Clearing House

Research and Innovation Action (RIA)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242

Start date : 2019-09-01 Duration : 48 Months
http://clearinghouseproject.eu

Report on a novel standardised Sino- European UFBS typology

Authors : Mrs. Sebastian SCHEUER (HU Berlin), JACHE Jessica (HUB), WELLMAN Thilo (HUB), WOLFF Manuel (HUB), HAASE Dagmar (HUB)

Clearing House - Contract Number: 821242

Project officer: Sofie VANDEWOESTIJNE

Document title	Report on a novel standardised Sino- European UFBS typology
Author(s)	Mrs. Sebastian SCHEUER, JACHE Jessica (HUB), WELLMAN Thilo (HUB), WOLFF Manuel (HUB), HAASE Dagmar (HUB)
Number of pages	72
Document type	Deliverable
Work Package	WP1
Document number	D1.1
Issued by	HU Berlin
Date of completion	2021-03-31 17:50:12
Dissemination level	Public

Summary

This deliverable outlines the CLEARING HOUSE typology of urban forests as nature-based solutions (UF-NBS). The typology thus conceptualizes entities relevant to UF-NBS. To do so, elements of greenblue infrastructure (GBI) are defined in the typology. Contrary to purely textual representations of knowledge, CLEARING HOUSE proposes a definition of GBI elements through traits, i.e., characteristic and defining morphological, physical, functional, and institutional attributes, including for example the composition, spatial grouping, and topology of UF-NBS elements, and the ecosystem services and benefits provided them. CLEARING HOUSE proposes a semantic approach to express this knowledge, i.e., a formalization of knowledge as an ontology using the Web Ontology Language. Such ontologies are machineinterpretable series of statements of facts to define a taxonomy (a vocabulary). The definitions of GBI elements are embedded within a formalization of overarching concepts, particularly, of urban forest, nature-based solutions (NBS), and of UF-NBS. Here, urban forest is conceptually understood as the entirety of trees within an urban-ecological system. NBS are perceived in CLEARING HOUSE as an overarching concept that embraces natural and semi-natural elements of the GBI such as forests, engineered solutions such as permeable pavements, as well as actions inspired by nature. UF-NBS are then conceptualized as the intersection of the two previous entities, i.e., as the intersection of urban forest and NBS, and thus include any tree-related NBS. The proposed typology will provide the grounding knowledge of the comparative case study analysis to be conducted by CLEARING HOUSE, and will serve as a basis for the development of the CLEARING HOUSE benchmarking tool.

Approval

Date	By
2021-03-31 18:55:13	Dr. Rik DE VREESE (EFI)
2021-03-31 18:55:57	Dr. Rik DE VREESE (EFI)

Outlining a semantics-based Sino-European UF-NBS typology (Deliverable 1.1)

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

REFERENCE

Scheuer, S., Jache, S., Wellmann, T., Wolff, M., & Haase, D. (2021). Outlining a semantics-based Sino-European UF-NBS typology (Deliverable 1.1). H2020 project CLEARING HOUSE, grant no. 821242.

STATUS AND REVISIONS

Version	Date	Author	Partner	Description
DRAFT	23/10/2020	Scheuer, S., Wolff, M., Haase, D.	HUB	Working draft for online workshop (M1.2)
DRAFT	17/03/2021	Scheuer, S., Jache, J., Wellmann, T., Wolff, M., Haase, D.	HUB	Draft for approval
1.0	30/03/2021	Scheuer, S., Jache, J., Wellmann, T., Wolff, M., Haase, D. Basnou, C., Roitsch, D.	HUB	Revised draft for approval

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

EXECUTIVE SUMMARY

This deliverable outlines the CLEARING HOUSE typology of urban forests as nature-based solutions (UF-NBS). The typology thus conceptualizes entities relevant to UF-NBS. To do so, elements of green-blue infrastructure (GBI) are defined in the typology. Contrary to purely textual representations of knowledge, CLEARING HOUSE proposes a definition of GBI elements through traits, i.e., characteristic and defining morphological, physical, functional, and institutional attributes, including for example the composition, spatial grouping, and topology of UF-NBS elements, and the ecosystem services and benefits provided them.

CLEARING HOUSE proposes a semantic approach to express this knowledge, i.e., a formalization of knowledge as an ontology using the Web Ontology Language. Such ontologies are machine-interpretable series of statements of facts to define a taxonomy (a vocabulary). The definitions of GBI elements are embedded within a formalization of overarching concepts, particularly, of urban forest, nature-based solutions (NBS), and of UF-NBS. Here, urban forest is conceptually understood as the entirety of trees within an urban-ecological system. NBS are perceived in CLEARING HOUSE as an overarching concept that embraces natural and semi-natural elements of the GBI such as forests, engineered solutions such as permeable pavements, as well as actions inspired by nature. UF-NBS are then conceptualized as the intersection of the two previous entities, i.e., as the intersection of urban forest and NBS, and thus include any tree-related NBS.

The proposed typology will provide the grounding knowledge of the comparative case study analysis to be conducted by CLEARING HOUSE, and will serve as a basis for the development of the CLEARING HOUSE benchmarking tool.

KEYWORDS

nature-based solutions; urban forests as nature-based solutions; green-blue infrastructure; green-blue infrastructure elements; typology; grouping principles; morphology; function; traits; ontology; taxonomy; semantic model; Web Ontology Language; controlled natural language

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

TYPOGRAPHIC CONVENTIONS

In this document, the following typographic conventions apply to specific Web Ontology Language (OWL) features and/or constructs:

`Large Urban Park`	class
`is composed of`	property
`TREPTOWER PARK`	individual

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

LIST OF FIGURES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

LIST OF TABLES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

1 Introduction

1.1 Making a case for the CLEARING HOUSE UF-NBS typology

This document starts with an introductory case to illustrate a typical application field of the typology which will be presented:

CLEARING HOUSE case study Leipzig. The city of Leipzig, as many other cities in Europe, suffers from unequal access and availability to recreational green space including trees that provide cool and fresh air as well as enjoyment. Planning new recreational spaces is a complex endeavour. The here developed typology can serve in supporting the choice of the NBS type which best suits for local recreation and the way trees can be assembled. It can further serve with information about co-benefits of tree-planting and—in a prospective sense—the impact of heat and drought on the trees planted (being linked with a traits database such as CiTree[1]).

1.2 Objectives

The intent of the typology to be developed in the CLEARING HOUSE project is, due to the nature of the CLEARING HOUSE project, to define types of tree-based/forest-based nature-based solutions (UF-NBS). The proposed UF-NBS typology of the CLEARING HOUSE project, in the following referred to as UF-NBS typology, builds upon existing typologies of nature-based solutions and/or green-blue infrastructure (GBI). These typologies—particularly the types they define as well as the grouping principles they employ—were reviewed for developing the UF-NBS typology and were subsequently aligned and integrated (when feasible). In addition, the UF-NBS typology considers types of UF-NBS not previously defined in these typologies, as they were identified through the review of academic and grey literate (cf. D1.2). In the CLEARING HOUSE typology, types of UF-NBS are defined on traits, i.e., distinct and defining characteristics. These traits are derived from a set of grouping principles that include morphological attributes, e.g., object grouping and form; physical attributes, e.g., location and biophysical processes; functional attributes, i.e., ecosystem services and thus benefits provided; and institutional, management and governance attributes, e.g., accessibility or entitlements.

1.3 Determining the scope and purpose of the CLEARING HOUSE typology

1.3.1 Scope of the CLEARING HOUSE typology

The scope of the proposed UF-NBS typology is first, urban forestry/urban forests (UF), and second, nature-based solutions (NBS). In this context, nature-based solutions (NBS), following the European Commission, are understood as “solutions that are inspired and supported by nature” (European Commission, 2015). This is similar to the notion of NBS proposed by the IUCN (Hanson et al., 2020). However, while the European Commission includes within the NBS concept what could be referred to as engineered elements, i.e., artificial, man-made solutions “inspired by nature” (European Commission, 2015; Nature4Cities, 2018), the IUCN stresses that NBS refers to actions to protect, manage, and/or restore ecosystems (Cohen-Shacham et al., 2016; Hanson et al. 2020). Somarakis et al. (2019) emphasize that NBS subsumes manifold types of actions, and identify the better use of

[1] cf. https://citree.de/

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

protected ecosystems, more sustainable and multifunctional managed ecosystems, and the design and management of new ecosystems as three main types of NBS interventions. In either case, emphasis is given to the fact that NBS shall provide (multiple) benefits, to address societal, environmental or economic challenges (Almenar et al., 2021; Hanson et al., 2020).

However, it also needs to be noted that the nature of NBS may not be fully comprehended only based on actions, since various neighbouring concepts are relevant. These neighbouring concepts include, e.g., ecological engineering, ecosystem (dis-)services or green-blue infrastructure (Almenar et al., 2021; Somarakis et al., 2019). Green infrastructure[2] is understood as all interconnected natural, semi-natural and man-made landscape elements that (could) form a green-blue network (Vlaamse Landmaatschappij, 2019). Following Suppakittpaisarn et al. (2019), GBI refers to the natural areas in urban spaces that improve urban ecology and provide social, environmental, and economic benefits; this closely resembles the provisioning of ecosystem services as crucial aspect of NBS.

The UF-NBS typology proposed for CLEARING HOUSE builds on these definitions and conceptualizes NBS in a broader perspective. Thus, the NBS definition proposed for this typology embraces: (i) actions, e.g., for the implementation, restoration, or management of green-blue infrastructure; (ii) the classification of such green-blue infrastructure elements, e.g., as an urban park; (iii) and benefits, i.e., in particular the ecosystem services intended as outcomes of actions or provided by elements of the green-blue infrastructure. In line with the NBS notion proposed by the European Commission (2015), the proposed CLEARING HOUSE typology additionally includes man-made, artificial and thus engineered elements.

In relation to the more specific objectives of the CLEARING HOUSE project, the typology further conceptualizes urban forests as nature-based solutions (UF-NBS) in the context of NBS and GBI. To do so, the typology assumes a perspective that formalizes UF-NBS as intersection of neighbouring entities (Figure 1), particularly, NBS on the one hand, and the conceptual urban forest on the other, with the latter being considered as the totality of trees in an urban area, inclusive of individual street trees and clusters of trees in city parks etc. (Davies et al., 2017; Endreny, 2018; Konijnendijk, 2003).

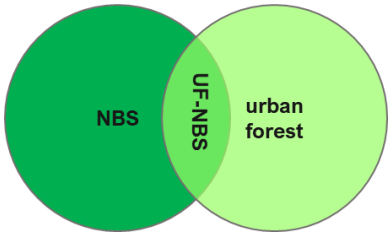

Figure 1. Graphical representation of the proposed UF-NBS concept that is understood as the intersection of the neighbouring conceptual entities NBS and urban forest.

[2] in the following, the term green-blue infrastructure (GBI) will be used synonymously for both the green infrastructure and the blue infrastructure

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

1.3.2 Purpose of the CLEARING HOUSE typology

The purpose of the typology is: (i) to define distinct types of UF-NBS; (ii) to devise a systematic taxonomy of UF-NBS types; and (iii) to embed defined types and their taxonomical relationships within a definition of overarching concepts. These overarching concepts include the urban forest concept, the green-blue infrastructure concept, and the concepts of NBS and UF-NBS, respectively. The knowledge that will be formalized in this typology provides the grounding knowledge for the comparative case study analysis of CLEARING HOUSE and will provide one basis for the development of the CLEARING HOUSE UF-NBS benchmarking tool (cf. section 5.1).

1.4 Review of existing typologies

The following section provides a brief outline of existing NBS typologies to address potential shortcomings or challenges for implementing the proposed UF-NBS typology.

