/natureconservation.22.13840.

Marchi, M. *et al.* (2015) 'Carbon dioxide sequestration model of a vertical greenery system', *Ecological Modelling*. Elsevier B.V., 306, pp. 46–56. doi: 10.1016/j.ecolmodel.2014.08.013.

Marin, A. R., Masscheleyn, P. H. and Patrick, W. H. (1993) 'Soil redox-pH stability of arsenic species and its influence on arsenic uptake by rice', *Plant and Soil*, 152(2), pp. 245–253. doi: 10.1007/BF00029094.

Martinez-Moyano, I. J. and Richardson, G. P. (2013) 'Best practices in system dynamics modeling', *System Dynamics Review*, 29(2), pp. 102–123. doi: 10.1002/sdr.1495.

Martínez, C. E. and Motto, H. L. (2000) 'Solubility of lead, zinc and copper added to mineral soils', *Environmental Pollution*, 107(1), pp. 153–158. doi: 10.1016/S0269-7491(99)00111-6.

De Martis, G. *et al.* (2016) 'Can Artificial Ecosystems Enhance Local Biodiversity? The Case of a Constructed Wetland in a Mediterranean Urban Context', *ENVIRONMENTAL MANAGEMENT*, 57(5), pp. 1088–1097. doi: 10.1007/s00267-016-0668-4.

McGarigal, K. and Marks, B. J. (1994) *FRAGSTATS: spatial pattern analysis program for quantifying landscape structure - Version 2.0*. Second. doi: 10.2737/PNW-GTR-351.

McPhearson, T. *et al.* (2016) 'Advancing understanding of the complex nature of urban systems', *Ecological Indicators*, 70(April), pp. 566–573. doi: 10.1016/j.ecolind.2016.03.054.

Van Meerbeek, K. *et al.* (2015) 'The bioenergy potential of conservation areas and roadsides for biogas in an urbanized region', *Applied Energy*. Elsevier Ltd, 154, pp. 742–751. doi: 10.1016/j.apenergy.2015.05.007.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Meerow, S., Newell, J. P. and Stults, M. (2016) 'Defining urban resilience: A review', *Landscape and Urban Planning*. Elsevier B.V., 147, pp. 38–49. doi: 10.1016/j.landurbplan.2015.11.011.

Meixler, M. S. (2017) 'Assessment of Hurricane Sandy damage and resulting loss in ecosystem services in a coastal-urban setting', *ECOSYSTEM SERVICES*, 24, pp. 28–46. doi: 10.1016/j.ecoser.2016.12.009.

Meri, J. and Lian, L. (2017) 'A mixed methods approach to urban ecosystem services: Experienced environmental quality and its role in ecosystem assessment within an inner-city estate', *LANDSCAPE AND URBAN PLANNING*, 161, pp. 10–21. doi: 10.1016/j.landurbplan.2017.01.002.

Mohammed, A. and Babatunde, A. O. (2017) 'Modelling heavy metals transformation in vertical flow constructed wetlands', *Ecological Modelling*. Elsevier B.V., 354, pp. 62–71. doi: 10.1016/j.ecolmodel.2017.03.012.

Montoya-Tangarife, C. *et al.* (2017) 'Monitoring the effects of land cover change on the supply of ecosystem services in an urban region: A study of Santiago-Valparaiso Chile', *PLOS ONE*, 12(11). doi: 10.1371/journal.pone.0188117.

Moores, J. P. *et al.* (2017) 'Evaluation of a new method for assessing resilience in urban aquatic social-ecological systems', *ECOLOGY AND SOCIETY*, 22(4). doi: 10.5751/ES-09727-220415.

Morgan, R. P. C. (2013) *Soil Erosion and Conservation*, *Environmental Modelling: Finding Simplicity in Complexity: Second Edition*. doi: 10.1002/9781118351475.ch22.

Morrison, J. L. and Chapm, W. C. (2017) 'Can Urban Parks Provide Habitat for Woodpeckers ? Author (s): Joan L . Morrison and William C . Chapman Published by : Eagle Hill Institute Stable URL : http://www.jstor.org/stable/3858682 REFERENCES Linked references are available on JSTOR for this art', 12(3), pp. 253–262.

Moseley, D. *et al.* (2017) 'Developing an indicator for the physical health benefits of recreation in woodlands', *Ecosystem Services*. doi: 10.1016/j.ecoser.2017.12.008.

Müller, A. *et al.* (2018) '"Wild" in the city context: Do relative wild areas offer opportunities for urban biodiversity?', *Landscape and Urban Planning*, 170(February 2017), pp. 256–265. doi: 10.1016/j.landurbplan.2017.09.027.

Munang, R. *et al.* (2013) 'The role of ecosystem services in climate change adaptation and disaster risk reduction', *Current Opinion in Environmental Sustainability*. Elsevier B.V., 5(1), pp. 47–52. doi: 10.1016/j.cosust.2013.02.002.

Neitsch, S. . *et al.* (2011) 'Soil & Water Assessment Tool Theoretical Documentation Version 2009', *Texas Water Resources Institute*, pp. 1–647. doi: 10.1016/j.scitotenv.2015.11.063.

Nesshover, C. *et al.* (2017) 'The science, policy and practice of nature-based solutions: An interdisciplinary perspective', *Sci Total Environ*, 579, pp. 1215–1227. doi: 10.1016/j.scitotenv.2016.11.106.

Newell, J. P. and Cousins, J. J. (2014) 'The boundaries of urban metabolism: Towards a political-industrial ecology', *Progress in Human Geography*, 39(6), pp. 702–728. doi: 10.1177/0309132514558442.

Nocco, M. A., Rouse, S. E. and Balster, N. J. (2016) 'Vegetation type alters water and nitrogen budgets in a controlled, replicated experiment on residential-sized rain gardens planted with

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

prairie, shrub, and turfgrass', *URBAN ECOSYSTEMS*, 19(4), pp. 1665–1691. doi: 10.1007/s11252-016-0568-7.

Nowak, D. J. (2000) 'UFORE Methods', *Diversity*, 21.

Nowak, D. J. *et al.* (2008) 'A Ground-Based Method of Assessing Urban Forest Structure and Ecosystem Services', *Arboriculture & Urban Forestry*, 34(6), pp. 347–358. doi: 10.1039/b712015j.

Nowak, D. J. *et al.* (2013) 'Carbon storage and sequestration by trees in urban and community areas of the United States', *Environmental Pollution*, 178, pp. 229–236. doi: 10.1016/j.envpol.2013.03.019.

O'Brien, L., Morris, J. and Stewart, A. (2014) 'Engaging with peri-urban woodlands in england: The contribution to people's health and well-being and implications for future management', *International Journal of Environmental Research and Public Health*, 11(6), pp. 6171–6192. doi: 10.3390/ijerph110606171.

Ode, Å., Tveit, M. S. and Fry, G. (2008) 'Capturing Landscape Visual Character Using Indicators: Touching Base with Landscape Aesthetic Theory', *Landscape Research*, 33(1), pp. 89–117. doi: 10.1080/01426390701773854.

Ode, Å., Tveit, M. S. and Fry, G. (2010) 'Advantages of using different data sources in assessment of landscape change and its effect on visual scale', *Ecological Indicators*, 10(1), pp. 24–31. doi: 10.1016/j.ecolind.2009.02.013.

Olguín, E. J. *et al.* (2017) 'Long-term assessment at field scale of Floating Treatment Wetlands for improvement of water quality and provision of ecosystem services in a eutrophic urban pond', *Science of the Total Environment*, 584–585, pp. 561–571. doi: 10.1016/j.scitotenv.2017.01.072.

Omer, I. and Kaplan, N. (2017) 'Using space syntax and agent-based approaches for modeling pedestrian volume at the urban scale', *Computers, Environment and Urban Systems*. Elsevier Ltd, 64, pp. 57–67. doi: 10.1016/j.compenvurbsys.2017.01.007.

Oosterbroek, B. *et al.* (2016) 'Assessing ecosystem impacts on health: A tool review', *Ecosystem Services*. Elsevier, 17, pp. 237–254. doi: 10.1016/j.ecoser.2015.12.008.

Ouyang, Y. *et al.* (2007) 'Simulating uptake and transport of TNT by plants using STELLA', *Chemosphere*, 69(8), pp. 1245–1252. doi: 10.1016/j.chemosphere.2007.05.081.

Pappalardo, V. *et al.* (2017) 'The potential of green infrastructure application in urban runoff control for land use planning: A preliminary evaluation from a southern Italy case study', *Ecosystem Services*. Elsevier B.V., (June 2016), pp. 1–10. doi: 10.1016/j.ecoser.2017.04.015.

Park, J.-H. and Cho, G.-H. (2016) 'Examining the Association between Physical Characteristics of Green Space and Land Surface Temperature: A Case Study of Ulsan, Korea', *Sustainability*, 8(8), p. 777. doi: 10.3390/su8080777.

Pataki, D. E. *et al.* (2011) 'Coupling biogeochemical cycles in urban environments: Ecosystem services, green solutions, and misconceptions', *Frontiers in Ecology and the Environment*, 9(1), pp. 27–36. doi: 10.1890/090220.

Pauleit, S. *et al.* (2017) 'Nature-Based Solutions and Climate Change – Four Shades of Green BT - Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice', in Kabisch, N. et al. (eds). Cham: Springer International Publishing, pp. 29–49. doi: 10.1007/978-3-319-56091-5_3.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Pelorosso, R., Gobattoni, F. and Leone, A. (2017) 'The low-entropy city: A thermodynamic approach to reconnect urban systems with nature', *Landscape and Urban Planning*. Elsevier, 168, pp. 22–30. doi: 10.1016/j.landurbplan.2017.10.002.

Perrow, M. *et al.* (1997) 'Biomanipulation in shallow lakes: state of the art', *Hydrobiologia*, 33, pp. 355–365. doi: PDF 13.

Peters, E. B., Hiller, R. V. and McFadden, J. P. (2011) 'Seasonal contributions of vegetation types to suburban evapotranspiration', *Journal of Geophysical Research: Biogeosciences*, 116(1), pp. 1–16. doi: 10.1029/2010JG001463.

Pickett, S. T. A. *et al.* (2008) 'Beyond Urban Legends: An Emerging Framework of Urban Ecology, as Illustrated by the Baltimore Ecosystem Study', *BioScience*, 58(2), pp. 139–150. doi: 10.1641/B580208.

Pickett, S. T. A., Cadenasso, M. L. and Grove, J. M. (2005) 'Biocomplexity in coupled natural-human systems: A multidimensional framework', *Ecosystems*, 8(3), pp. 225–232. doi: 10.1007/s10021-004-0098-7.

Pincetl, S. (2012) 'Nature, urban development and sustainability – What new elements are needed for a more comprehensive understanding?', *Cities*, 29, pp. S32–S37. doi: 10.1016/j.cities.2012.06.009.

Pincetl, S., Bunje, P. and Holmes, T. (2012) 'An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes', *Landscape and Urban Planning*, 107(3), pp. 193–202. doi: 10.1016/j.landurbplan.2012.06.006.

Pincetl, S. and Newell, J. P. (2017) 'Why data for a political-industrial ecology of cities?', *Geoforum*. doi: 10.1016/j.geoforum.2017.03.002.

Potschin, M. *et al.* (2016) 'Nature-based-solutions', in *OpenNESS Ecosystem Services Reference Book*.

Pulford, I. D. and Watson, C. (2003) 'Phytoremediation of heavy metal-contaminated land by trees - A review', *Environment International*, 29(4), pp. 529–540. doi: 10.1016/S0160-4120(02)00152-6.

Pulighe, G., Fava, F. and Lupia, F. (2016) 'Insights and opportunities from mapping ecosystem services of urban green spaces and potentials in planning', *Ecosystem Services*. Elsevier, 22, pp. 1–10. doi: 10.1016/j.ecoser.2016.09.004.

Qian, Y. *et al.* (2017) 'Risk assessment and interpretation of heavy metal contaminated soils on an urban brownfield site in New York metropolitan area', *Environmental Science and Pollution Research*. Environmental Science and Pollution Research, 24(30), pp. 23549–23558. doi: 10.1007/s11356-017-9918-0.

Qureshi, S., Haase, D. and Coles, R. (2014a) 'The Theorized Urban Gradient (TUG) method—A conceptual framework for socio-ecological sampling in complex urban agglomerations', *Ecological Indicators*, 36, pp. 100–110. doi: 10.1016/j.ecolind.2013.07.010.

Qureshi, S., Haase, D. and Coles, R. (2014b) 'The Theorized Urban Gradient (TUG) method - A conceptual framework for socio-ecological sampling in complex urban agglomerations', *Ecological Indicators*. Elsevier Ltd, 36, pp. 100–110. doi: 10.1016/j.ecolind.2013.07.010.

Rayfield, B., Fortin, M. J. and Fall, A. (2011) 'Connectivity for conservation: A framework to

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

classify network measures', *Ecology*, 92(4), pp. 847–858. doi: 10.1890/09-2190.1.

Ready, K. R. *et al.* (1999) 'Phosphorus retention in streams and wetlands: A review', *Critical Reviews in Environmental Science and Technology*, 29(1), pp. 83–146. doi: 10.1080/10643389991259182.

Renard, K. G. *et al.* (1991) 'RUSLE: Revised universal soil loss equation', *Journal of Soil and Water Conservation*, 46(1), pp. 30–33. Available at: http://www.jswconline.org/content/46/1/30.short.

Van Renterghem, T. *et al.* (2015) 'Using natural means to reduce surface transport noise during propagation outdoors', *Applied Acoustics*. Elsevier Ltd, 92, pp. 86–101. doi: 10.1016/j.apacoust.2015.01.004.

Van Renterghem, T., Botteldooren, D. and Verheyen, K. (2012) 'Road traffic noise shielding by vegetation belts of limited depth', *Journal of Sound and Vibration*. Elsevier, 331(10), pp. 2404–2425. doi: 10.1016/j.jsv.2012.01.006.

Réquia Júnior, W. J., Roig, H. L. and Koutrakis, P. (2015) 'A novel land use approach for assessment of human health: The relationship between urban structure types and cardiorespiratory disease risk', *Environment International*, 85, pp. 334–342. doi: 10.1016/j.envint.2015.09.026.

Reynolds, C. *et al.* (2017) 'Does "Greening" of Neotropical Cities Considerably Mitigate Carbon Dioxide Emissions? The Case of Medellin, Colombia', *Sustainability*, 9(5), p. 785. doi: 10.3390/su9050785.

Ribeiro, F. P. and Ribeiro, K. T. (2016) 'Participative mapping of cultural ecosystem services in Pedra Branca State Park, Brazil', *NATUREZA & CONSERVACAO*, 14(2), pp. 120–127. doi: 10.1016/j.ncon.2016.09.004.

Rooney, R. C. *et al.* (2015) 'Replacing natural wetlands with stormwater management facilities: Biophysical and perceived social values', *Water Research*. Elsevier Ltd, 73, pp. 17–28. doi: 10.1016/j.watres.2014.12.035.

Rosado, L., Kalmykova, Y. and Patrício, J. (2017) 'Reprint of: Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden', *Journal of Cleaner Production*, pp. 1–13. doi: 10.1016/j.jclepro.2017.05.143.

Rossman, L. A. and Huber, W. C. (2016) 'Storm Water Management Model Reference Manual Volume I–Hydrology (Revised)', *US Environmental Protection Agency: Cincinnati, OH, USA*.

Roussel, F. *et al.* (2017) 'Testing the applicability of ecosystem services mapping methods for peri-urban contexts: A case study for Paris', *ECOLOGICAL INDICATORS*, 83, pp. 504–514. doi: 10.1016/j.ecolind.2017.07.046.

Rytter, R. M. (2012) 'The potential of willow and poplar plantations as carbon sinks in Sweden', *Biomass and Bioenergy*. Elsevier Ltd, 36, pp. 86–95. doi: 10.1016/j.biombioe.2011.10.012.

Sacristan, D., Peñarroya, B. and Recatala, L. (2015) 'Increasing the Knowledge on the Management of Cu-Contaminated Agricultural Soils by Cropping Tomato (Solanum Lycopersicum L.)', *Land Degradation and Development*, 26(6), pp. 587–595. doi: 10.1002/ldr.2319.

Sala, P. (2009) 'Els catalegs del paisatge de Catalunya', in NOGUé, J., PUIGBERT, L., and BRETCHA, G. (eds) *Ordenació i gestió del paisatge a Europa*. Barcelona: Observatori del

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Paisatge de Catalunya.

Salvati, L. *et al.* (2016a) '"Land-use mixité": Evaluating urban hierarchy and the urban-to-rural gradient with an evenness-based approach', *Ecological Indicators*. Elsevier Ltd, 70, pp. 35–42. doi: 10.1016/j.ecolind.2016.05.046.

Salvati, L. *et al.* (2016b) '"Land-use mixité": Evaluating urban hierarchy and the urban-to-rural gradient with an evenness-based approach', *Ecological Indicators*. Elsevier Ltd, 70, pp. 35–42. doi: 10.1016/j.ecolind.2016.05.046.

Sanderson, M. G. *et al.* (2007) 'Stomatal conductance changes due to increasing carbon dioxide levels: Projected impact on surface ozone levels', *Tellus, Series B: Chemical and Physical Meteorology*, 59(3), pp. 404–411. doi: 10.1111/j.1600-0889.2007.00277.x.

Sandström, U. G., Angelstam, P. and Mikusiński, G. (2006) 'Ecological diversity of birds in relation to the structure of urban green space', *Landscape and Urban Planning*, 77(1–2), pp. 39–53. doi: 10.1016/j.landurbplan.2005.01.004.

Saura, S. and Rubio, L. (2010) 'A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape', *Ecography*, 33(3), pp. 523–537. doi: 10.1111/j.1600-0587.2009.05760.x.

Schäfer, K. V. R. *et al.* (2014) 'Carbon dioxide fluxes of an urban tidal marsh in the Hudson-Raritan estuary', *Journal of Geophysical Research: Biogeosciences*, 119, pp. 557–566. doi: 10.1002/2013JG002433.

Schelhaas, M. J. *et al.* (2004) 'CO2FIX V 3.1 - A modelling framework for quantifying carbon sequestration in forest ecosystems', *Evolution*, 48(1068), pp. 965–978. doi: 10.2307/2410359.

Schipperijn, J. *et al.* (2010) 'Influences on the use of urban green space - A case study in Odense, Denmark', *Urban Forestry and Urban Greening*. Elsevier, 9(1), pp. 25–32. doi: 10.1016/j.ufug.2009.09.002.

Schipperijn, J. *et al.* (2013) 'Associations between physical activity and characteristics of urban green space', *Urban Forestry and Urban Greening*. Elsevier GmbH., 12(1), pp. 109–116. doi: 10.1016/j.ufug.2012.12.002.

Schmidt, K. *et al.* (2016) 'The Sociocultural Value of Upland Regions in the Vicinity of Cities in Comparison With Urban Green Spaces', *MOUNTAIN RESEARCH AND DEVELOPMENT*, 36(4, SI), pp. 465–474. doi: 10.1659/MRD-JOURNAL-D-16-00044.1.

Schneider, A. and Woodcock, C. E. (2008) 'Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information', *Urban Studies*, 45(3), pp. 659–692. doi: 10.1177/0042098007087340.

Scholz, M. *et al.* (2013) 'Selecting sustainable drainage structures based on ecosystem service variables estimated by different stakeholder groups', *Water (Switzerland)*, 5(4), pp. 1741–1759. doi: 10.3390/w5041741.

Schwarz, N. (2010a) 'Urban form revisited-Selecting indicators for characterising European cities', *Landscape and Urban Planning*. Elsevier B.V., 96, pp. 29–47. doi: 10.1016/j.landurbplan.2010.01.007.

Schwarz, N. (2010b) 'Urban form revisited—Selecting indicators for characterising European

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

cities', *Landscape and Urban Planning*, 96(1), pp. 29–47. doi: 10.1016/j.landurbplan.2010.01.007.

SEEA (2012) 'System of Environmental-Economic Accounting 2012: Central Framework (United Nations, New York)'.

Selmi, W. *et al.* (2016) 'Air pollution removal by trees in public green spaces in Strasbourg city, France', *URBAN FORESTRY & URBAN GREENING*, 17, pp. 192–201. doi: 10.1016/j.ufug.2016.04.010.

Setälä, H. *et al.* (2017) 'Urban parks provide ecosystem services by retaining metals and nutrients in soils', *Environmental Pollution*, 231, pp. 451–461. doi: 10.1016/j.envpol.2017.08.010.

She, Q. *et al.* (2017) 'Air quality and its response to satellite-derived urban form in the Yangtze River Delta, China', *Ecological Indicators*. Elsevier Ltd, 75, pp. 297–306. doi: 10.1016/j.ecolind.2016.12.045.

Shekhar, S. and Xiong, H. (2008) 'Soil and Water Assessment Tool "SWAT"', *Encyclopedia of GIS*, pp. 1068–1068. doi: 10.1007/978-0-387-35973-1_1231.