The GREEN SURGE project proposes an inventory of urban green spaces from a green infrastructure perspective (Cvejić et al., 2015). The inventory describes 44 different types of urban green space elements, including, for example, street green, green roofs, large urban parks, as well as selected elements of blue infrastructure, including lakes/ponds, rivers, or canals. These types are grouped into various categories, i.e., building green; private, commercial, industrial, institutional urban green spaces and urban green spaces connected to grey infrastructure; riverbank green; parks and recreation; allotments and community gardens; agricultural land; natural, semi-natural and feral areas; and blue spaces. In regard to this classification schema used by GREEN SURGE, it must be noted that the proposed categories lack in coherence, as multiple aspects such as institutional accessibility (public, private), use (commercial, industrial etc.), or topology (connection to grey infrastructure) are used undifferentiated and in combination for some categories, whereas for other categories, some of these aspects are implied only but not explicitly stated, or not applied altogether. Function (in terms of empirical evidence for provided ecosystem services) is provided in tabular form, but is not applied to group urban green space types. Consequently, whilst the types (elements) of urban green spaces as defined by GREEN SURGE are of relevance, the applied classification schema would require revision to be more systematic.

The Urban Nature Labs typology structures NBS pragmatically based on concepts from a planning and construction perspective (Eisenberg & Polcher, 2019). The devised categories include greening interventions, public green spaces, vertical greening, green roofs, water sensitive urban design measures, (river) restoration, measures of bioengineering, and other nature-based solutions, hence, mixing management and interventions strategies such as channel widening or daylighting with types of NBS such as residential park, boulevards, or bioswale. For each NBS, a type is stated as well as challenges addressed, and their performance regarding selected ecosystem services. As additional grouping principles are not applied, the proposed classification features a comparatively flat taxonomy of concepts.

The ThinkNature project proposes a multilevel classification schema for NBS that considers (i) the level and type of engineering or management applied to biodiversity and ecosystems; (ii) the chosen overall NBS approach; (iii) the NBS challenge a type shall address; and (iv) the delivered ecosystem services (Nikolaidis et al., 2019). This approach considers demand (challenge) and function (in form of delivered

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

ecosystem services) and encapsulates various types of urban green spaces within its schema, as well as NBS. However, in the resulting classification, types of NBS are intertwined with approaches to their management. A revised classification approach may further differentiate this level for improved coherence.

Nature4Cities (Nature4Cities, 2018) constructs and characterizes types of NBS through a set of variables to cluster cases, and express relationships between them, in order to achieve a large-spectrum, accessible, flexible and compact classification. Nature4Cities (2018) propose another multilevel approach of nested categories to classify NBS, that distinguishes, at the top level, between (constructed) physical object-/shape-based properties as well as actions and strategies, thus resulting in a twofold typology. This is similar to the wider notion of NBS proposed for CLEARING HOUSE. Relevant types of NBS are related to physical properties, that are differentiated according to the following subcategories referring to physical support (soil cover): (i) on the ground; (ii) water; and (iii) on building structures. Within each subcategory, various classes are defined, including parks and gardens, structures associated with urban networks, structures characterized by food and resources production, natural and semi-natural water bodies and hydrographic network, constructed wetlands and build structures for water management, green roofs, and green walls. Similar to ThinkNature, the typology proposed by Nature4Cities reflects upon physical features of NBS. Function is considered mainly through the naming of categories, however, challenges—for example, resource efficiency, biodiversity, climate adaptation, or water management and water quality—are linked to each defined type of NBS.

Looking at these examples of typologies, it follows that various grouping principles may be used to support a classification schema, including physical properties, function, actions and strategies for (sustainable) management, principles that stem from planning and construction, or challenges addressed by an NBS. We subsequently propose to include grouping principles based on morphology (form), physical properties (physical appearance and features, location, and topology), function (ecosystem services, traits), as well as institutional attributes (governance, management, property rights such as private or public or institutional accessibility) However, when applying multiple grouping principles at once, it also follows that a typology must find a means to deal with one-to-many cardinalities, that is often rather neglected in existing typologies (cf. Example 1). To consequently achieve a systematic grouping of UF-NBS based on multiple grouping principles we propose to employ semantic modelling for building the UF-NBS typology within CLEARING HOUSE.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Example 1

The GREEN SURGE typology implies—through the naming schema of their categories—that a large urban park has public access (Cvejić et al., 2015). A semantic equivalent is defined in the Nature4Cities typology as large urban public park (Nature4Cities, 2018). However, we argue that both concepts may be invariant, i.e., that the actual green space type they refer to is the same "thing". However, it also needs to be acknowledged that different large urban parks may have different properties, e.g., in regard to size in terms of total area (i.e., reflecting on the attribute "large"), or regarding modes of institutional accessibility (e.g., public or semi-public, or with/without temporally (un-)restricted access). Consequently, when applying such grouping principles, a one-to-many cardinality results, requiring that a given type of urban green space may be a member of different categories of (a) grouping principle(s). Such one-to-many (as well as possible many-to-many relationships) are rather neglected in existing typologies.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

2 Semantic modelling of the UF-NBS domain

We propose the UF-NBS typology to be based semantics, hence, to employ semantic modelling and semantic languages in designing the typology and to thus implement the UF-NBS typology in form of an ontology. An ontology can be referred to as a formal, machine-interpretable specification of a consensual conceptualization of a specific domain, i.e., an abstract model that identifies relevant terms—concepts—within the domain (subject) in question, and that defines axioms to account for the intended meaning of these terms (Atkinson et al., 2006; Baader et al., 2004; Chandrasekaran et al., 1999; Gašević et al., 2006; Kalfoglou, 2001). Here, within the scope of the UF-NBS typology, domain refers to the concept of urban forest, i.e., the totality of UF-NBS.

In an ontology, entities—i.e., concepts, phenomena or objects of the real world—are prescinded and formalized through classes, for example, **`forest`**. For a given class, axioms may be defined to further specify the meaning of the class in question, i.e., through the formulation of taxonomic relationships that include aspects of inheritance, the formalization of specific relationships between different classes, or through providing the vocabulary to express traits, e.g., through restrictions in the form of object or datatype properties, and/or cardinality restrictions. In addition to the definition of classes, ontologies may also include so-called individuals, i.e., instances of classes. Individuals correspond to specific real-world entities (see example 2 and the glossary of terms). Ontologies additionally support the use of annotations, i.e., labels and comments, that may be used to convey "human-readable" definitions and meaning in addition to formal statements. Annotations can be provided in multiple languages. Documentation and interactive visualizations of the ontology can be generated automatically[3] in form of HTML, e.g., to be made accessible online (Figure 2 and section 6).

Example 2

Let us consider some distinct **`Urban Park`**, *for example, the Clara-Zetkin-Park in the city of Leipzig, or* `TREPTOWER PARK` *and* `TEMPELHOFER FELD` *located in the city of Berlin. Here, in OWL,* **`Urban Park`** *refers to a class, and we may define the three examples as individuals* `CLARA-ZETKIN-PARK`, `TREPTOWER PARK` *and* `TEMPELHOFER FELD` *of the class* **`Urban Park`**, *so that they represent instances of this class. Regarding the example of* **`forest`** *(in terms of class), an individual would correspond to an actual forest in terms of forest stand/forested area, e.g.,* `ELSTER-PLEIßE-AUWALD` *(Leipzig) or* `GRUNEWALD` *(Berlin).*

[3] WIDOCO, cf. https://zenodo.org/badge/latestdoi/11427075

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

The proposed ontology will be built supported by controlled natural language (CNL), which makes stating/reading semantic facts easier compared to other, e.g., XML-based syntax. The required editing tool is freely available for academic use (research and education)[4]. Alternatives in form of open-source editing and visualization tools are also available[5]. An example of a CNL statement and corresponding alternative syntax that are commonly used in semantic web applications, i.e., OWL/XML and RDF/XML, are given in Table 1.

Table 1. Example of a controlled natural language (CNL) statement as used for the proposed ontology, and corresponding alternative syntax used by other editors.

Syntax	**Expression**
CNL	`Something is a single-street-tree if-and-only-if-it is a single-tree that has-physical-location Ground-Based and is-adjacent-to a street.`

OWL/XML	`<EquivalentClasses>`
	`  <Class IRI="SingleStreetTree" />`
	`  <ObjectIntersectionOf>`
	`  <Class IRI="SingleTree" />`
	`  <ObjectSomeValuesFrom>`
	`  <ObjectProperty IRI="hasPhysicalLocation" />`
	`  <ObjectOneOf>`
	`  <NamedIndividual IRI="GroundBased" />`
	`  </ObjectOneOf>`
	`  </ObjectSomeValuesFrom>`
	`  <ObjectSomeValuesFrom>`
	`  <ObjectProperty IRI="isAdjacentTo" />`
	`  <Class IRI="Street" />`
	`  </ObjectSomeValuesFrom>`
	`  </ObjectIntersectionOf>`
	`  </EquivalentClasses>`

RDF/XML	`<owl:Class rdf:about="#SingleStreetTree">`
	`  <owl:equivalentClass>`
	`  <owl:Class>`
	`  <owl:intersectionOf rdf:parseType="Collection">`
	`  <rdf:Description rdf:about="#SingleTree" />`
	`  <owl:Restriction>`
	`  <owl:onProperty rdf:resource="#hasPhysicalLocation" />`
	`  <owl:someValuesFrom>`
	`  <owl:Class>`
	`  <owl:oneOf rdf:parseType="Collection">`
	`  <rdf:Description rdf:about="#GroundBased" />`
	`  </owl:oneOf>`
	`  </owl:Class>`
	`  </owl:someValuesFrom>`
	`  </owl:Restriction>`
	`  <owl:Restriction>`
	`  <owl:onProperty rdf:resource="#isAdjacentTo" />`
	`  <owl:someValuesFrom rdf:resource="#Street" />`
	`  </owl:Restriction>`
	`  </owl:intersectionOf>`
	`  </owl:Class>`
	`  </owl:equivalentClass>`
	`  <rdfs:subClassOf>`
	`  </owl:Class>`

[4] Cognitum's Ontarion Fluent Editor 2015, cf. https://www.cognitum.eu/semantics/FluentEditor/

[5] E.g., Protégé, cf. https://protege.stanford.edu/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

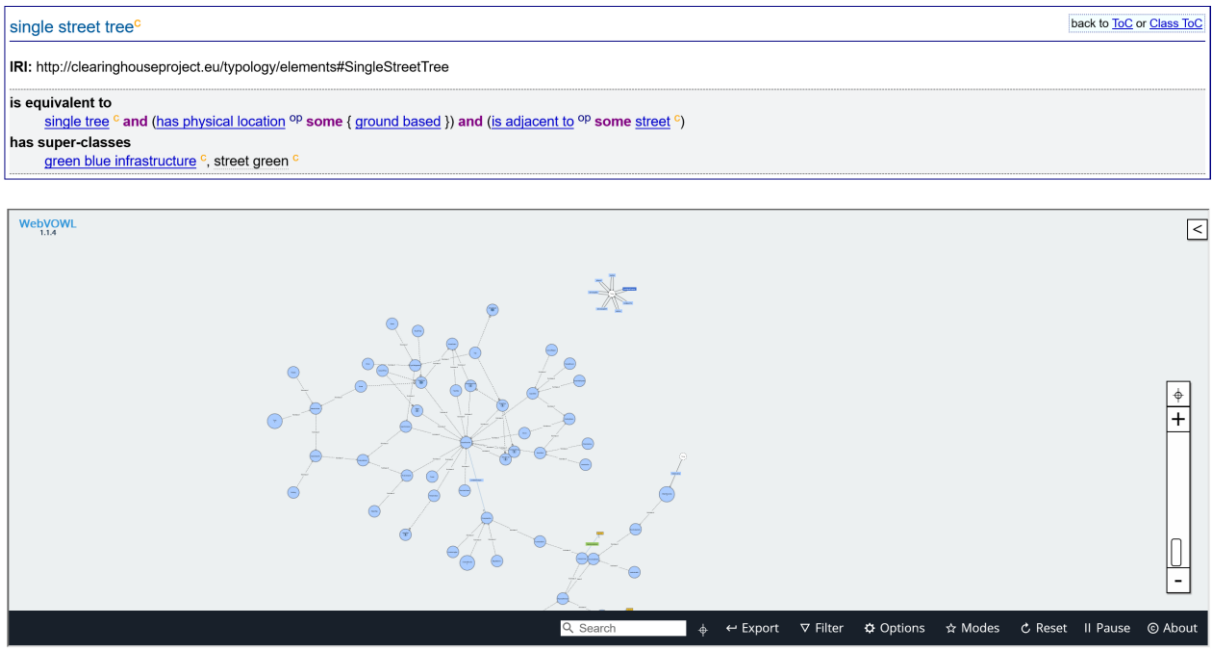

Figure 2. Generated typology documentation is browser-based and includes descriptions of concepts (top) with an interactive visualization of the class taxonomy (bottom). Here, classes are shown as circles, and taxonomical relationship is indicated as directed, labelled graph. Properties are shown as rectangles.