Shi, X. *et al.* (2016) 'Growth and efficiency of nutrient removal by Salix jiangsuensis J172 for phytoremediation of urban wastewater', *Environmental Science and Pollution Research*, 23(3), pp. 2715–2723. doi: 10.1007/s11356-015-5508-1.

Sikorska, D., Sikorski, P. and Hopkins, R. J. (2017) 'High Biodiversity of Green Infrastructure Does Not Contribute to Recreational Ecosystem Services', *SUSTAINABILITY*, 9(3). doi: 10.3390/su9030334.

Singh, N. P. and Santal, A. R. (2015) 'Phytoremediation of Heavy Metals: The Use of Green Approaches to Clean the Environment BT - Phytoremediation: Management of Environmental Contaminants, Volume 2', in Ansari, A. A. et al. (eds). Cham: Springer International Publishing, pp. 115–129. doi: 10.1007/978-3-319-10969-5_10.

Smith, J. *et al.* (2010) 'Model to Estimate Carbon in Organic Soils – Sequestration and Emissions (ECOSSE).', *Carbon*, 44(August), pp. 1–73.

Solecki, W. *et al.* (2015) 'A conceptual framework for an urban areas typology to integrate climate change mitigation and adaptation', *Urban Climate*, 14, pp. 116–137. doi: 10.1016/j.uclim.2015.07.001.

Song, Y., Popkin, B. and Gordon-Larsen, P. (2013) 'A national-level analysis of neighborhood form metrics', *Landscape and Urban Planning*, 116, pp. 73–85. doi: 10.1016/j.landurbplan.2013.04.002.

de Sosa, L. L. *et al.* (2018) 'Quantifying the contribution of riparian soils to the provision of ecosystem services', *Science of the Total Environment*. Elsevier B.V., 624, pp. 807–819. doi: 10.1016/j.scitotenv.2017.12.179.

Southon, G. E. *et al.* (2017) 'Biodiverse perennial meadows have aesthetic value and increase residents' perceptions of site quality in urban green-space', *Landscape and Urban Planning*, 158, pp. 105–118. doi: 10.1016/j.landurbplan.2016.08.003.

Stearns, C. A., Sakai, R. K. and Joseph, E. (2016) 'A novel method of urban land type identification utilizing meteorological station network temperature data, as developed for the Baltimore-Washington region', *Urban Climate*. Elsevier B.V., 17, pp. 146–160. doi: 10.1016/j.uclim.2016.05.002.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Stewart, I. D. and Oke, T. R. (2012) 'Local Climate Zones for Urban Temperature Studies', *Bulletin of the American Meteorological Society*, 93(12), pp. 1879–1900. doi: 10.1175/bams-d-11-00019.1.

Strohbach, M. W. and Haase, D. (2012) 'Above-ground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city', *Landscape and Urban Planning*, 104(1), pp. 95–104. doi: 10.1016/j.landurbplan.2011.10.001.

Su, M., Chen, B. and Yang, Z. (2010) 'Implication of ecosystem health assessment for urban management', in *Procedia Environmental Sciences*, pp. 674–680. doi: 10.1016/j.proenv.2010.10.076.

Sun, X. *et al.* (2017) 'Integrative assessment and management implications on ecosystem services loss of coastal wetlands due to reclamation', *JOURNAL OF CLEANER PRODUCTION*, 163(S), pp. S101–S112. doi: 10.1016/j.jclepro.2015.10.048.

Syrbe, R.-U. and Walz, U. (2012) 'Spatial indicators for the assessment of ecosystem services: Providing, benefiting and connecting areas and landscape metrics', *Ecological Indicators*, 21, pp. 80–88. doi: 10.1016/j.ecolind.2012.02.013.

Szücs, L., Anders, U. and Bürger-Arndt, R. (2015) 'Assessment and illustration of cultural ecosystem services at the local scale - A retrospective trend analysis', *Ecological Indicators*. Elsevier Ltd, 50, pp. 120–134. doi: 10.1016/j.ecolind.2014.09.015.

Tannier, C. and Thomas, I. (2013) 'Defining and characterizing urban boundaries: A fractal analysis of theoretical cities and Belgian cities', *Computers, Environment and Urban Systems*, 41, pp. 234–248. doi: 10.1016/j.compenvurbsys.2013.07.003.

Tao, Y. *et al.* (2015) 'Effects of land use and cover change on terrestrial carbon stocks in urbanized areas: A study from Changzhou, China', *Journal of Cleaner Production*. Elsevier Ltd, 103, pp. 651–657. doi: 10.1016/j.jclepro.2014.07.055.

Teeb (2011) 'TEEB manual for cities: Ecosystem services in urban management', *The Economics of ecosystems and biodiversity (TEEB)*, p. 48.

Thinh, N. X. *et al.* (2002) 'Evaluation of urban land-use structures with a view to sustainable development', *Environmental Impact Assessment Review*, 22(5), pp. 475–492. doi: 10.1016/S0195-9255(02)00023-9.

Thornton, I. *et al.* (2008) 'Urban geochemistry: Research strategies to assist risk assessment and remediation of brownfield sites in urban areas', *Environmental Geochemistry and Health*, 30(6), pp. 565–576. doi: 10.1007/s10653-008-9182-9.

Thornton, P. E., Running, S. W. and Hunt, E. R. (2005) 'Biome-BGC: Terrestrial Ecosystem Process Model, Version 4.1.1'. ORNL Distributed Active Archive Center, p. doi: 10.3334/ornldaac/805.

Tian, Y. *et al.* (2011) 'Landscape ecological assessment of green space fragmentation in Hong Kong', *Urban Forestry & Urban Greening*. Elsevier GmbH., 10(2), pp. 79–86. doi: 10.1016/j.ufug.2010.11.002.

Toftager, M. *et al.* (2011) 'Distance to Green Space and Physical Activity: A Danish National Representative Survey', *Journal of Physical Activity and Health*, 8(6), pp. 741–749. doi: 10.1123/jpah.8.6.741.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Tombolini, I., Munafo, M. and Salvati, L. (2016) 'Soil sealing footprint as an indicator of dispersed urban growth: a multivariate statistics approach', *URBAN RESEARCH & PRACTICE*, 9(1), pp. 1–15. doi: 10.1080/17535069.2015.1037340.

Tratalos, J. *et al.* (2007) 'Urban form , biodiversity potential and ecosystem services', 83, pp. 308–317. doi: 10.1016/j.landurbplan.2007.05.003.

Tratalos, J. A. *et al.* (2016) 'Cultural ecosystem services in the UK: Lessons on designing indicators to inform management and policy', *ECOLOGICAL INDICATORS*, 61(1, SI), pp. 63–73. doi: 10.1016/j.ecolind.2015.03.040.

Triest, L., Stiers, I. and Van Onsem, S. (2016) 'Biomanipulation as a nature-based solution to reduce cyanobacterial blooms', *Aquatic Ecology*. Springer Netherlands, 50(3), pp. 461–483. doi: 10.1007/s10452-015-9548-x.

De Troyer, N. *et al.* (2016) 'Water Quality Assessment of Streams and Wetlands in a Fast Growing East African City', *WATER*, 8(4). doi: 10.3390/w8040123.

Tudor, C. (2014) 'An Approach to Landscape Character Assessment', *Natural England*, (October), p. 56. doi: NE579.

Turner, K. G. *et al.* (2015) 'A review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration', *Ecological Modelling*. Elsevier B.V., 319, pp. 190–207. doi: 10.1016/j.ecolmodel.2015.07.017.

Tveit, M., Ode, Å. and Fry, G. (2006) 'Key concepts in a framework for analysing visual landscape character', *Landscape Research*, 31(3), pp. 229–255. doi: 10.1080/01426390600783269.

UKNEA (2013) 'The UK national ecosystem assessment: Synthesis of the key findings. Cambridge: UNEP-WCMC'.

Vaccari, F. P. *et al.* (2013) 'Carbon dioxide balance assessment of the city of Florence (Italy), and implications for urban planning', *Landscape and Urban Planning*. Elsevier B.V., 120, pp. 138–146. doi: 10.1016/j.landurbplan.2013.08.004.

del Valle, R. M. G. *et al.* (2009) 'Urban system and knowledge society: Towards a tipology of Spanish cities ', *Investigaciones Regionales*, (16), pp. 117–142. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-78650826303&partnerID=40&md5=9aa30f7c40b7f19ce52f86e74bf8e54b.

Vanderhaegen, S. and Canters, F. (2017) 'Mapping urban form and function at city block level using spatial metrics', *Landscape and Urban Planning*. Elsevier, 167(May), pp. 399–409. doi: 10.1016/j.landurbplan.2017.05.023.

Voltersen, M. *et al.* (2014) 'Object-based land cover mapping and comprehensive feature calculation for an automated derivation of urban structure types at block level', *Remote Sensing of Environment*. Elsevier Inc., 154, pp. 192–201. doi: 10.1016/j.rse.2014.08.024.

Van de Voorde, T., Jacquet, W. and Canters, F. (2011) 'Landscape and Urban Planning Mapping form and function in urban areas : An approach based on urban metrics and continuous impervious surface data', *Landscape and Urban Planning*. Elsevier B.V., 102, pp. 143–155. doi: 10.1016/j.landurbplan.2011.03.017.

Voorde, T. Van De, Jacquet, W. and Canters, F. (2011) 'Landscape and Urban Planning Mapping form and function in urban areas : An approach based on urban metrics and continuous

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

impervious surface data', *Landscape and Urban Planning*. Elsevier B.V., 102(3), pp. 143–155. doi: 10.1016/j.landurbplan.2011.03.017.

Voulgaris, C. T. *et al.* (2017) 'Synergistic neighborhood relationships with travel behavior: An analysis of travel in 30,000 US neighborhoods', *Journal of Transport and Land Use*, 10(1), pp. 437–461. doi: 10.5198/jtlu.2016.840.

Weber, F., Kowarik, I. and Säumel, I. (2014) 'Herbaceous plants as filters: Immobilization of particulates along urban street corridors', *Environmental Pollution*. Elsevier Ltd, 186, pp. 234–240. doi: 10.1016/j.envpol.2013.12.011.

Weerakkody, U. *et al.* (2017) 'Particulate Matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station', *Urban Forestry & Urban Greening*. Elsevier, 27(July), pp. 173–186. doi: 10.1016/j.ufug.2017.07.005.

Weng, Y.-C. (2007) 'Spatiotemporal changes of landscape pattern in response to urbanization', *Landscape and Urban Planning*, 81, pp. 341–353. doi: 10.1016/j.landurbplan.2007.01.009.