Due to their formal, machine-interpretable character, ontologies provide the possibility to perform reasoning and inference, i.e., querying and reasoning on captured knowledge. This would, e.g., allow users to infer a type of UF-NBS not from stating the class (type) itself (i.e., the user describing something as a specific type), but from the description of its traits that in turn are defining characteristics of a given UF-NBS. Thereby, the description of UF-NBS avoids an a priori and deterministic specification of UF-NBS types, but allows a certain level of fuzziness and overlaps between them. That is also why ontologies, as extendible knowledge implementation methods, provide a profound basis for the implementation of knowledge-based systems, particularly when compared to spreadsheet-like solutions. Other advantages and disadvantages of using ontologies, including possible mitigation strategies, are outlined in Table 2.

Example 3

In a traditional sense, an urban green space may be assigned a type a priori*, based on an underlying classification schema and the textual definitions provided therein. I.e., for example, the* ELSTER-PLEIßE-AUWALD *in Leipzig may be designated a* **`riparian forest`**. *The CLEARING HOUSE typology, being an OWL ontology, allows reasoning and inference on the formalized knowledge. Thus, an UF-NBS type must not be designated* a priori*, but may be inferred from the expressed traits of an UF-NBS. The* ELSTER-PLEIßE-AUWALD*, for example, may be described as a forested area, i.e., an area of 5900 hectares with a canopy cover of more than 50%, adjacent to the rivers Elster and Pleiße. A semantic reasoner may infer, based on the UF-NBS typology, that the* ELSTER-PLEIßE-AUWALD *is an instance of (i.e., of the type)* **`riparian forest`**.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Table 2. Advantages and disadvantages of semantic modelling regarding the proposed UF-NBS typology, and possible mitigation strategies.

Aspect	**Advantage**	**Disadvantage**	**Mitigation strategies**
Character	Formal implementation of domain knowledge	Steeper initial effort compared to spreadsheet- or word-based solutions	
Expressed knowledge	Trait-based, consistent, and coherent specification of UF-NBS types, taxonomies, and relationships	Identification of traits required higher effort when compared to purely text-based definitions	Build upon existing classification schemas/typologies
	Ensures a common and shared understanding of information	Consensus needed amongst project partners	Prioritize most relevant UF-NBS, iterative development cycles
Readability	Machine-readable and machine-interpretable	Readability for human users potentially reduced	Provide annotations and visualizations
Re-usability	Provides a strong basis for implementation of knowledge-based tools due to the availability of reasoning and inference	Semantic tools required	
	Reusability and extensibility by adding or referencing knowledge of additional domains (modular character)	Possibly less easily adapted or re-used by third parties compared to spreadsheet or word-based solutions due to the technical nature	Provide annotations and visualizations

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

3 Implementation of the UF-NBS ontology

The ontology building process involves multiple steps, including the specification of scope and purpose of the proposed ontology, the semantic modelling, i.e., conceptualization of concepts through (taxonomical) relationships and axioms, the actual implementation of the ontology, here, using CNL, as well as its evaluation, i.e., testing and maintenance (Gómez-Pérez et al., 2004; Scheuer et al., 2013). In the following, aligned to the typical phases of ontology building, we outline the (initial) assumptions and principles behind the draft UF-NBS typology[6] in form of the ontology and describe the guiding principles for its design.

3.1 Scope and purpose of the ontology

Section 1.3 set out the scope and purpose of the proposed UF-NBS typology. This section describes the purpose in more detail, based on so-called use cases. Here, a use case is understood as a specific purpose or goal to be achieved by the UF-NBS implementation; it can be considered as a product description. Use cases described earlier are again summarized in Table 3 and Figure 3; additional use cases may be formulated iteratively.

Table 3. Summary of use cases.

No	Title	Description
1	Define distinct UF-NBS types and actions	The purpose of the UF-NBS typology is to define and describe distinct UF-NBS, i.e., NBS actions and types that are tree-based or forest-based (here collectively referred to as UF-NBS).
2	Devise a systematic taxonomy of UF-NBS	The UF-NBS typology shall formalize a systematic taxonomy of the UF-NBS types and actions it defines.
3	Embed defined types and actions and their taxonomical relationships within a definition of overarching concepts	The UF-NBS typology should define overarching concepts, including the concepts of NBS/UF-NBS themselves, as well as the concepts of green-blue infrastructure and urban forest, respectively. The relationships between these overarching concepts and the defined UF-NBS types should be formalized accordingly.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

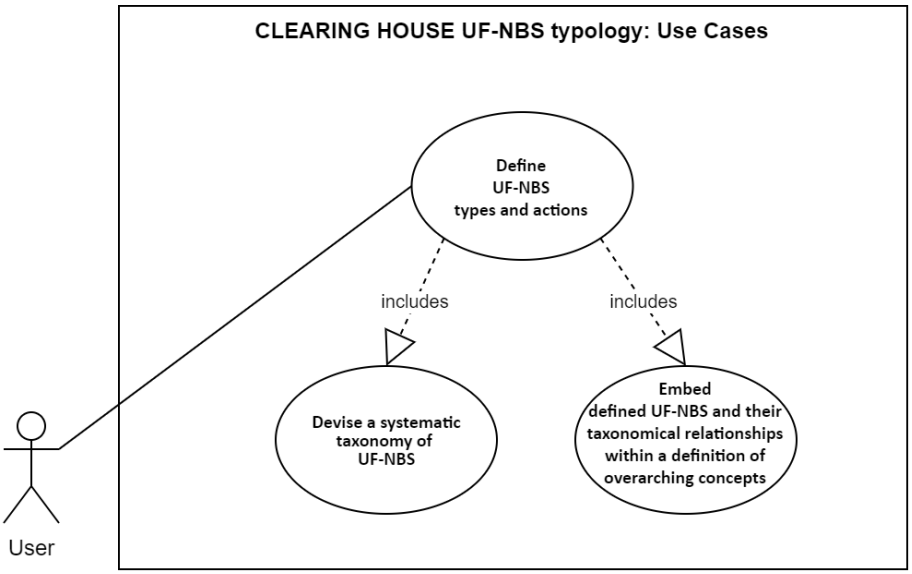

Figure 3. Summary of use cases.

In addition to specifying the product to be delivered, use cases have the additional purpose to aid in eliciting relevant information for the typology. To do so, for each use case, competency questions are formulated (Scheuer et al., 2013). Competency questions shall also ensure a common and shared understanding of the knowledge formalized in the UF-NBS typology. Table 4 summarizes the competency questions for the use cases currently identified for the UF-NBS typology.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Table 4. Summary of competency questions.

Use case	Competency question	Answer
1	What distinct types and actions of UF-NBS need to be included in the UF-NBS typology?	Reviewing existing typologies, concepts/entities to potentially be formalized in the UF-NBS typology encompass natural and semi-natural areas including forests, orchards/tree meadows, urban green spaces such as urban parks or historical gardens, areas with specific functions or purposes such as cemeteries, as well as green elements associated with network infrastructure elements, e.g., street trees or green verges. An analysis of findings from Task T1.2 additionally emphasizes concepts potentially of relevance, including tree nurseries, plantations, and the urban food forest. T1.2 further aided in eliciting actions of relevance including, for example, afforestation and reforestation action, tree and forest monitoring, or orchard restoration. The specific relevancy of each of these entities shall be reviewed under careful consideration of the scope of the UF-NBS typology, and more relevant entities prioritized for formalization.
	What is the definition of a forest stand?	Generally, a forest can be understood as an area dominated by trees. Janssen & Rosu (2015) consider a tree-dominated area (i.e., a treed area) those areas with a canopy cover of at least 50%. Moreover, following FAO (2018), a forest is a portion of land bigger than 0.5ha (5000m^2), covered by forest trees. We consider any treed area that meets this size condition a forest, or within an urban area, an urban forest (in terms of forest stand).
	What is the definition of a forest tree?	Following FAO (2018), trees with a tree height of more than 5m at maturity, or a tree able to reach this condition in-situ, may be referred to as forest tree.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Table 4 *continued*

Use case	Competency question	Answer
2	Which grouping principles can be identified to provide a basis for deriving a taxonomy of concepts?	To derive a systematic description of UF-NBS, and thereby a taxonomic tree of concepts, CLEARING HOUSE proposes to consider: (i) form and topology; (ii) physical attributes such as location; (iii) functional attributes, particularly, the provisioning of ecosystem services; and (iv) institutional attributes.
3	How is urban forest defined conceptually?	The urban forest is defined to comprise all trees in the urban area (Konijnendijk, 2003), inclusive of individual street trees and clusters of park trees, and peri-urban forests extend to the outer metropolitan area. Within the urban forest, forest types include city parks and urban forests, gardens with trees, trees on streets or in public squares, and any other green spaces with trees, such as riparian corridors, rooftops, and nurseries (Endreny, 2018; Davies et al., 2017). Patarkalashvili (2017) refers to it as the sum of green tissue.
	What is an NBS?	Following the definition of NBS proposed by the European Commission (2015), and as discussed in Almenar et al. (2021), we conceptualize NBS as entities providing—through natural functions or by design—one or more ecosystem services. This subsumes green-blue infrastructure elements, as well as engineered elements—e.g., permeable pavements—under the NBS definition. This further includes actions that seek the provisioning, improvement, or maintenance of ecosystem services.
	What is an UF-NBS?	Based on the above definition of the concept of urban forest and the understanding of NBS, UF-NBS are understood in CLEARING HOUSE as the intersection of these two framing concepts, i.e., NBS linked to trees and by extension the urban forest concept.
	What is the definition of green-blue infrastructure, and how are thus elements of the green-blue infrastructure defined?	Green and blue infrastructure is to be understood as all natural and semi-natural landscape elements that (could) form a green-blue network. It can refer to landscape elements on various spatial scale levels: from individual rows of trees to complete valley systems (Vlaamse Landmaatschappij, 2019).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

3.2 Conceptualization and formalization of relevant entities

3.2.1 Formalization of grouping principles

We group UF-NBS types based on various grouping principles, that are derived, e.g., through the review of existing typologies and literature. These grouping principles are formalized through an OWL class **grouping principle**, that in turn is superclass to in the classes **morphological attribute**, **physical attribute**, **functional attribute**, and **institutional attribute**, describing concepts such as institutional accessibility (Figure 4).

The morphology (form) of UF-NBS types is described through (non-)grouping of elements (as in solitary tree, row of trees, or group of trees). We thus define a class **object grouping** to implement this aspect, and define the necessary individuals including SOLITARY, LINEAR-GROUP and CLUSTERED-GROUP etc. accordingly—e.g., following approaches by Lehmann et al. (2014) and Arlt et al. (2005). These individuals express corresponding spatial arrangements of objects akin to 0D (point), 1D (line) or 2D (plane, cf. Figure 5). In that way, in perspective, also GIS geometry types may be linked to the typology's definition of form.

Physical attributes are used to describe, for example, the physical location of landscape elements and their topology, as well as physical processes or planting conditions such as **sealing**, i.e., PAVED or UNPAVED. Topological relations such as adjacency or containment are formalized through a set of object properties, including is adjacent to, is within, is enclosed by (Figure 6). To describe physical location, the UF-NBS typology proposes a concise taxonomy of classes, e.g., **location not associated with a support structure**, **location on support structure**, **location on building**, and defines individuals to describe specific conditions, e.g., GROUND-BASED, ON PERGOLA, ON BUILDING FAÇADE, etc. (Figure 7).