Whittinghill, L. J. and Rowe, D. B. (2011) 'The role of green roof technology in urban agriculture', 27(4), pp. 314–322. doi: 10.1017/S174217051100038X.

Woldegerima, T., Yeshitela, K. and Lindley, S. (2017) 'Ecosystem services assessment of the urban forests of Addis Ababa, Ethiopia', *Urban Ecosystems*. Urban Ecosystems, 20(3), pp. 683–699. doi: 10.1007/s11252-016-0624-3.

Wu, J. (2013) 'Landscape sustainability science: ecosystem services and human well-being in changing landscapes', *Landscape Ecology*, 28(6), pp. 999–1023. doi: 10.1007/s10980-013-9894-9.

Wu, J. (2014) 'Urban ecology and sustainability: The state-of-the-science and future directions', *Landscape and Urban Planning*, 125, pp. 209–221. doi: 10.1016/j.landurbplan.2014.01.018.

Wu, M. *et al.* (2017) 'Neighbourhood-scale urban riparian ecosystem classification', *Ecological Indicators*. Elsevier Ltd, 72, pp. 330–339. doi: 10.1016/j.ecolind.2016.08.025.

Yevdokimov, I., Larionova, A. and Blagodatskaya, E. (2016) 'Microbial immobilisation of phosphorus in soils exposed to drying-rewetting and freeze-thawing cycles', *Biology and Fertility of Soils*. Biology and Fertility of Soils, 52(5), pp. 685–696. doi: 10.1007/s00374-016-1112-x.

Zandvliet, R. and Dijst, M. (2006) 'Short-term dynamics in the use of places: A space-time typology of visitor populations in the Netherlands', *Urban Studies*, 43(7), pp. 1159–1176. doi: 10.1080/00420980500406702.

Zardo, L. *et al.* (2017) 'Estimating the cooling capacity of green infrastructures to support urban planning', *ECOSYSTEM SERVICES*, 26(A), pp. 225–235. doi: 10.1016/j.ecoser.2017.06.016.

Zeng, C., He, S. and Cui, J. (2014) 'A multi-level and multi-dimensional measuring on urban sprawl: A case study in Wuhan metropolitan area, central China', *Sustainability (Switzerland)*, 6(6), pp. 3571–3598. doi: 10.3390/su6063571.

Zhou, W. *et al.* (2014) 'Quantifying Spatial Heterogeneity in Urban Landscapes: Integrating Visual Interpretation and Object-Based Classification', *Remote Sensing*, 6(4), pp. 3369–3386. doi: 10.3390/rs6043369.

Zhou, W., Pickett, S. T. A. and Cadenasso, M. L. (2016) 'Shifting concepts of urban spatial

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

heterogeneity and their implications for sustainability', *Landscape Ecology*, 32(1), pp. 15–30. doi: 10.1007/s10980-016-0432-4.

Zhou, W., Wang, J. and Cadenasso, M. L. (2017) 'Effects of the spatial configuration of trees on urban heat mitigation: A comparative study', *Remote Sensing of Environment*, 195, pp. 1–12. doi: 10.1016/j.rse.2017.03.043.

Ziter, C. (2016) 'The biodiversity-ecosystem service relationship in urban areas: A quantitative review', *Oikos*, 125(6), pp. 761–768. doi: 10.1111/oik.02883.

Zölch, T. *et al.* (2016) 'Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale', *Urban Forestry and Urban Greening*. Elsevier GmbH., 20, pp. 305–316. doi: 10.1016/j.ufug.2016.09.011.

Zölch, T. *et al.* (2017) 'Regulating urban surface runo ff through nature-based solutions – An assessment at the micro-scale', *Environmental Research*. Elsevier Inc., 157(April), pp. 135–144. doi: 10.1016/j.envres.2017.05.023.

Zube, E. H. (1984) 'Themes in landscape assessment theory', *Landscape Journal*. University of Wisconsin Press, 3(2), pp. 104–110.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Appendix I: Supplementary Material

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table S1. Advanced search string in Web of Knowledge

Search String	(("urban*") AND ("ecosystem servic*" OR "landscape servic*" OR ("ecosystem functio*" OR "landscape functio*" OR "ecosystem structur*" OR "landscape structur*"))
Refined by	DOCUMENT TYPES: (ARTICLE OR REVIEW) AND LANGUAGES: (ENGLISH)
Timespan	1998-2018

Table S2. Advanced search string in Science Direct

Search string for environmental aspects	*((urban OR neighbourhood OR neighborhood OR city) AND (typology OR system OR type OR class OR classification OR form OR structure OR zoning OR mapping OR cluster OR boundary) AND (indicator OR metric OR index OR indice))) AND (ecological OR environmental OR landscape OR (land AND (use OR cover)) OR species OR "spatial configuration" OR fragmentation))*
Search string for environmental aspects	*((urban OR neighbourhood OR neighborhood OR city) AND (typology OR system OR type OR class OR classification OR form OR structure OR zoning OR mapping OR cluster OR boundary) AND (indicator OR metric OR index OR indice) AND (material AND (flow OR storage)))*
Search string for social, economy, infrastructure, governance and energy	*(("urban form" OR "urban morphol*" OR "urban region*" OR "urban system*") AND ("typol*" OR "type*") AND ("indicator*" OR "metric" OR "factor")) AND ("energ*" OR "soc*" OR "gov*" OR "econ*" OR "physic*" OR "land") AND PUBYEAR > 1998 AND (LIMIT-TO (DOCTYPE "ar") OR LIMIT-TO (DOCTYPE "re")) AND (LIMIT-TO (SUBJAREA "AGRI") OR LIMIT-TO (SUBJAREA "DECI") OR LIMIT-TO (SUBJAREA "ENVI") OR LIMIT-TO (SUBJAREA "SOCI") OR LIMIT-TO (SUBJAREA "ENER")) AND (LIMIT-TO(LANGUAGE, "English "))"*
Refined by	DOCUMENT TYPES: (ARTICLE OR REVIEW) AND LANGUAGES: (ENGLISH)
Timespan	1998-2018

Note: Additional articles were gathered making use of snow-ball sampling methods, selecting relevant references from the papers of the systematic literature review.

Table S3a. Correspondence of NBS Type 1 with NBS Types 1.1

Type of actions	Detailed NBS Type 1	Equivalent types Task 1.1.
Control of movement	Control access of people and livestock	Limit or prevent access to an area
Control of chemicals	Abolish fertilisation and pesticide practices	Reasoned or no use of chemical
		Reasoned use of organic fertilisers
Soil/Land management	Reduce agricultural fencing	Limit or prevent certain practices
	Contour tillage	
	Strip tillage	
	Reduced tillage	
	Mulch tillage	
	Haymaking	
		Composting
Vegetation management	Conserve deadwood on the ground	Conserving deadwood on the ground
	Keeping old trees	Keeping old trees
	Increase biocomplexity in planting	Choice of plants
	Frequent cutting or mowing	Use of grazing animals
	Low intensity grazing or mowing	No management/Limited management/Use of grazing animals
	Maintain a low intense production regime	
	Multiple cropping	
	Strip cropping	
	High density planting	
	Maintain natural agricultural buffer strips	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

	Macrophytes harvesting	
Trophic chain management	Biomanipulation	
Landscape scale management	Natural flood management	

Table S3b. Correspondence of NBS Type 2 with NBS Types 1.1

Type of actions	Detailed NBS Type 2	Equivalent types Task 1.1.	
Modification of soil conditions (Land)	Mulching	Mulching	Quarry restoration
	Soil amendment	Reinforced/structural soil	
		Smart soils	
		Soil melioration/amendment/improvement	
	Sod cutting	Soil melioration/amendment/improvement	
	Top soil removal		
	Abolish drainage by filling them		
	Addition of non degradated peat to stimulate decomposition processes		
	Sediment traps		
Modification of bed conditions (Water)	Gravel traps (spawning habitat)		
	Introduction of gravel (spawning habitat)		
Modification of land form (Water and Land)		Gravity fountain	
	Restricting beach rackling		
	Removal of artificial structures to enhance waterflow	infrastructure removed on rivers	
	Re-meandering rivers	Re-meander rivers	
	Creation of inner islands	Excavation of new waterbodies & Re-opened streams	
	Creation of backwaters		
	Creation of pools and riffles		
	Creation of wet berms		
	Provision of floodplain scrapes		
	Increase tidal amplitude		
	De-embankment		
	Re-shaping lake bed		
	Re-shaping land form to retain water	Re-profiling river banks	Quarry restoration
	Re-shaping land form for planting establishment		
	Stabilisation of moving sand		
	Narrowing river channels with revegetated banks	Vegetation engineering system for riverbanks erosion control	
Modification of vegetation conditions (Water and Land)	Remove scrub/tree encroachment		Quarry restoration
	Grass/legume cover		
	Sowing of herbaceous cover crops		
	Re-seedling	Vegetation engineering systems for wind erosion control	
		Vegetation engineering systems for slope erosion control	
	Revegetation (planting)	Vegetation engineering systems for wind erosion control	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

		Vegetation engineering systems for slope erosion control
		Revegetation for aquatic planting
Enhancement of ecological conditions through vegetation	Tree shelters and bird perches	
	Phytoremediation and Phytomanagement	Management of polluted areas by plants (phytoremediation)

Notes: Light green cells indicate partial correspondence and light grey cells indicate no correspondence

Table S3c. Correspondence of NBS Type 3 with NBS Types 1.1

Type of actions	Detailed NBS Type 3	Equivalent types Task 1.1.
On built structures	indoor planting	
	green roofs	Intensive green roofs
		Extensive green roofs
		Roof ponds
	green walls	Climber green walls
		Living wall systems
		Build or attached planter systems
Land	Urban paddy fields	
	Horticultural urban gardens	Vegetable gardens
		Urban farms
		Heritage gardens
		Botanical gardens
		Pocket gardens
	Urban orchards and horticultural urban gardens with woody plants	Urban orchards
		Urban vineyards
	Aquaponics	
	Urban Silvopastoral System in lines (living fences)	
	Urban agrisilviculture of trees/hedge strips	
	Urban agrisilviculture of forest gardening	
	Urban woodland, transitional urban woodland, lines of trees and scrub, and individual trees	Single trees
		Planted car parks
		Street trees
		Hedge and planted fences
		Woods
		Urban forests
	Urban grassland and Permanent meadows	Lawns
		Flower fields
		Meadow
		Grass tram tracks
	Urban heathland & scrubs	
		Use of terraces
		Vegetated pergolas
Land for water management	Raingarden	Rain/infiltration gardens
	Swales & bioretention swales	Swales
	Filter strips	Green strips
		De-sealed areas
		Unsealed car parks
Water	Natural drainage corridor	
	Naturalised pond	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