Furthermore, the typology considers physical processes, e.g., PHOTOSYNTHESIS, TRANSPIRATION, EVAPORATION, SHADING, but also processes such as FLOODING. Relevant processes are used, first, to express the biophysical functions that are the basis of the corresponding ecosystem services. This is conceptualized as follows: **something** contributes-to **physical process phenomenon**. For example, **water bodies** contribute-to EVAPORATION, or **type of vegetation** contributes-to TRANSPIRATION and PHOTOSYNTHESIS. Then, processes are linked to ecosystem services by defining an equivalence of roles: **something** that contributes-to **physical process phenomenon** provides ecosystem service **ecosystem service**. For example, entities that contribute to transpiration provide the ecosystem service regulation of air temperature and humidity. Entities that contribute to PHOTOSYNTHESIS provide the ecosystem services CARBON SEQUESTRATION as well as CARBON STORAGE. Second, processes are used to express specific process-related traits. For example, being affected by FLOODING as a characteristic trait to of **riparian forest**.

To capture function, we consider ecosystem service provisioning (formalized at the level of **NBS** as described below, and implemented through an object property provides ecosystem service; cf. Figure 8). Following MA (2005), we consider ecosystem services broadly as the many different benefits that ecosystems provide to people. From a root class **ecosystem service**, we define subclasses as required to represent specific types of ecosystem services, e.g., **supporting service**, i.e., services

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

such as nutrient cycling and soil formation, which are needed for the production of all other services (Science for Environment Policy, 2015); **`provisioning service`**, i.e., products obtained from ecosystems, such as food or timber (Science for Environment Policy, 2015); **`regulation and maintenance service`**, i.e., the benefits obtained from the regulation of ecosystems, including services such as purification of water, flood control, or regulation of the climate via carbon sequestration (Science for Environment Policy, 2015); and **`cultural service`**, i.e., the benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences (Science for Environment Policy, 2015). We then define OWL individuals respectively, e.g., `HERITAGE VALUE`. Relevant ecosystem services may be assigned either to specific classes or individuals such as (a specific genus/species of) tree, or be assigned to compositions of such elements, i.e., green-blue infrastructure elements or NBS. As described above, ecosystem services may also be derived based on physical processes, i.e., biophysical functions that an entity contributes to. In addition, it is also implied that a given characteristic (such as a passive or active recreational use) may be attributed to a specific combination of present **`landscape element`**.

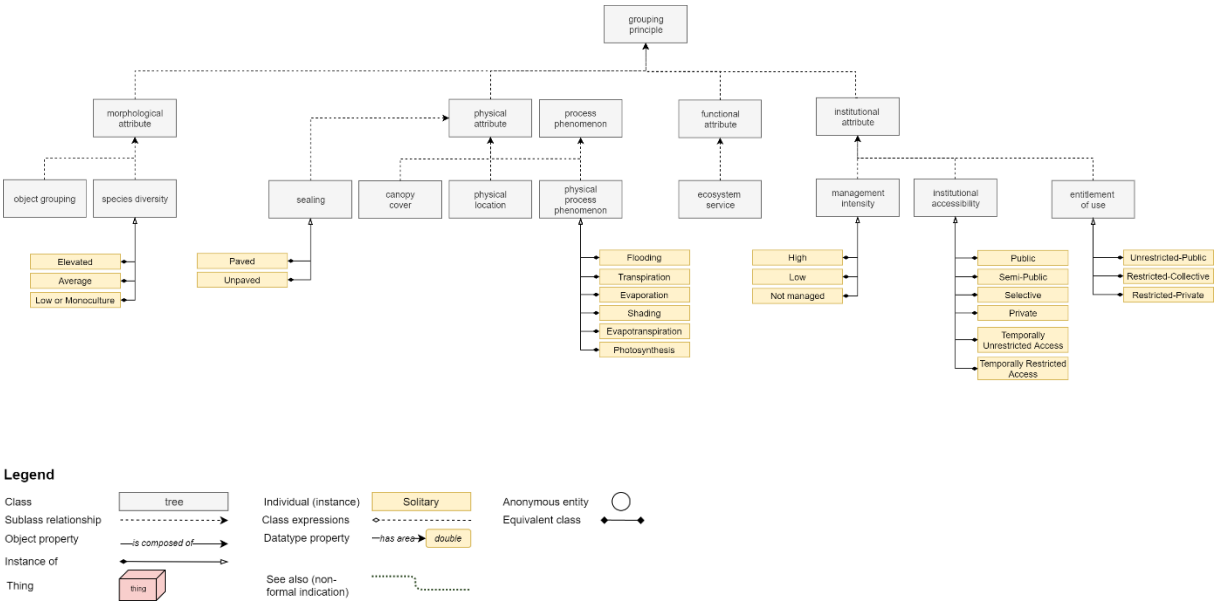

Figure 4. Formalization of grouping principles proposed for the UF-NBS typology (see also the Glossary for further explanations). In addition to classes and their taxonomy, individuals are shown that are used throughout the typology for the expression of distinct traits (cf. also Figure 5 to Figure 8).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Institutional, governance or management attributes that we initially consider for the CLEARING HOUSE typology include **`management intensity`**, **`institutional accessibility`** and **`entitlement of use`**. Management intensity reflects on the inputs necessary for the maintenance of GBI elements, e.g., in terms of labour. The latter two concepts are used to express different means of access and entitlement of use (Nissen, 2008). We conceptualize accessibilities `PUBLIC` (unlimited access, typically publicly owned spaces); `SEMI-PUBLIC` (typically accessible by everyone, however, often privately owned or managed so that restrictions may apply); `SELECTIVE` (access for a defined group of individuals); and `PRIVATE` (restricted access). To express temporal restrictions, e.g., opening times, we furthermore devise the concepts `TEMPORALLY UNRESTRICTED ACCESS` and `TEMPORALLY RESTRICTED ACCESS`, to be used in combination with the other accessibility concepts, as required. Concomitantly, to express entitlements of use of spaces, we devise the concepts `UNRESTRICTED-PUBLIC` (generally unrestricted use), `RESTRICTED-COLLECTIVE` (use restricted to a collective/defined group of individuals); and `RESTRICTED-PRIVATE` (generally restricted use).

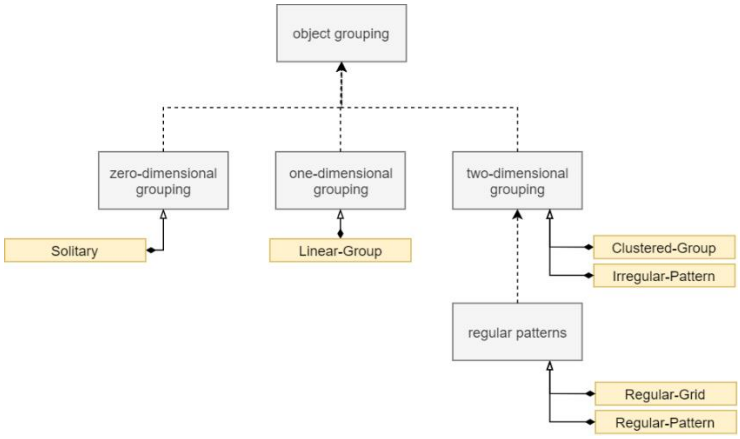

Figure 5. Formalization of object grouping. The categories zero-dimensional grouping (0D), one-dimensional grouping (1D) and two-dimensional grouping (2D) reflect on similar geometric dimensions, with Solitary expressing a single object (akin to a 0D geometric point, e.g., single tree); Linear-Group expressing line or row of objects (akin to a 1D geometric line, e.g., a row of trees); and two-dimensional grouping expressing objects grouped clusters, or in a given type of (regular) pattern (akin to a 2D geometric plane, e.g., trees in plantations).

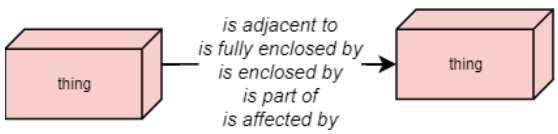

Figure 6. Formalization of object properties to describe topological relationships between entities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

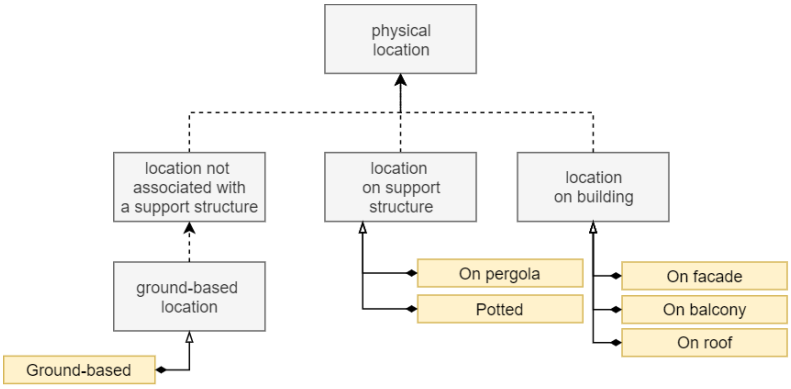

Figure 7. Formalization of physical locations.

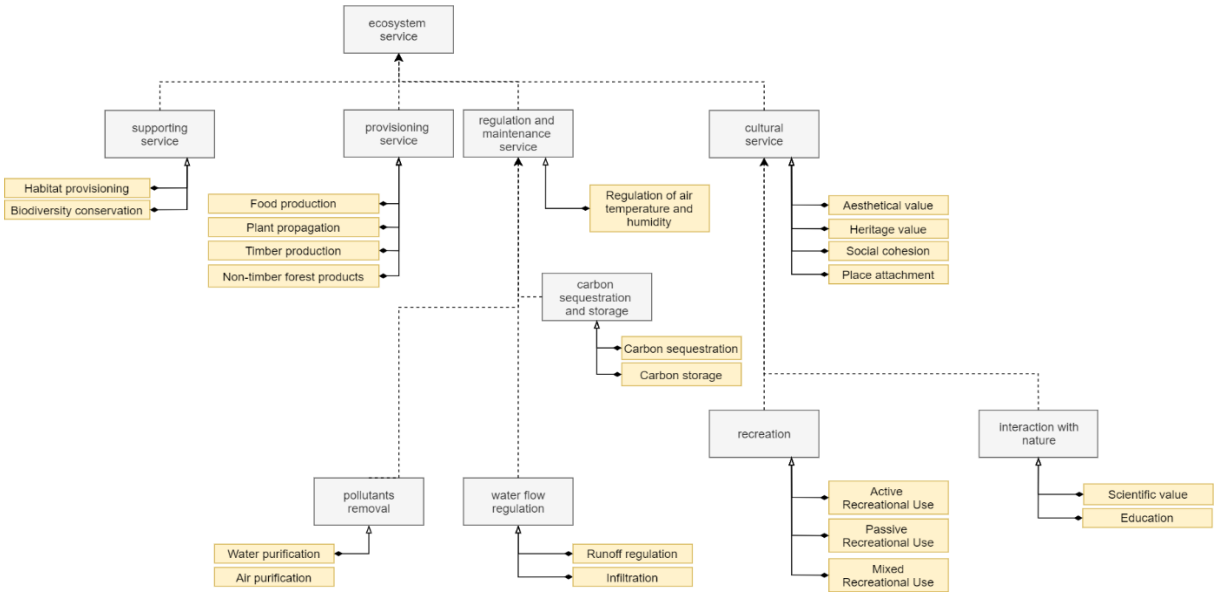

Figure 8. Formalization of ecosystem services.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

3.2.2 Formalization of landscape elements

We consider so-called landscape elements to be all entities that are derived from a common superclass, **`landscape element`**, and we subsequently define a taxonomy of such landscape elements through a set of subclasses including **`green landscape element`** (defining, e.g., different types of vegetation), **`blue landscape element`** (defining different bodies of water), and **`grey landscape element`** defining, e.g., street networks, buildings, or other infrastructure facilities. All landscape elements are considered a **`spatial entity`**. Spatial entities are entities that cover a given geographic (measurable, spatial) area (conceptualized by the property has area). Landscape elements are conceptualized as the building blocks of elements of green-blue infrastructure.

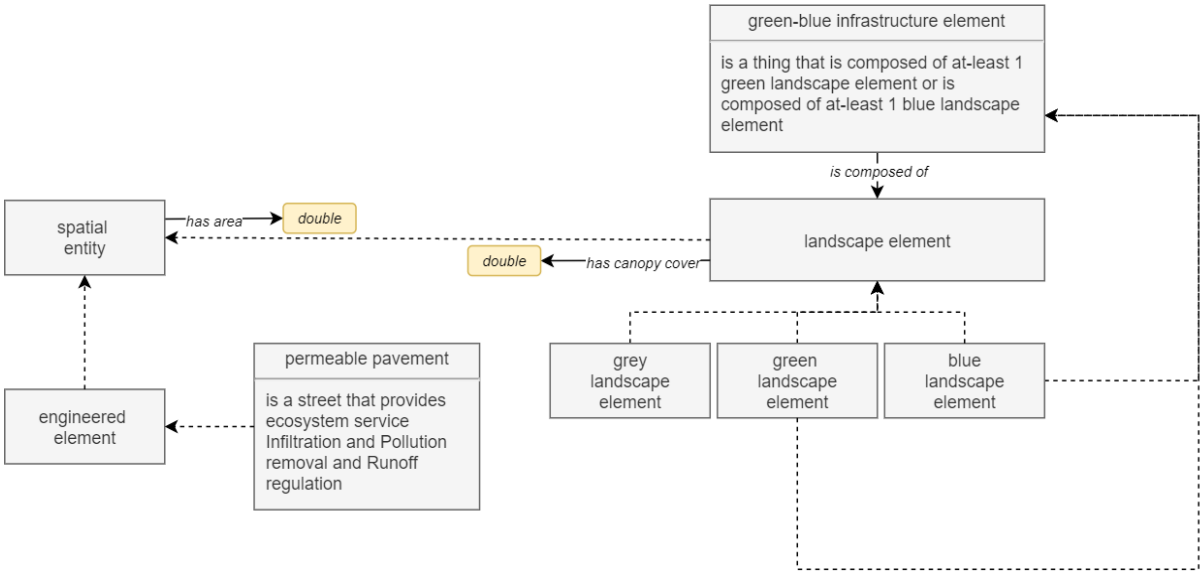

Figure 9. Taxonomy of landscape elements, and examples of engineered elements.

3.2.2.1 Green landscape elements

The class **`green landscape element`** encompasses, in principle, all entities derived from selected types of vegetation, including the classes **`non-woody vegetation`** (**`grass`**) and **`woody vegetation`** (**`shrub`**, **`tree`**, **`hedge`**). From these entities, the UF-NBS typology derives various types of tree-based entities based on morphological and physical attributes, e.g., **`single tree`**, **`single street tree`**, **`row of trees`** and **`group of trees`** etc. (Figure 10). Moreover, for trees, several datatype properties are included to express various tree traits, following Helletsgruber et al. (2020). Besides has mature height and has height, these traits include has trunk circumference, has crown area, has crown base, has crown volume, has leaf area index, and has leaf area density (Figure 11). As a function of has mature height, the UF-NBS typology distinguishes between **`forest tree`** and **`non-forest tree`**.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

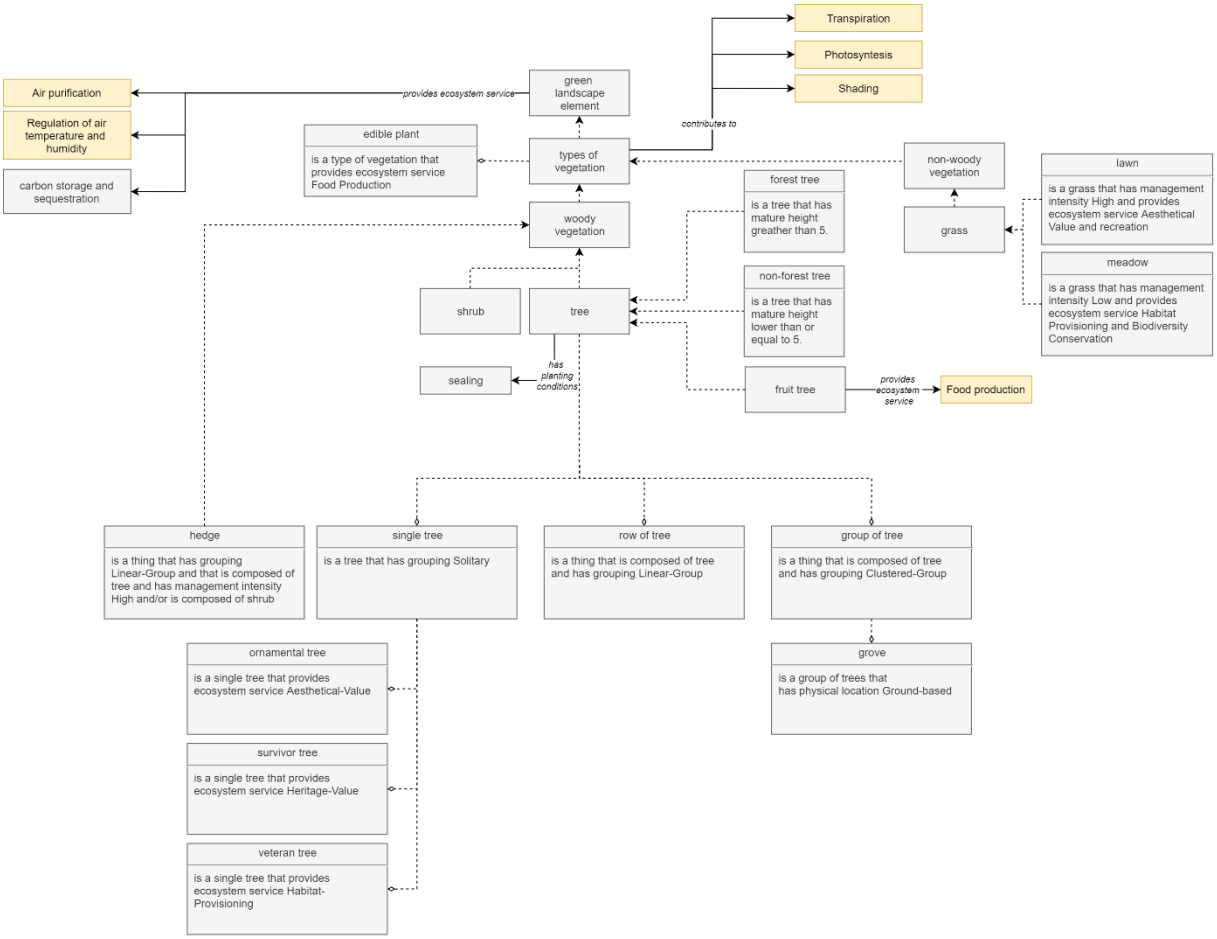

Figure 10. Formalization of green landscape elements. The tree class provides an anchor point for the integration of tree-specific databases.

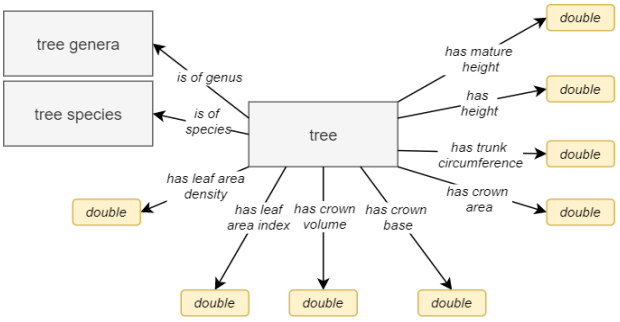

Figure 11. Formalized tree traits following Helletsgruber et al. (2020).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

3.2.2.2 Blue landscape elements

Blue landscape elements include different types of water bodies. As the objective of CLEARING HOUSE is the development of a UF-NBS typology, only those bodies of water are broadly captured in the typology as needed for distinguishing different types of relevant UF-NBS, e.g., **`riparian forest`**, or **`riverbank green`**. They include permanent body of standing water, e.g., **`lake`**, and **`pond`**, as well as different types of **`watercourse`**, e.g., **`river`**, **`stream`**, **`canal`**, as well as the **`wetland`** class (Figure 12).

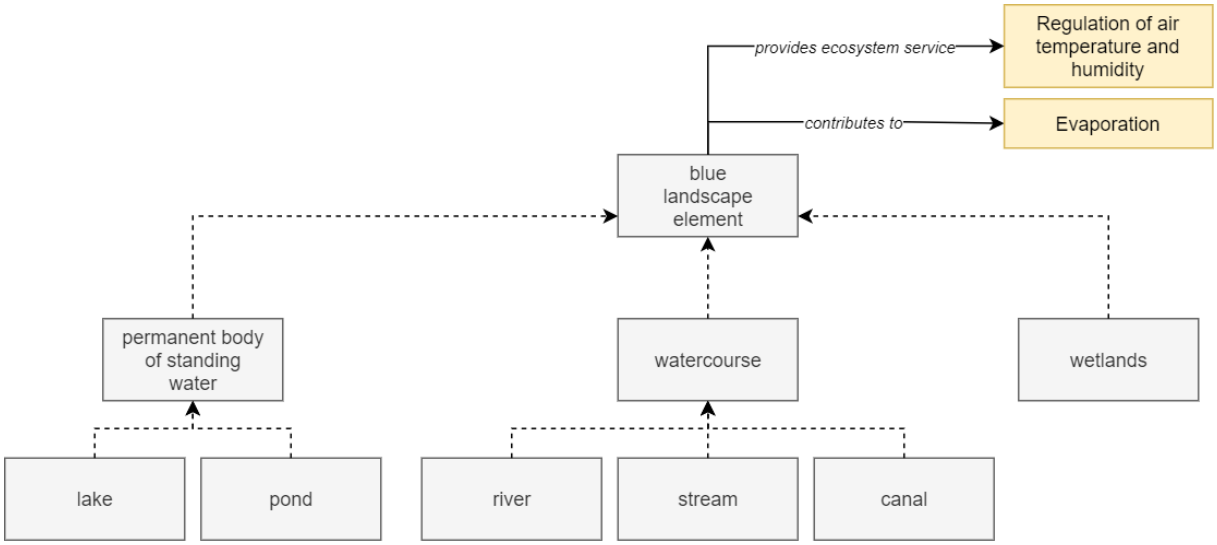

Figure 12. Formalization of blue landscape elements.