	Bioretention pond	
	Aquaculture	
	Algae Cultivation	
	Floating wetlands	
	Naturalised freshwater and saline wetland	
	Constructed wetland	Constructed wetland for phytoremediation
		Constructed wetland for wastewater treatment
Others		Bio-indicators
		Insect hotels
		Beehives
Mixed	Combination of NBS Type 3	Public green spaces with specific uses
		Public urban green spaces
		Large urban public parks
		Cemetery
		Green waterfront city
Planning		Integration in the flooding map
		Take into account the distribution of the green spaces through the city

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table S4. List of UC indicators of D2.1

1.1.1	**CO2 - Annual carbon sequestration**
1.1.2	GHG - Avoided GHG emissions
1.2.1	**AT - Air temperature**
1.2.2	TLO - Thermal load of outstreaming body
1.2.3	AC - Adaptive Comfort (indoor)
1.2.4	TCS - Thermal Comfort Score (outdoor)
1.2.5	PET - Physiological equivalent temperature
1.2.6	UTCI - Universal thermal climate index
1.2.7	**MRT - Mean radiant temperature**
1.2.8	PT - Perceived temperature
1.2.9	PMV - Predicted mean vote
1.2.10	β - Bowen ratio
2.1.1	EPTvar - Evapotranspiration variation
2.1.2	**SWS - Soil water storage**
2.1.3	PFvar - Peak flow variation
2.1.4	WQ - Water quality
2.2.1	**TROvol - Total runoff volume**
2.2.2	**TRFvol - Total rainfall volume**
2.2.3	**RRR - Total runoff/Total rainfall ratio**
2.2.4	**FAV - Variation of flooded area**
2.2.5	WDT - Water Detention Time
3.1.1	**CAQI - Common Air Quality Index**
3.1.2	EAQLVcity - Exceedance of air quality limit value – City scale
3.1.3	**AAPCV - Annual amount of pollutants captured by vegetation**
3.2.1	EAQLVlocal - Exceedance of air quality limit value – Local scale
4.1.1	**UGSP - Urban Green Space Proportion**
4.1.2	**EHD - Ecological Habitat Diversity**
4.1.3	**AIS - Number of alien invasive species**
4.1.4	**PALHB - Potential of areas likely to host biodiversity**
4.1.5	RNPS - Ratio of Native Plant Species
4.1.6	PSL - Land Use and associated impacts on biodiversity
4.2.1	**BAF - Biotope Area Factor**
4.2.2	**CGS - Connectivity of green spaces**
4.2.3	LUsom – Land use related to Soil organic matter changes
4.2.4	**NDVI - Normalized Difference Vegetation Index**
5.1.1	Cfer - Chemical fertility of soil
5.1.2	EcoF - Ecotoxicology factor
5.1.3	SWI - Soil water infiltration
5.1.4	SBA - Soil biological activity
5.1.5	ScF - Soil classification Factor
5.1.6	SCr - Soil Crusting
5.1.7	Sct - Soil contamination
5.1.8	SMP - Soil macro porosity
5.1.9	SOM - Soil Organic Matter
5.1.10	SR - Soil respiration
5.1.11	SWR - Soil water reservoir for plants

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

5.1.12 | SQ - Soil quality
6.1.1 | EE - Energy Efficiency
6.1.2 | ES - Energy Security
6.1.3 | EIWS - Energy Intensity of Water Supply
6.1.4 | EUA - Energy use in Agriculture
6.1.5 | PCFPV - Per Capita Food Production Variability
6.1.6 | PCFSV - Per Capita Food Supply Variability
6.1.7 | WS - Water Security
6.1.8 | AWW - Agricultural water withdrawal
6.1.9 | BEN - Buildings Energy needs
6.1.10 | CED - Cumulative Energy Demand
6.1.11 | WSc - Water scarcity
6.1.12 | AWC - Absolute Water Consumption
6.1.13 | WE - Water Efficiency
6.1.14 | WI - Water Intensity
6.2.1 | RME - Raw Material Efficiency
6.2.2 | ARDfuels - Abiotic resource depletion – Fossil fuels
6.2.3 | ARDmetalmineral - Abiotic resource depletion – Metal and Mineral
6.3.1 | SWG - Specific waste generation
6.4.1 | ERP - Efficiency of valorisation as a result of recycling processes
6.4.2 | ROL - Rate of landfilling
6.4.3 | ROR - Rate of recycling
7.1.1 | Lden - Day-evening-night noise level
7.1.2 | Lnight - Night noise level
7.1.3 | ENNH - Effects of night noise on health
7.1.4 | PAI – Population Annoyance Index
7.2.1 | QOL - Quality of life
7.3.1 | PH - Perceived health
7.3.2 | HIM - Heat induced mortality
7.3.3 | AQEshort – Air quality indicators: short term health effects
7.3.4 | AQElong – Air quality indicators: long term health effects
8.1.1 | REC - Recognition
8.1.1.1 | PA - Place attachment
8.1.1.2 | BI - Bodily integrity
8.1.1.3 | AES - Availability ES
8.1.2 | PJ - Procedural justice
8.1.3 | DJ - Distributional justice
8.1.3.1 | GEN - Gentrification
8.1.4 | CAP - Capabilities
8.1.5 | RES - Responsibility
8.2.1 | SC - Social capital
9.1.1 | AS - Areal Sprawl
9.1.2 | BN - Betweenness
9.2.1 | BBGM - annual budget of urban blue and green infrastructure management
9.2.2 | Segregation index
10.1.1 | CC - Crime counts
10.1.2 | PC - Perceived crime

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

10.1.3	PCFS - Percentage of citizens feeling safe
10.1.4	PGV - Percentage of gender violence
10.1.5	PV - Percentage of victimization
10.2.1	DPIC - Domestic Property Insurance Claims
10.2.2	NDMP - Number of deaths and missing people
10.2.3	NPIRE - Number of people injured, relocated and evacuated
11.1.1	C&DW - Construction and demolition waste
11.1.2	MCI - Material Circulatory Indicator
11.1.3	RRMW - Recycling rate of municipal waste
11.2.1	**GVAEGS – Gross Value Added in the local Environmental Good & Services sector**
11.2.2	LPB - Labour productivity of bioeconomy
11.2.3	NVATRBB - N° of VAT registered bioeconomy business
11.3.1	ANS - Adjusted Net Saving
11.3.2	**HPI - House Pricing Index**
11.3.3	DIPSB - Direct and indirect public spending on bioeconomy
11.3.4	PIB - Private investment on bioeconomy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table S5a. Literature review on urban system boundaries and urban typologies for environmental aspects (in green: articles from systematic review; in blue: additional articles identified based on references obtained in the papers selected in the systematic literature review)

Authors	Year	Type of indicators (social, economic, environmental / physical, personal...) -	Detailed type and name of the indicators	Availability	System boundary or urban typology or both	Spatial level / level of differentiation (For urban typology only)
Arnaiz-Schmitz et al.	2018	Social, environmental (Combination of social welfare metrics with landscape metrics)	Landscape metrics: Shannon's evenness index, Shannon's diversity index, Patch richness, Splitting index, Edge contrast index, Euclidean nearest neighbor distance, Largest patch index	Can be easily obtained (based on land cover maps and GIS processing)	Boundary	-
Benza et al.	2016	Environmental (Combination of texture metrics with landscape metrics)	Landscape metrics: Patch density, Patch size coefficient of variation, Area weighted mean fractal dimension, Contagion index	Can be easily obtained (based on land cover maps and GIS processing)	Both	Urban region
Budiyantini and Pratiwi	2016	Social, economic and environmental/physical	Physical characteristics: Topographic (Slope, Elevation), Land-use (Area of agricultural land, Area of non-agricultural land), Density, Public facilities, Accessibility	Not easily obtained (various secondary sources)	Urban typology	Urban region
Cárdenas-Rodríguez et al.	2016	Social, economic and environmental/physical	Urban variables (number of fragments,shares of artificial, agricultural, wetland and forest areas, population density, population decentralization, LUZ surface) - Link with air quality (concentrations of NO_2, PM_{10}, SO_2)	Landscape metrics can be easily obtained (based on land cover maps and GIS processing), air quality data depend on available urban air quality platform	Urban typology	Urban region (Large Urban Zones level)
Cochran and Brunsell	2017	Environmental	Landscape metrics: Patch Density (PD), Patch Cohesion Index (PCI), Landscape Shape Index (LSI), Landscape Division Index (LDI)	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Urban region
Deslauriers et al.	2017	Environmental	Connectivity measure in the City Biodiversity Index (CBI) improved with the effective mesh size metric	Can be easily obtained (based on geospatial data and GIS processing)	Urban typology	City and neighbourhood (city part)
Dumas et al.	2008	Environmental	Landscape indices: Percentage of landscape (PLAND), landscape shape index (LSI) and Shannon diversity (SHDI)	Can be easily obtained (based on land cover maps and GIS processing)	Both	Urban region
Fan et al.	2017	Environmental	1) Landscape metrics: 1a) Class-level metrics: PLAND (proportion of the landscape occupied by the patch type), AREA_MN (mean area of all patches of a class in a hectare), FDI (fractal dimension index), PD (patch	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Urban region

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			density), 1b) Landscape-level metrics: SHDI (Shannon's diversity index), SHEI (Shannon's evenness index) - 2) Environmental indicators: total urban green space (GREEN), and green space per capita (GREENpc)			
Godefroid and Koedam	2007	Environmental	Directly urban land use types (based on an available, precise land cover map) - Link with biodiversity indicators: plant species composition and site conditions (21 metrics, including species richness, species rarity, number of exotic species...)	Land cover map can be easily obtained (but location-specific). Biodiversity data generally more difficult to obtain (field data)	Urban typology	Neighbourhood
Gonçalves et al.	2017	Social, economic, environmental/physical, and personal aspects	Indicators of Mobility, Identity and lifestyle, Natural elements, Land cover, Economic activities, Spatial functions	Depend on the data (some easily accessible e.g. land covers, others more difficult to access e.g. local statistics)	Both	Neighbourhood (parishes)
Hamstead et al.	2015	Environmental/Physical	STURLA classes based on land cover and building height types - Link with surface temperature	Can be easily obtained (based on land cover maps, LANDSAT ST data, and GIS processing)	Urban typology	Neighbourhood (urban structure classes)
Herold et al.	2002	Environmental	Spatial metrics: Fractal dimension, percent of landscape, patch density, patch size standard deviation, edge density, area weighted mean patch, contagion index	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neighbourhood
Herold et al.	2003	Environmental (Combination of image texture metrics and spatial metrics)	Spatial metrics: PLAND (Percentage of landscape), PD (Patch density), AREA_MN (Mean patch size), AREA_SD (Area standard deviation), ED (Edge density), LPI (Largest patch index), ENN_MN (Euclidian mean nearest neighbor distance), ENN_SD (Euclidian nearest neighbor distance standard deviation), FRAC-AM (Area weighted mean patch fractal dimension), FRAC-SD (Fractal dimension standard deviation), COHESION, CONTAG - Contagion	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neighbourhood
Herold et al.	2005	Environmental	Spatial metrics: Landscape contagion, Fractal dimension of vegetation patches, Urban patch density, Building nearest neighbor standard deviation	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neighbourhood
Hu et al.	2015	Environmental	Landscape metric: Land-use information entropy (LUIE)	Can be easily obtained (based on land cover	Boundary	-

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

				maps and GIS processing)		
Huang et al.	2007	Environmental	Spatial metrics: AWMSI: area weighted mean shape index, AWMPFD: area weighted mean patch fractal dimension, Centrality, CI: compactness index; CILP: Compactness index of the largest patch, ROS: ratio of open space, density	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Urban region
Kim and Zhou	2012	Environmental	Landscape metrics: Percentage of Landscape (PLAND), Patch Density (PD), Edge Density (ED), Mean Patch Size (MPS), Landscape Shape Index (LSI), Euclidean Nearest-Neighbor Distance (ENN)	Can be easily obtained (based on land cover maps and GIS processing)	Both	Neighbourhood (block and community level)
Larondelle et al.	2014	Environmental	Land cover and building height types - Link with surface temperature	Can be easily obtained (based on land cover maps, LANDSAT ST data, and GIS processing)	Urban typology	Neighbourhood (urban structure classes)
Lowry and Lowry	2014	Environmental	18 spatial metrics (thirteen recommended out of the eighteen metrics)	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neighbourhood
Qureshi et al.	2014	Social, economic and environmental/physical	6 urban indicators: Impervious, Pervious/porous, Green cover, Population, Road network, Socio-economic status	Land cover maps can be easily obtained. Socio-economic studies and geographical surveys generally more difficult to obtain	Both	Urban region
Salvati et al.	2016	Environmental	Spatial metrics: Shannon diversity and Pielou evenness index applied to land-use composition and land imperviousness	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	City (municipal units)
Sandström et al.	2006	Environmental	Spatial treatment of maps (contrasts between man-made built-up features and natural areas, buffer zone from the river...). Link with biodiversity indicators: Bird species richness, abundance and diversity (Shannon's diversity indexes)	Land cover maps can be easily obtained. Biodiversity data generally more difficult to obtain (field data)	Urban typology	Urban region
Schwarz	2010	Social, economic and environmental/physical	Landscape metrics and socio-economic indicators (review)	Publicly available	Urban typology	City
She et al.	2017	Environmental	Landscape metrics (Total Urban Area (CA), Number of urban patches (NP), Largest Patch Index (LPI), Mean Perimeter-area ratio (PARA MN), Mean EuclideanNearest Neighbor Distance (ENN MN)	Lanscape metrics can be easily obtained (based on land cover maps and GIS processing), air quality data	Urban typology	City

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			and Traffic Coupling Factor(CF)) - Link with air quality (concentrations of SO2, NO2, PM10, PM2.5, CO)	depend on available urban air quality platform		
Stearns et al.	2016	Environmental	Temperature data (Tmax and Tmin)	Can be easily obtained (data recorded at meteorological weather stations)	Both	Urban region
Tannier and Thomas	2013	Environmental	Fractal dimension, dendricity, compactness, proportion of buildings close to the urban boundary	Data can be easily obtained, but mathematical treatment can be complex	Both	Urban region
Tratalos et al.	2007	Environmental	Population density, Address density, Building densities, Household density, Proportion detached/semi-detached houses, Proportion social group AB - Link with biodiversity potential (8 measures) and ecosystem performance (run-off, max temperature, carbon sequestration)	Not easily obtained	Urban typology	Neighbourhood
Vanderhaegen and Canters	2017	Environmental - (Combination of 1)patch-based metrics i.e. traditional landscape ecological metrics with 2) profile-based metrics i.e. spatial positioning of built-up and open space areas and 3)building-based metrics i.e. internal structure of the built-up area)	Patch-based metrics: % of landscape, Patch density, Median patch size, Patch size standard deviation, Total edge, Edge density, Mean patch edge, Mean perimeter-area ratio, Mean shape index, Area weighted mean shape index, Mean patch fractal dimension, Area weighted mean patch fractal dimension	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neighbourhood (city block level)
Van de Voorde et al.	2011	Environmental/Physical	Spatial metrics: Average impervious surface cover, shape characteristics of the frequency distribution and spatial variance	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neighbourhood
Voltersen et al.	2014	Environmental/Physical	Building and vegetation features, landscape metrics, 3D density metrics, additional block characteristics	Land cover maps can be easily obtained (data on buildings might be more difficult to obtain)	Urban typology	Neighbourhood
Weng	2007	Environmental	Landscape metrics: Percentage of landscape (PLAND), Shannon's evenness index (SHEI), patch density (PD), and mean patch size (MPS)	Can be easily obtained (based on land cover maps and GIS processing)	Boundary	-
Wu et al.	2017	Social, Environmental/Physical (Combinaison of biophysical landscape, built	Biophysical landscape: Vegetation (Plant species, % Canopy/Shrub/Grass cover, Vegetation connectivity), Soil (% Subsoil Sand\Silt\Clay fraction), Topography (Slop	Some very specific data	Urban typology	Neighbourhood

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

		environment and human population)	position of Depression\Flat\Hilltop, Shoal width, Curvature of the river)			
Zhou et al.	2014	Environmental	Spatial treatment of aerial maps (HERCULES land cover classification)	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neighbourhood

Table S5b. Literature review on urban system boundaries and urban typologies for material flow aspects (green: articles from systematic review; in blue: additional articles identified based on references obtained in the papers selected in the systematic literature review)

Authors	Year	Type of indicators (social, economic, environmental / physical, personal...)	Detailed type and name of the indicators	Availability (the data needed can be easily obtained from public sources or not)	System boundary or urban typology or both	Spatial level (For urban typology only)
Kennedy et al.	2014	Social, economic, environmental/physical (4 layers: Definition of megacity, biophysical characteristics, urban metabolism parameters, role of utilities)	Metabolic flows: water, waste, materials, and all types of energy	Not easily available	Both	City (megacity)
Rosado et al.	2017	Physical	Material Flow Accounting (MFA) indicators: Direct Material Input (DMI), Imports (Imp), Exports (Exp), Domestic Extraction (DE), Domestic Material Consumption (DMC), Net Addition to Stock (NAS), Industrial Production (IP), Domestic Processed Output (DPO) and Recovery	Not easily available (but existing databases)	Urban typology	City
Su et al.	2010	Physical	Emergy-based urban ecosystem health indicators (UEHIem) - 5 aspects: Vigor, structure, resilience, ecosystem service function maintenance, environmental impact	Not easily available (but existing databases)	Urban typology	City
Pelorosso et al.	2017	Physical	Internal and external entropy indicators	Not easily available	Urban typology	City and neighbourhood

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table S5c. Literature review on urban system boundaries and urban typologies for social, infrastructure, economy, infrastructure and energy indicators

Author(s)	Year	**Type of indicators** (social, economic, environmental / physical, personal...) - *Combinaison is precised*	**Detailed type** and **name** of the **indicators**	**Availability** (the data needed can be easily obtained from public sources or not)	**System boundary** or **urban typology** or **both**	For urban typology only: **Spatial level / level of differentiation** (urban region, city/metropolis, neighbourhood)
(Voulgaris *et al.*, 2017)	2017	Socio-economic, mobility.	A set of 20 indicators: Job access, job share, percent jobs, percent office, percent retail, job-housing balance, housing density, job density, activity density, road density, pedestrial density, cart network density, intersection density, transit supply index, percent SFR, percent rented, short-term homes, long-term homes, new homes, old homes	Census and EPA - Environmental Protection Agency US- Smart Location Database. Not easily replicable.	Both	Urban and *suburban* neighbourhoods
(Fusco, 2016)	2016	Built environment, socio-economic (maybe more)	73 indicators have been defined (not listed in the paper): 27 to describe spatial affordance and 46 to describe dwelling regimes (Appendix A and B not included in the paper)	Not easily obtained: GIS data & mobility survey.	Urban typology	Neighbourhoods (areas)
(Gil, 2016)	2016	Mobility, built environment, environmental /physical	**Modal shift:** non motorised share (neighbourhood walking share, neighbourhood cycling share, city cycling share), car share (neighbourhood car share, city car share, regional car share), public transport share (neighbourhood transit share, city transit share, regional transit share) **Travel reduction:** distance travelled (overall total distance, non-motorised distance share, cara distance share, public transport distance share), travel duration (overall total duration, non-motorised duration share, car duration share, public transport duration share), travel frequency (overall number of trips per day **Proximity:** distance to nearest rail station, distance to nearest cycle lane, distance to nearest motorway **Density:** street network connectivity, rail station provision, pedestrian network reach, shops within walking distance, jobs within walking distance	Urban form indicators can be obtained trough GIS meassuring. Mobility and socio-economic data has extracted from the mobility survey of the Netherlands (is more complicated to get this info)	Both	Modality environment types

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			Accessibility: jobs accessible by public transport, jobs accessible by car **Configuration:** network centrality of rail stations, network hierarchy of local cycle network			
(Réquia Júnior, Roig and Koutrakis, 2015).	2015	physical properties, environmental characteristics, and function properties to describe the morphology of the city	There is no any list of indicators. **To define UST:** green area index, income and lotsize. No health related indicators	Spatial data obtained through SIG processing of Orthoimages but health data can be difficult to obtain.	Urban typology	Neighbourhood (Urban Structure Types (UST))
(Solecki *et al.*, 2015).	2015	Socio-economic, Environmental/physical, governance, built environment, infrastructure, energy.	**Demographics:** total population (E), age structure (E), proportion of population who have migrated to city within past 5 years (V) **Socio-economics:** income (V & E), income inequality (V), average years of schooling (A), schooling inequality by income and gender (A) **Institutions and governance:** years sisnce incorporation-formal (A), number of jurisdictions in metro region (A), measure of spatial centrality (X) **Ecosystems and resources:** water availability (scarcity) (V), temperature (X) and precipitation (X), arable land (V) **Built environment, location and land use:** total build land area, urban perimeter, fraction pop. living in informal settlements, flooding vulnerability (V), coastal vulnerability (V), local pollution (V), vertical dimension of city (X) **Infrastructure:** presence of public transit rail system (E), transportation infrastructure (E), transportation modes (X), energy resource, GHG emissions energy consumption (E) **Additional indicators:** Life expectanci (X), population density (E), proportion of state population residing in city (X), decadal growth (V & E), city contribution to national GDP (X) sex ratio (X), percent workforce employed or looking for work actively (X), proportion of households served by safe sanitation (V),	Can be easily obtained. Varied sources (Census, UNDP, World Bank, Urban Plans…).	Urban typology	Neighbourhood