3.2.2.3 Grey landscape elements

Like blue landscape elements, the UF-NBS typology as developed in CLEARING HOUSE only formalizes broad concepts of grey infrastructure—e.g., **`street`** or **`building`**—as deemed necessary and sufficient for the expression of relevant types of UF-NBS (Figure 13). Other types considered as **`grey landscape element`** include distinguishing entities and features that may be used to describe entities in more detail, which are encapsulated by the **`object feature`** class. As object features, the typology considers e.g. **`grave`**, **`bench`**, **`sports field`**, **`playground`**, **`fitness equipment`**, and **`skate park`**. For object features that are considered to facilitate specific types of (recreational) ecosystem services, e.g. `ACTIVE RECREATIONAL USE` or `PASSIVE RECREATIONAL USE`, the respective ecosystem service types are attributed accordingly. Due to transitivity of the object properties `is composed of` and `provides ecosystem service`, it can subsequently be reasoned that an entity that is composed of a specific object feature also provides the respective type of ecosystem service.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

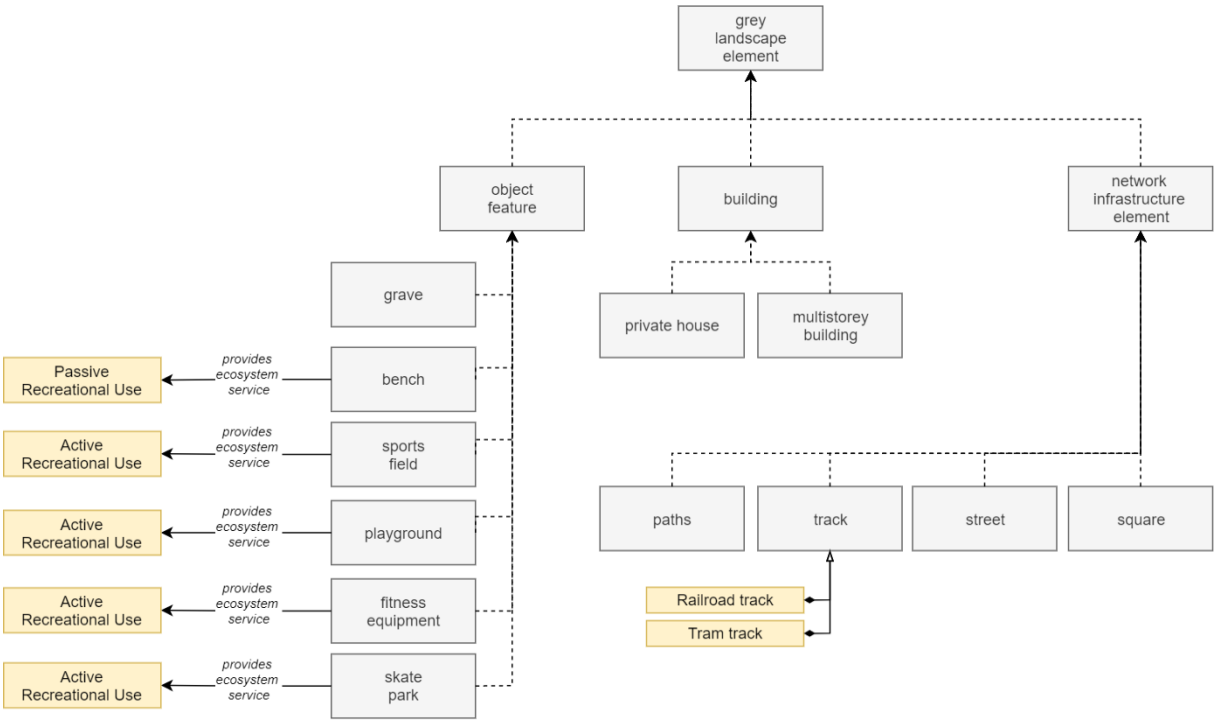

Figure 13. Formalization of grey landscape elements. Support for distinct ecosystem services is ascribed to applicable elements of the grey infrastructure as illustrated by the support of active and/or passive recreational uses through various object features.

3.2.3 Formalization of green-blue infrastructure elements

Landscape elements are the building blocks of green-blue infrastructure elements. Green-blue infrastructure elements are subsumed under the class **`green-blue infrastructure element`**.

Different types of the GBI, and more specifically the composition of these types such urban parks or forests, is derived from (being composed of) **`landscape element`**, and from their topological relationships (e.g., adjacency), with the restriction that to be considered a **`green-blue infrastructure element`**, something must be composed of at least one **`green landscape element`** or at-least one **`blue landscape element`** (Figure 9). However, **`grey landscape element`** may also be part of a given **`green-blue infrastructure element`**. As an example, a **`tree alley`** may be defined as being composed of at least two **`row of trees`** (constituting **`green landscape element`**), that has physical location **`ground-based location`** and is adjacent to a **`street`** (constituting a **`grey landscape element`**, see Example 4 **Fehler! Verweisquelle konnte nicht gefunden werden.**). Both **`green landscape element`** as well as **`blue landscape element`** are themselves considered elements of the green-blue infrastructure (Figure 9).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Example 4

Using the entities and grouping principles formalized in the UF-NBS typology, the pictured entity can be described as follows: It is a thing that is composed of two rows of trees that are adjacent to a street. It can be inferred from these expressed traits that the described entity corresponds to a ***tree alley****.*

As a consequence of this general and broad existential restriction, individual entities, for example **urban park** or **forest**, might be represented by identical compositions in regard to being composed of different types of vegetation (**tree**, **shrub**, **grass**), green landscape elements (e.g., **tree alley**), or present relations to grey landscape elements (such as **building**, **street**, etc.) and/or blue landscape elements (such as **lake**, **pond**, or **watercourse**, etc.). Hence, from the perspective of composition, none of these entities may be distinguished satisfactorily from one another.

This implies that in addition to composition, additional distinctive traits will need to be formalized in the proposed UF-NBS typology. These traits are related to the grouping principles at the core of the UF-NBS typology, including, e.g., morphological/physical attributes such as **canopy cover**, or processes, i.e., expressing that an entity is affected by a **physical process phenomenon**, functional attributes such as specific ecosystem services provided, or attributes detailing distinguishing modes/practices of governance, management, or institutional accessibility. In so doing, the UF-NBS typology defines various elements of the GBI that correspond to natural and semi-natural areas, the urban food forest, plantations, nurseries etc., urban green areas, elements associated with network

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

infrastructure, with specific purposes, as well as elements associated with buildings (see Figure 14, Figure 16, Figure 15, Figure 17, Figure 18, and Figure 20).

The UF-NBS typology considers one-to-many as well as many-to-many cardinalities through declaring few classes as disjoint. For example, two disjoint classes require that an entity may be an instance of exactly one class and thus cannot be a member of the respective other class. Instead, comparable to the concept of polymorphism, the UF-NBS typology adopts the notion that, based on composition/morphology, topology, or other grouping principles, a given type of green space may indeed be a member of multiple classes at once (cf. Example 5).

Example 5

An urban green space has been typed a **historical park**. *This urban green space, however,* is adjacent to *a* **canal**. *It would thus be inferred that the entity in question is not only an instance of* **historical park**, *but it would be inferred that it is also an instance of* **riverbank green**. *This is because* **riverbank green** *is not defined as being disjoint with* **historical park**.

3.2.3.1 Forests as natural and semi-natural areas

Forests are part of the green-blue infrastructure, and are characterized as areas dominated by trees (Figure 14). Cvejić et al. (2015) define forests as natural or planted areas of dense tree vegetation. We refer to such areas that are densely planted with trees as a **treed area**, whereas Nature4Cities (2018) refers to them as **wood**., i.e., areas covered by trees (ibid.). Treed areas are defined as ground-based entities that are composed of trees grouped in a two-dimensional regular (e.g., when planted) or irregular (e.g., in natural areas) pattern. Furthermore, they are areas with canopy cover (has canopy cover) of more than 50% (following Janssen & Rosu, 2015). The **forest** class is then derived from treed areas as having a minimum size of 5000m², i.e., an area of 0.5ha following FAO (2018). The typology further conceptualizes **riparian forest**, that is defined as a forest adjacent to steams or rivers, and that is affected by seasonal or irregular flooding due to changes in water level (following Martin-Smith, 2004). It is considered synonymous to **floodplain forest**.

Forests are conceptualized to provide, at-least, the ecosystem services TIMBER PRODUCTION and NON-TIMBER FOREST PRODUCTS.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

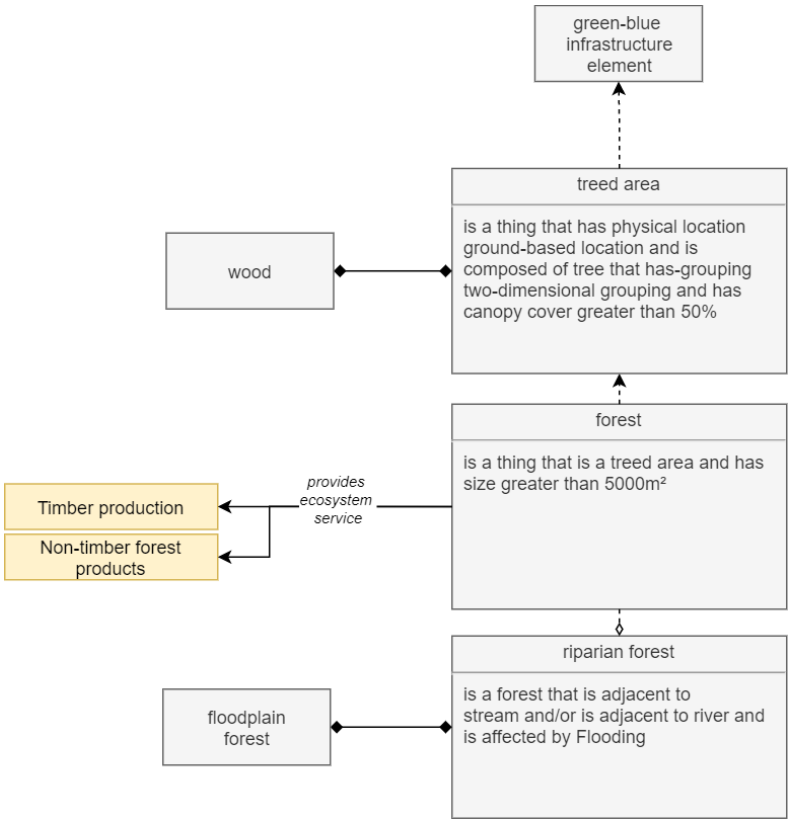

Figure 14. Formalization of forests as natural and semi-natural areas as types of GBI.

3.2.3.2 Urban food forests, nurseries, and forest plantations

Figure 15 depicts the classes that we consider as part of the urban food forest, i.e., orchards, nurseries, and forms of plantations, i.e., forest plantations. Looking at this Figure, first, nurseries are conceptualized as a broad concept, that may be relevant to UF-NBS if they are involve the cultivation of trees. They are defined in the class **`nursery`** as entities that are composed of at-least one type of vegetation for the purpose of the propagation of plants.

Second, forest plantations are included in the typology as ground-based entities composed of trees grouped in a regular pattern. They are characterized by their deliberate planting or seeding of trees (Evans, 2004). Liu et al. (2018) report that monoculture plantations have been the dominant type of plantation in practice, so that we define forest plantations as having a species diversity equal to either `LOW` or `MONOCULTURE`. Goods provided by plantations include timber but may involve non-timber forest products (Zhang and Stanturf, 2008). According to Boyle et al., 2016, forest plantations require intensive management inputs, and are thus defined as has `management intensity` `HIGH`.

Third, an **`orchard`** is considered as ground-based entity that `is composed of` **`fruit tree`**, i.e., fruit- and/or nuts-bearing trees grouped in any form of two-dimensional pattern (following the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

definition by Cvejić et al., 2015). Due to their composition, orchards provide the ecosystem service `FOOD PRODUCTION`. They are therefore considered as part of the urban food forest, that is defined as an "edible green infrastructure" (Gori et al., 2019).

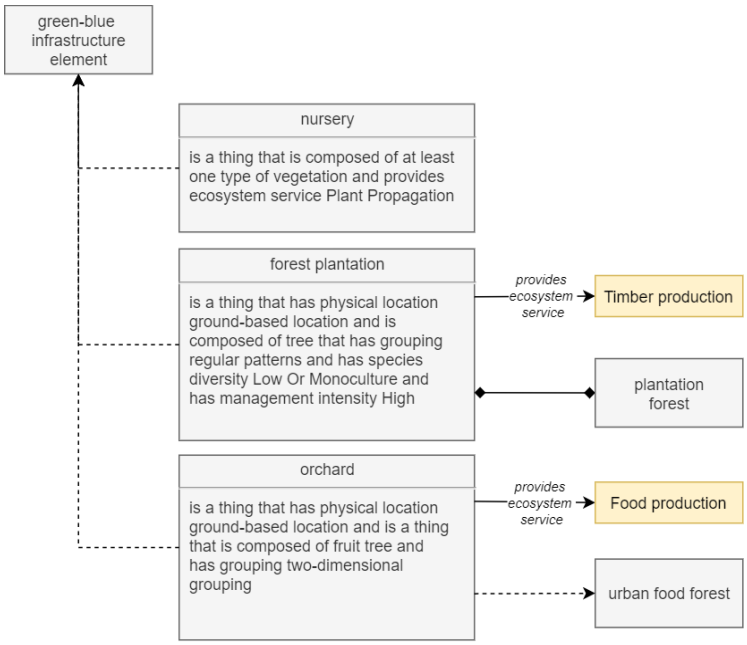

Figure 15. Formalization of elements of the urban food forest, nurseries, and forest plantations, as types of GBI.