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			households with access to regular solid waste collection (V), climate change action index (V & E), disaster risk index (V), percent wastewater treated (V), percent households with access to safe and regular water supply (V), death rate per 100000 residents (X), household cellphone access (X), percent households with adequate living (V), urban green space (V)			
(Hermosilla *et al.*, 2014)	2014	Environmental/physical, built environment	**Urban block metrics (descriptors of the shape and geoetric properties of urban block polygons, geometric and volumetric attributes regarding buildings and features describing vegetation patches):** Area, Perimeter, Compactness, Shape index, Fractal dimension, Building coverage area, Building coverage ratio, Mean built-up height, Maximum built-up height, Standard deviation of building height, Number of buildings, Built-up volume, Mean built-up volume, Normalised built-up volume, Vegetation covered area, Vegetation covered ratio, Vegetation volume , Normalised vegetation volume **Street based urban metrics (geometry, neighbouring block connectivity, presence of vegetation and relationship with urban block buildings):** UBRSA area, mean street width, standard deviation street width, maximum street width, minimum street width, number of neighbouring urban blocks, UBRSA vegetation covered aea, UBRSA vegetation covered ratio, UBRSA vegetation volume, normalised UBRSA vegetation volume, ratio between the area of the building in an urban block and the area of the UBRSA, ratio between the built-up volume and the area of the UBRSA	Can be easily obtained (remotely sensed data – high spatial-resolution imagery and Li-DAR)	Urban typology	Neighbourhoods
(John H Lowry and Lowry, 2014)	2014	Environmental / physical	18 spatial metrics (13 recommended): **Density:** median single family residential lot size, housing density, median number of rooms, population density,	Can be easily obtained (based on land cover maps and GIS processing)	Urban typology	Neigbourhood

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			average household size **Centrality:** mean distance to commercial zone, mean distance to public parks, mean distance to K-12 schools, mean distance to transit bus stops **Accesibility:** street conectivity, median perimeter of residential blocks, dendritic street patterns, median length of cul-de-sacs **Neighbor-hood mix:** land use contiguity, land use richness, land use diversity, pop. working outside city of residence, renter-owner balance			
(Zeng, He and Cui, 2014)	2014	Socio-economic, infrastructure and environmental/ physical	**Composition:** Built-up patch density, percentage of settlement area, percentage of transportation area, percentage of industrial site and percentage of built-up land for special use, percentage of development zone. **Configuration:** shannon diversity index, shannon entropy, shape index, derived contagion index, perimeter-area fractal index, spatial autocorrelation index. **Gradient:** Area-distance coefficient, density-distance coefficient **Density:** population density, non-agricultural population, density, GDP density, fixed asset invesment, density **Proximity:** proximity to sub-center, proximity to transportation, proximity to city center **Accesibility:** comprehensive highway index, comprehensive railway index, comprehensive aviation index **Dynamics:** settlement centroid migration, transportation centroid, migration	Can be easily obtained (land use maps, Geographic information and statistical info)	Urban typology	Parcel, district (neighbourhood) and Metropolitan area (City/metropolis)
(Song, Popkin and Gordon-Larsen, 2013)	2013	Environmental / physical	A set of 27 metrics (6 to 9 selected depending on Neigbourhood size): **Permeability:** road length, road density by road types (primary roads with limited access, primary roads without limited access, secondary roads, local roads with lower speed limits and possibly sidewalks), intersection density, intersection	Land cover, census and aerial photographs can be easily obtained. Add Health - a school based longitudinal survey of youths- the information from this data source has to be generated.	Urban typology	Neigbourhood

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			proportion, cul-de-sac density, connectivity beta index, connectivity gamma index, connectivity alpha index, connectivity cyclomatic index **Vitality and accesibility:** development area, land patch size and density (meand land patch size, root mean squared error in patch size, land patch density) **Variety measures:** land type richness, recreation, natures, rural area, parks, Simpson's diversity index, contagion index, perimeter-area fractal dimension, mean shape index, mean fractal dimension index			
(da Costa, Fumega and Louro, 2013)	2013	Environmental /physical, socio-economic, infrastructures, environmental, mobility, built environment and governance	A set of 111 indicators categorized in 8 groups (and subgroups): **Housing and built environment:** Housing (16 indicators), Green urban areas (2), land use (8) **Local economy:** education (3), employment (8), household income and expenses (3) **Transport and connectivity:** roads and public transport system (5), mobility (19), connectivity (2) **Services:** Satisfaction with services (1), health services and facilities (1), education services and equipment (5), other services (2) **Environment:** natural resources (2), recycling (2), urban sanitation (3) **Social and cultural:** services and facilities for leisure sports and culture (6), satisfaction with services (2), security (2) **Equity and social capital:** feeling of belonging and involvement with the community (6), community (9) **Governance:** confidence (1), information (1), participation (2)	Statistics from official sources, cartography related to land use can be easily obtained. Surveys are difficult to obtain (necessary to generate this data)	Urban typology	Neigbourhood
(Manaugh, Miranda-Moreno and El-Geneidy, 2010)	2010	Environmental/physical, socio-economic, infrastructure, built environment, mobility	The paper is a previous version and is uncompleted so we don't know exactly the indicators that have been selected. Some are mentioned but we are not pretty sure about them, but they have been clasiffied in the following way: **Land use:** open space, park, commercial, residential, industrial, institutional, water,	Origin destination survey difficult to obtain. Urban form variables (covering land use, employment, economics, demographics and sevice accesibility) can be easily obtained (based on census and	System boundary	City / Region

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

				length of train track, total length of road, separate length of local roads, separate length of major roads and separate length of expressways **Employment:** number of manufacturing jobs, total number of workers, total number of people with a high scholl diploma, total number of people with trade school certification, total number of people with university degree **Housing/demographics:** average household size, average number of children, median household income, average number of bedrooms, average numver of rooms, dwelling types, year of construction **Service accesibility:** accesibility to downtown, commuter train /bus, restaurants, retails **Economics:** average dwelling value, average rent, median household income	land cover maps and GIS processing)		
Schwarz	2010	Environmental/ physical, built environment and socio-economic	A set of 38 indicators have been selected regarding landscape and population related indicators to define cities considering their urban form (<u>6 are selected as minimum</u>): **Landscape metrics:** <u>size of continuous area</u>, size of discontinuous area, size of total area, size of sealed urban area, area weighted mean patch fractal dimension, area weighted mean shape index, centrality index, compactnesss index, <u>compactness index of the largest patch</u>, share of continuous/residential land, share of continuous/urban land, <u>edge density,</u> median patch size, mean perimeter-area ratio, mean patch edge, <u>mean patch size, number of patches,</u> number of districts, patch size coefficient of variance, patch size standard deviation, porosity, total edge, share of sealed urban area **Population related indicators:** Total land area (km2) according to cadastral register (UA), index of dissimilarity in population distribution, dwelling number, Gini coefficient of population distribution, household	Data can be easily obtained from Urban Audit initiative and Corine Land Cover.	Urban typology	City/metropolis

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			number, density of housing, density of housing in urban land, population density - total resident population per square km (UA), population number, density of population, density of population in urban land, sealed urban area per person **Socio-economic:** car availability, GDP per capita, proportion higher education, IT availability, percentage of households with internet access at home.			
(del Valle *et al.*, 2009)	2009	Socio-economic and infrastructures (ICT)	**Human capital:** Bachelor's degree/population >16; Bachelor's degree + secondary/population >16; creative classes/ total of occupieds (CEOs; professionals and techinicians with high qualification; support techinicians and proffesionals) **Economy of knowledge:** employment in high-tech intensity industries; employment in services based in knowledge; employment in other creative sector; employment in innovation cluster **Innovative effort:** investment in CDTI projects; exporting company; patents and utility models; Companies with quality accreditation) **Digital networks:** RDSI and ADSL lines	Publicly available (at least in Spain)	Urban typology	City/metropolis
(Schneider and Woodcock, 2008)	2008	Environmental /physical, built environment	A set of 9 indicators: **Size of built-up area and rate of change:** spatial extent of urban area in 1990 and 2000, amount of new urban land 1990-2000, percentage increase 1990-2000 anual percentage increase **Density of built-up land:** ratio of amount of urban land to all land 1990 and 2000, change in density of urban land:difference in ratio of urban expansion to all land 1990-2000 **Fragmentation scatter:** patch density 1990-2000, percentage change in patch density **Population density:** population per sq km of urban land, ratio of hange in population to change in amount of built-up land	Landsat images and census data both can be easily obtained	Urban typology	City/metropolis

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

(Zandvliet and Dijst, 2006)	2006	Socio-economic, mobility	Socio-economic characteristic of population: work, leisure, social activities, used public transport, travel time>30, travel time <10, destination municipality is not residential municipality, high educational level, no cars available, used car, used bicycle, residential municipality at a higher spatial scale, residential municipality at a lower spatial scale, ages<12, education, age 18<30, couple-workers-adult, female, single-worker-adult, low income, high income, two or more cars available, non-worker-adult, age>65	National travel surveys (it can be difficult to obtain the same data considering that each nation can be looking for different info)	Both	Urban, suburban and rural municipalities - city/metropolis
(Thinh *et al.*, 2002)	2002	Environmental/ physical and socio-economic	A set of 11 indicators: Settlement and transport landtake, population density, settlement density, recreation area provision , open space provision, degree of sealing in urban nucleus , eco-value of urban nucleus (non dimensional), gross value-added measured, gross value-added of settlement areas and transport land, land price in form of purchase values for developed land and unemployment rate	Land price value and land use info (based on land cover maps - CORINE and DLM-and GIS processing) can be easily obtained	Urban typology	City/metropolis
(Huang, Lai and Lee, 2001)	2001	Energy, socio-economic, built environment and environmental	The paper mention 30 indicators (24 are selected): **Emergy index:** Transformity, total empower density, turnover time, emergy investment ratio, per capita emergy used, per capita fuel emergy used, ratio of waste to renewable emergy, fraction of renewable emergy used, ratio of waste to total emergy used, fraction of fuel emergy used, fraction of electricity emergy used **Resource consumption:** wastewater generation, water consumption, solid waste generation, natural gas, imported goods, imported services **Renewable emergy:** rain (geopotential), altitutde, rain (chemical), solar energy **Economic activity:** labor input, electricity use, fertilizer use, gasoline use, imported petroleum products **Urbanization:** urban productivity, wind energy, distance to urban core, population migration	Geographic (land use and GIS processing) can be easily obtained. Economic and statistic data regarding energy consumes is more difficult to obtain.	Urban typology	Neigbourhood