3.2.3.3 Urban green areas

The typology furthermore describes various kinds of urban green areas. This includes parks and gardens, riverbank green, and various classes derived from either one of these concepts.

The class **`parks and gardens`** is defined as ground-based entity that `is composed of` some **`green-blue infrastructure element`**, and that `is composed of` some **`grey landscape element`**; moreover, also treed areas that do not meet the size requirements to be considered a forest are included in the definition of parks and gardens. Consequently, this broad concept captures many different green-blue areas.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

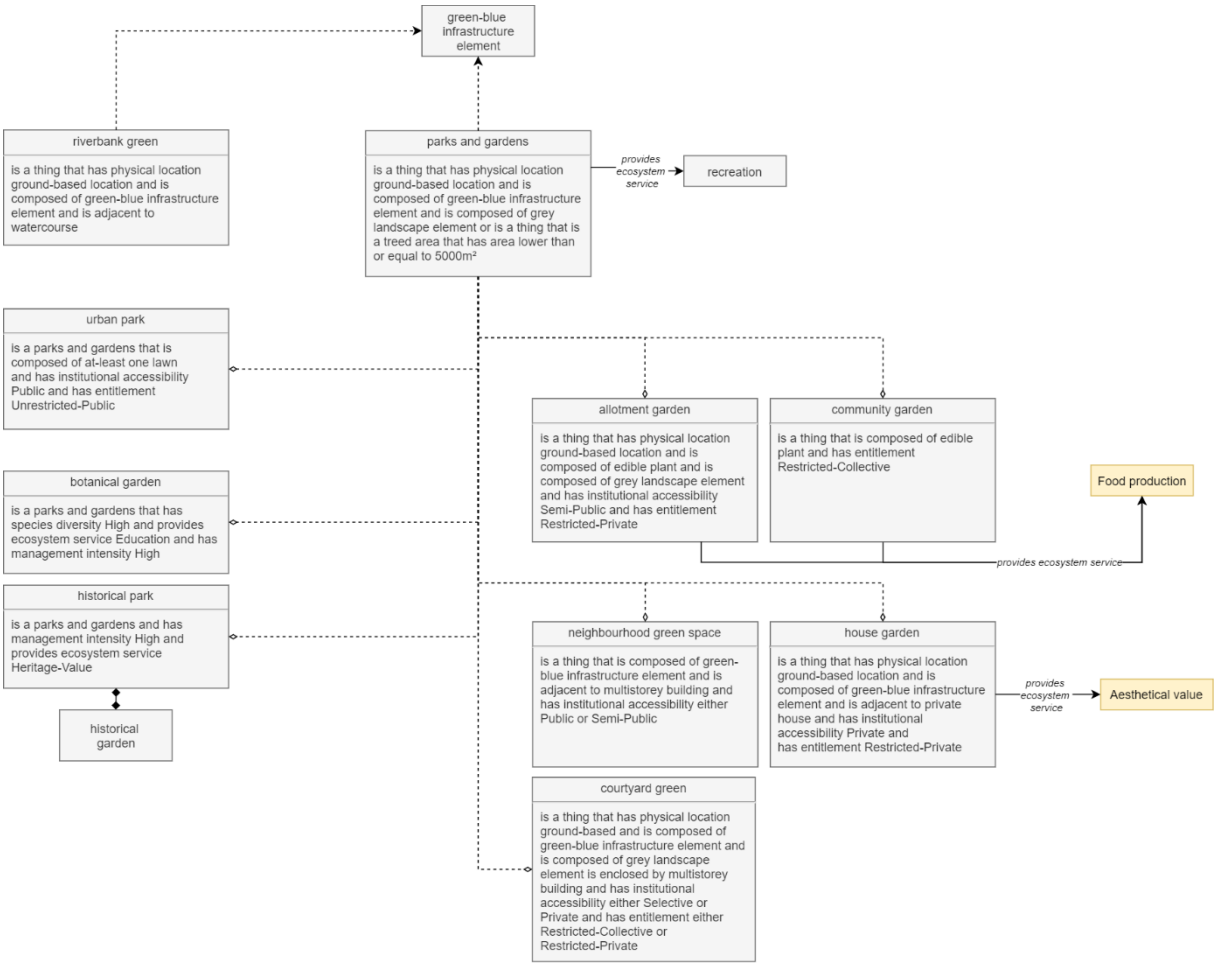

Figure 16. Formalization of urban green areas (parks, and gardens) as types of GBI.

Figure 16 shows the green-blue infrastructure elements that are considered. Broadly conceptualized is the class **`riverbank green`**. Riverbank green is defined by GREENSURGE as green spaces sideways rivers, streams and canals, typically with different types of paths (Cvejić et al., 2015). We define members of this class as ground-based green-blue infrastructure elements adjacent to watercourses, i.e., rivers, streams, or canals. With no additional restrictions expressed, this class may be considered an umbrella term that subsumes many different types of green areas.

An **`urban park`** is a **`parks and gardens`**. More specifically, following Cvejić et al. (2015) and Nature4Cities (2018), we consider this a park area of varying size and design, typically including different features, i.e., areas being composed of at-least of **`lawn`**, and/or (other) grass(es), and/or shrubs, and/or trees, and grey landscape element(s) such as paths or streets or playgrounds etc. Urban parks offer passive, active and/or mixed recreational activities, and cater to social needs of the population. We define an urban park as being accessible by the general public, and with unrestricted use by the public.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

A **historical park**—and the class **historical garden** that is defined as equivalent class to be used synonymously—is, following Cvejić et al. (2015), similar in character to large urban parks, but with distinct management due to heritage status. Historical parks feature outstanding aesthetic or scientific values from the past, and thus have aesthetic, historic, scientific, social or spiritual values (Nature4Cities, 2018). We consider these values expressed through provisioning of the ecosystem service HERITAGE VALUE. Restrictions regarding institutional accessibility and entitlement may apply.

Entities of type **botanical garden** are defined, following Cvejić et al. (2015), as areas planted with a high diversity of plants, for educational purposes, and requiring high human maintenance. This is expressed in the typology though has species diversity HIGH and provides ecosystem service EDUCATION.

We furthermore conceptualize the entities allotment garden and community garden. Here, an **allotment garden** is understood as ground-based, leased garden in an urban setting for non-commercial gardening use, in particular for the extraction of horticultural products and for recreation uses (Cvejić et al. 2015; Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2019). We consider foods produced within allotment gardens a defining trait (expressed through their composition including **edible plant**, thus providing ecosystem service FOOD PRODUCTION). In regard to institutional accessibility and entitlement, we define allotments as semi-public spaces—i.e., areas that may, under conditions, be accessed by the wider public—but with entitlements for their use limited/restricted to private individuals/groups. In contrast, a **community garden** is defined as collectively used areas for food production and recreation (Cvejić et al., 2015). The Abgeordnetenhaus von Berlin (2018) characterizes them as community-managed gardens in an urban context with a focus on social, intercultural and ecological topics. They are formalized as areas with entitlement for use restricted to a specific collective of individuals, and the production of foods is seen as a characteristic trait similar to allotments. Restrictions regarding institutional accessibility may apply, but are not formally expressed due to the diverse nature of community gardens.

Neighbourhood green spaces are defined by Cvejić et al. (2015) as areas often vegetated by grass, shrubs, and trees, i.e., composed of various types of vegetation—or by extension blue-green infrastructure elements—in multistorey residential areas. We subsequently define **neighbourhood green space** as an entity that is adjacent to MULTISTOREY BUILDING. We furthermore assume public or semi-public access to these entities as characteristic traits.

Courtyard green, i.e., a greened inner courtyard, is conceptualized as a composition of green-blue infrastructure elements and grey landscape elements that is enclosed by multistorey buildings. We consider this type of green space as only selectively or privately accessible, and entitlements limited/restricted to a defined group of individuals (collective), or as entirely private.

Finally, house gardens are considered. Following Cvejić et al. (2015), they can be considered as area in the immediate vicinity, i.e., in adjacency to privately owned or rented houses, cultivated for ornamental purposes, and/or for the non-commercial production of food. Entities of the **house garden** class are consequently formalized as ground-based entities composed of **green-blue infrastructure element**, adjacent to **private house** (irrespective of building structure type), with private access and restricted (private) entitlements, and that at-least providing ecosystem service AESTHETICAL VALUE.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

3.2.3.4 Elements of the green-blue infrastructure that are associated with urban networks

Elements of the GBI associated with urban networks include railroad banks and green verges. A **`green verge`**, following Foster et al. (2019) also referred to as margin, is defined as ground-based strip of vegetation—i.e., grasses, shrub vegetation or trees planted for ornamental purposes—along patch boundaries (ibid.). For the purpose of CLEARING HOUSE, here, a focus is put on green verges adjacent to **`network infrastructure element`** (Figure 17). Following Foster et al. (2019), the class **`margin`** is defined equivalent to the class **`green verge`**. Cvejić et al. (2015) define railroad banks as a green space along railroads. Consequently, we define a **`railroad bank`** broadly as ground-based **`green landscape element`** adjacent to RAILROAD TRACK. Both types are conceptualized to be members of the class called **`network associated green`**, that generalized the previous definitions to include **`green-blue infrastructure element`** adjacent to **`network infrastructure element`**. Other devised entities include **`single street tree`**, i.e., solitary trees adjacent to streets, and **`tree alley`**, i.e., rows of trees adjacent to streets.

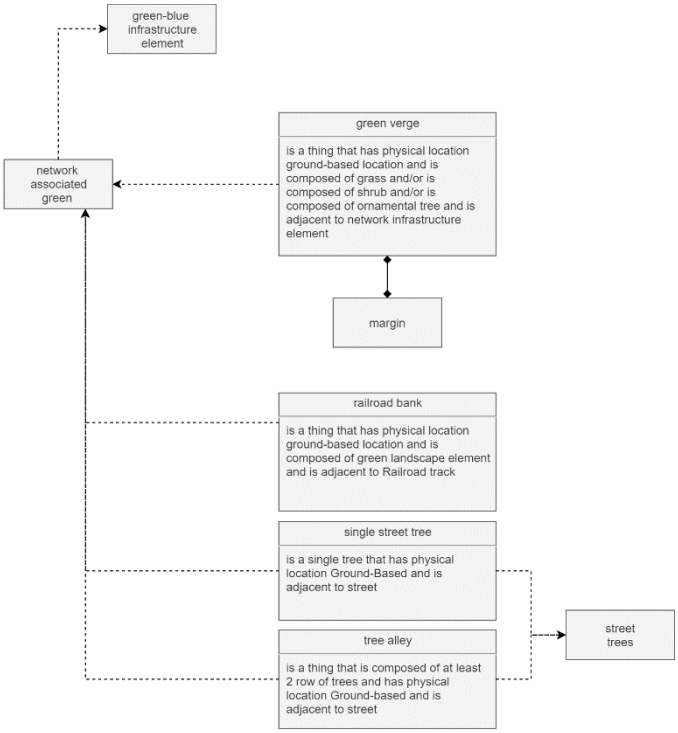

Figure 17. Formalization of GBI elements associated with network infrastructure.

3.2.3.5 Other types of green-blue infrastructure elements

Other types of GBI elements that are potentially of relevance to UF-NBS include cemeteries and arboreta. We conceptualize a **`cemetery`** as a ground-based entity that `is composed of` some **`green-blue infrastructure element`**, with the restriction that at-least one **`grave`**, i.e., a place of burial or sepulture, must be present. This concept is in line with the definition of cemeteries by Cvejić et al. (2015), that define this concept as burial ground often covered by lawns, trees, and other

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

ornamental plants (Figure 18). Arboreta are defined by Cvejić et al. (2015) as areas planted with a high diversity of trees for educational purposes. We consequently conceptualize an **arboretum** as a ground-based entity composed of some tree with ELEVATED species diversity, and as entity that provides ecosystem service EDUCATION (Figure 18).