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table S5d. Reference list of environmental indicators and material flow storage indicators

Environmental indicators	(Herold, Scepan and Clarke, 2002b; Herold, Liu and Clark, 2003; Herold, Couclelis and Clarke, 2005; Sandström, Angelstam and Mikusiński, 2006; Huang, Lu and Sellers, 2007; Tratalos *et al.*, 2007; Weng, 2007; Godefroid and Koedam, 2007; Dumas, Jappiot and Tatoni, 2008; Schwarz, 2010a; Van de Voorde, Jacquet and Canters, 2011; Kim and Zhou, 2012; Tannier and Thomas, 2013; John H. Lowry and Lowry, 2014; Larondelle *et al.*, 2014b; Qureshi, Haase and Coles, 2014b; Voltersen *et al.*, 2014; Zhou *et al.*, 2014; Hu *et al.*, 2015; Benza *et al.*, 2016; Hamstead *et al.*, 2016; Budiyantini and Pratiwi, 2016; Salvati *et al.*, 2016b; Stearns, Sakai and Joseph, 2016; Cárdenas Rodríguez, Dupont-Courtade and Oueslati, 2016; Deslauriers *et al.*, 2016; She *et al.*, 2017; Vanderhaegen and Canters, 2017; Wu *et al.*, 2017; Cochran and Brunsell, 2017; Fan *et al.*, 2017; Gonçalves *et al.*, 2017; Arnaiz-Schmitz *et al.*, 2018)
Material flows/storage indicators	(Su, Chen and Yang, 2010; Kennedy *et al.*, 2014; Pelorosso, Gobattoni and Leone, 2017; Rosado, Kalmykova and Patrício, 2017)

.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

Table S7. Geocluster4NBS indicators

category	code	Name	Description / domain	spatial	temporal	update	format source	responsible	original data
		NUTS1	major socio-economic regions	NUTS1		2013	EPSG:4326	GE2O consortium (contact RINAC)	Eurostat
		NUTS2	basic regions for the application of regional policies	NUTS2		2013	EPSG:4327	GE2O consortium (contact RINAC)	Eurostat
		NUTS3	small regions for specific diagnoses	NUTS3		2013	EPSG:4328	GE2O consortium (contact RINAC)	Eurostat
Climate	Z.1.1	Average annual Heating Degree Days	Heating Degree Days (base air temperature BizEE software: 19°C).	NUTS3	years avg	2013	EPSG:4329	GE2O consortium (contact RINAC)	GE2O
	Z.1.2	Average annual Cooling Degree Days	Cooling Degree Days (base air temperature BizEE software: 26°C).	NUTS3	years avg	2013	EPSG:4330	GE2O consortium (contact RINAC)	GE2O
	Z.1.3	Annual incident energy on a south oriented 45° slope	Annual incident energy on a south oriented plane with a 45° Slope.	NUTS3	years avg	2013	EPSG:4331	GE2O consortium (contact RINAC)	GE2O
	Z.1.4	Annual incident energy on a south oriented vertical surface	Annual incident energy on a south oriented vertical surface	NUTS3	years avg	2013	EPSG:4332	GE2O consortium (contact RINAC)	GE2O
	Z.1.5	Annual Average External air Temperature	Average ambient temperature over year.	NUTS3	years avg	2013	EPSG:4333	GE2O consortium (contact RINAC)	Eurostat
	Z.1.6	Average Heating Seasonal External Air Temperature	Average Heating Seasonal External Air Temperature (Based on air floating average temperature of the last 15 days < 19°C).	NUTS3	years avg	2013	EPSG:4334	GE2O consortium (contact RINAC)	Eurostat
	Z.1.7	Average Cooling Seasonal External Air temperature	Average Cooling Seasonal External Air Temperature (Based on air floating average temperature of the last 15 days > 26°C).	NUTS3	years avg	2013	EPSG:4335	GE2O consortium (contact RINAC)	Eurostat
	Z.1.8	Maximum Annual External Air temperature	Maximum ambient temperature over year.	NUTS3	years	2013	EPSG:4336	GE2O consortium (contact RINAC)	Eurostat
	Z.1.9	Annual Average Ground / Water Temperature	Annual Average Ground / Water Temperature.	NUTS3	years avg	2013	EPSG:4337	GE2O consortium (contact RINAC)	Eurostat

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

	Z.1.10	Average Heating Seasonal Ground / Water Temperature	Average Heating Seasonal Ground / Water Temperature (Based on air floating average temperature of the last 15 days < 19°C).	NUTS3	years avg	2013	EPSG:4338	GE2O consortium (contact RINAC)	Eurostat
	Z.1.11	Average Cooling Seasonal Ground / water Temperature	Average Cooling Seasonal Ground / Water Temperature (Based on air floating average temperature of the last 15 days > 26°C).	NUTS3	years avg	2013	EPSG:4339	GE2O consortium (contact RINAC)	Eurostat
	Z.1.12	Average ambient wet bulb temperature over cooling season	Average ambient wet bulb temperature over cooling season.	NUTS3	years avg	2013	EPSG:4340	GE2O consortium (contact RINAC)	Eurostat
	Z.1.13	Average ambient temperature during daylight over cooling season	Average ambient temperature during daylight over cooling season.	NUTS3	years avg	2013	EPSG:4341	GE2O consortium (contact RINAC)	Eurostat
	Z.1.14	Average solar irradiation during daylight over cooling season	Average solar irradiation during daylight over cooling season on a south oriented plane with a 45° slope	NUTS3	years avg	2013	EPSG:4342	GE2O consortium (contact RINAC)	Eurostat
Building Typlogy	Z2.1	Age of Construction	Number of buildings constructed during the reference period.	NUTS3	before 1945; 1946-1960; 1961-1980; 1981-2000; after 2001;	2013	EPSG:4343	GE2O consortium (contact RINAC)	Eurostat
	Z.2.2.1	Use Residential	Building is considered as residential building if more than half of the floor area is used for dwelling purposes. Other buildings should be regarded as non-residential buildings (commercial, hospital, offices).	NUTS3	years avg	2013	EPSG:4344	GE2O consortium (contact RINAC)	Eurostat
	Z.2.2.1.1	Use Residential - Single	Use - Redidential > Single.	NUTS3	years avg	2013	EPSG:4345	GE2O consortium	Eurostat

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

								(contact RINAC)	
	Z.2.2.1.2	Use Residential - Apartment Flats	Use - Redidential > Apartment Flats.	NUTS3	years avg	2013	EPSG:4346	GE2O consortium (contact RINAC)	Eurostat
	Z.2.3.1	U-value for wall	A U-value is a measure of heat loss in a building wall. It can also be referred to as an 'overall heat transfer co-efficient' and measures how well parts of a building transfer heat.	NUTS3	before 1945; 1946-1960; 1961-1980; 1981-2000; after 2001;	2013	EPSG:4346	GE2O consortium (contact RINAC)	Tabula Project
	Z.2.3.2	U-value for roof	A U-value is a measure of heat loss in a building roof. It can also be referred to as an 'overall heat transfer co-efficient' and measures how well parts of a building transfer heat.	NUTS3	before 1945; 1946-1960; 1961-1980; 1981-2000; after 2001;	2013	EPSG:4346	GE2O consortium (contact RINAC)	Tabula Project
	Z.2.3.3	U-value for floor	A U-value is a measure of heat loss in a building floor. It can also be referred to as an 'overall heat transfer co-efficient' and measures how well parts of a building transfer heat.	NUTS3	before 1945; 1946-1960; 1961-1980; 1981-2000; after 2001;	2013	EPSG:4346	GE2O consortium (contact RINAC)	Tabula Project
Socio - economic	Z.3.1	Population living in the area at last census	Population living in the area at last census.	NUTS3	years avg	2013	EPSG:4347	GE2O consortium (contact RINAC)	Eurostat
	Z.3.2	Gross domestic product of the area at last census	Gross domestic product (GDP) is a measure for the economic activity. It is defined as the value of all goods and services produced less the value of any goods or services used.	NUTS3	years avg	2013	EPSG:4348	GE2O consortium (contact RINAC)	Eurostat
	Z.3.3	Gross domestic product in construction	Market value of all officially recognized final goods and services produced within construction	NUTS3	years avg	2013	EPSG:4349	GE2O consortium (contact RINAC)	Eurostat

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468

			sector within a country in a given period of time, expressed as aggregates at current prices.						
	Z.3.4	Employment rate	Measures the proportion of the country's working-age population (ages 15 to 64 in most OECD countries) that is employed.	NUTS3	years avg	2013	EPSG:4350	GE2O consortium (contact RINAC)	Eurostat
	Z.3.5	Employment in construction	Measures the proportion of the country's working-age population (ages 15 to 64 in most OECD countries) that is employed in construction sector.	NUTS3	years avg	2013	EPSG:4351	GE2O consortium (contact RINAC)	Eurostat
	Z.3.6	Labour cost	Total expenditure borne by employers for the purpose of employing staff (incl. employee compensation (including wages, salaries in cash and in kind, employers' social	NUTS3	years avg	2013	EPSG:4352	GE2O consortium (contact RINAC)	Eurostat
	Z.3.7	Gas prices for household consumers	This indicator presents the natural gas prices charged to final consumers.	NUTS1	years avg	2013	EPSG:4353	GE2O consortium (contact RINAC)	Eurostat
	Z.3.8	Electricity prices for household consumers	Electricity prices charged to final consumers (without taxes).	NUTS1	years avg	2013	EPSG:4354	GE2O consortium (contact RINAC)	Eurostat
	Z.3.9	Disposable income of households	Disposable income of households	NUTS3	years avg	2013	EPSG:4355	GE2O consortium (contact RINAC)	Eurostat
	Z.3.10	Electricity consumption of households	Defined as the quantity of electricity consumed by households. Household consumption covers all use of electricity for space and water heating and all electrical appliances.	NUTS1	years avg	2013	EPSG:4356	GE2O consortium (contact RINAC)	Eurostat

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730468