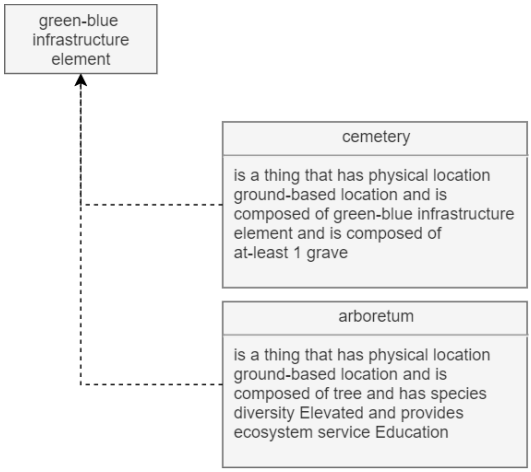

Figure 18. Formalization of other types of GBI elements.

3.2.3.6 Green-blue infrastructure elements associated with buildings and support structures

In regard to green-blue infrastructure elements that are associated with building structures, the CLEARING HOUSE typology considers green roofs and green walls, atria, and balcony green. The definition of these classes is visualized in Figure 20. More specifically, a **green roof** is considered as an entity that has physical location ON BUILDING ROOF, and that is composed of at-least one type of **green landscape element**, thus comprising any instance of a vegetated roof (Shafiq and Kim, 2017). The definition of a **green wall** is identical in that it is composed of at-least one type of **green landscape element**, but has physical location ON BUILDING FAÇADE; likewise, **balcony green** is defined similarly, has physical location ON BALCONY. Defined as an **atrium** is an entity that is composed of at-least one type of **green landscape element**, and that is enclosed by nothing but **building**. All these entities are members of the class **building associated green**. We furthermore propose the element **vegetated pergola**, defined as an entity that has physical location ON PERGOLA, and that is composed of at-least one type of **green landscape element**.

We realize that in many instances, and when focusing on UF-NBS, these concepts may not be of high relevance. However, using the expressiveness of the typology, relevant realizations of UF-NBS such as the Bosco Verticale in Milan, Italy, could be described semantically (Figure 19).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Figure 19. Bosco Verticale (Photo by Daniel Seßler).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

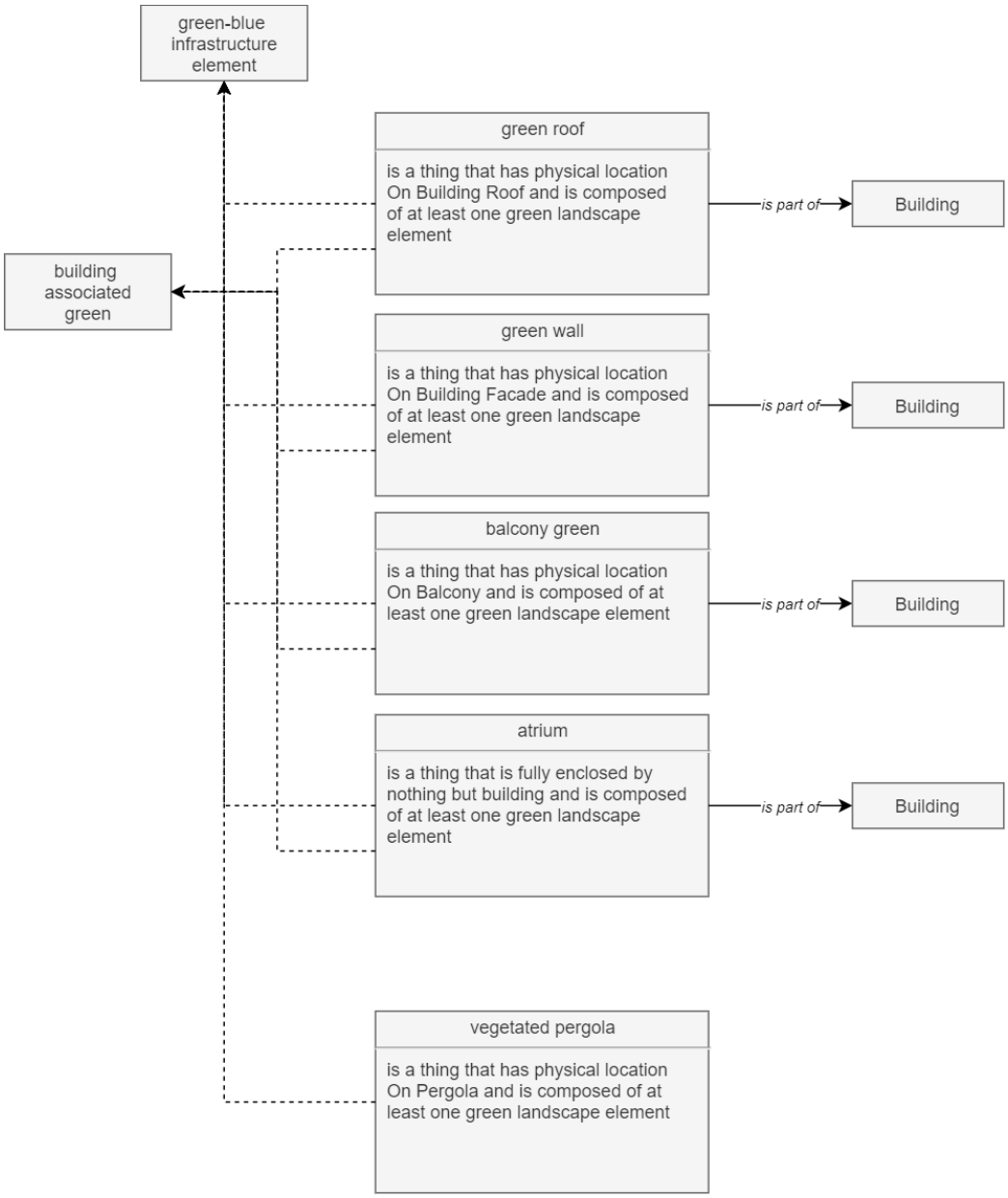

Figure 20. Formalization of GBI elements associated with buildings and other support structures.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

3.2.4 Formalization of actions

Somarakis et al. (2019) emphasized the importance of actions as notions of NBS. To formalize such actions and interventions, for example, greening or afforestation, the typology conceptualizes the class **nbs-action**. The conceptualization of this class takes inspiration from Somarakis et al. (2019), but seeks to establish more specific linkages between NBS as actions and the neighbouring concepts of ecosystem service and green-blue infrastructure. To do so, first, each action is linked with an ecosystem service to express the desired intentional benefits to be provided by the respective intervention as a response to societal, environmental or economic challenges. This link is established through the object property has intended outcome. Moreover, each action is linked to an **activity** (or a set thereof), i.e., to a specific action that is carried out as part of the intervention (Figure 21). Such activities include, for example, TREE PLANTING, PRUNING, MONITORING, CONSTRUCTION or RESTORATION. Finally, the typology proposes areas of interventions, i.e., the spatial entities within which the actual activity, and thus the NBS action, is carried out/implemented. This link is conceptualized through the property aims-at **spatial entity** (Figure 22).

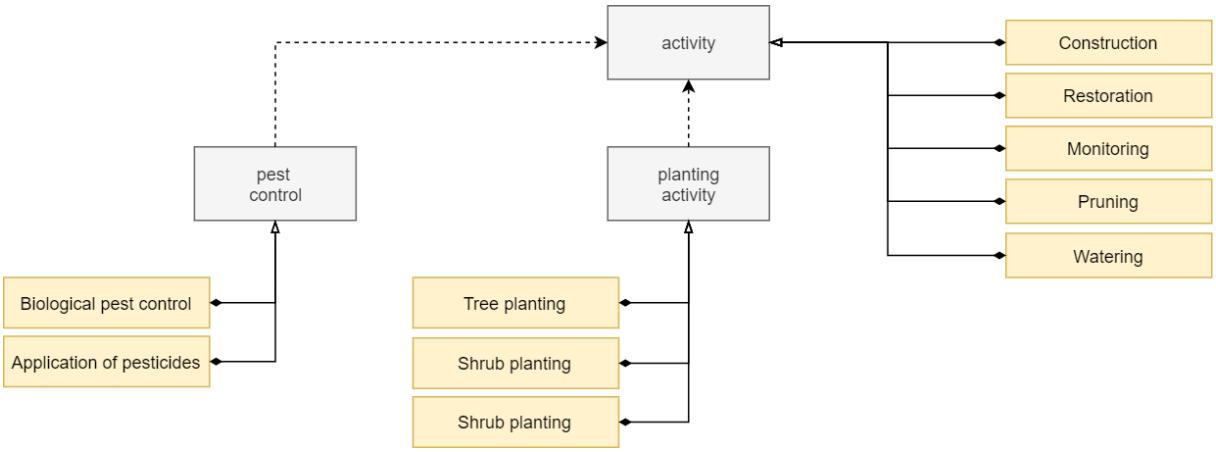

Figure 21. Taxonomy of considered activities for the conceptualization of actions as nature-based solutions.

More specifically, Somarakis et al. (2019) describe types of actions based on their intention to improve or maintain the delivery of ecosystem services or based on the intent to provide ecosystem services through the design and implementation of "new ecosystems" (ibid.). Here, we build on this notion of interventions through devising subclasses of **nbs-action**. We distinguish between **implementation action**, **restoration action**, and **management action** (Figure 22).

Actions of type **implementation action** are considered to seek provisioning of some **ecosystem service**, through implementing a given type of **nbs**. Members of this class include, for example, **afforestation**—i.e., the establishment of forests or forest plantations through TREE PLANTING in currently non-forested areas—and **wetland construction**, i.e., the CONSTRUCTION of new wetland areas. It is important to note that for this type of actions, often no specific spatial entity as the target area of intervention can be formalized a priori. This is due to the fact that the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

establishment of such "new ecosystems" may, in principle, occur anywhere, and is thus dependent on the context of an actual case.

Actions of type **restoration action** are considered to seek improvement of some **ecosystem service**, i.e., to assist in the conservation of still intact, and in the recovery or improvement of degraded ecosystems, and hence of the ecosystem services provided by them (Breed et al., 2020). This type of action includes, for example, **reforestation**, i.e., the intentional restocking of forested areas, forest plantations or of woodlands through TREE PLANTING; **wetland restoration**, i.e., the RESTORATION of existing wetlands; **orchard restoration**, i.e., RESTORATION of existing orchards; and **enrichment planting**, i.e., the improvement of the ecosystem service BIODIVERSITY CONSERVATION through the reintroduction or increase of rare or missing populations or functional groups through planting (Fayle et al., 2015; Margueira et al., 2019). Following Torquebiau (2000), enrichment planting may alter the type of addressed green-blue infrastructure element, e.g., to an urban agroforestry entity through planting of edible plants. We define enrichment planting synonymous to **species diversification**. In contrast to implementation action, actions of type restoration action can be linked to a specific spatial entity as the target area of intervention, e.g., forest or wetland, depending on the type of action.

Actions of type **management action** are considered to seek maintenance of some **ecosystem service**, i.e., the safeguarding and long-term protection of ecosystem services provided by a given spatial entity (Smith & Harrison, 2016). Similar to restoration actions, they are linked to specific spatial entities as zones of intervention. Here, we have devised actions involving MONITORING activities, i.e., **tree monitoring** as well as **forest monitoring**, with the former aiming at a **single tree** instance, and the latter addressing any entity that is a part of the (conceptual) urban forest. Furthermore, **tree pruning** and **tree watering** are devised as actions aiming at **single tree** entities that involve PRUNING in the former case, and WATERING in the latter case. Actions of type **pest management** involve **pest control** activities, e.g., BIOLOGICAL PEST CONTROL and/or the APPLICATION OF PESTICIDES, aimed at elements of the green-blue infrastructure. Many of these actions may be subsumed under the term **forest conservation**, that, following Pawar and Rothkar (2015), may be understood as all actions aiming at maintaining forested areas.

Finally, we consider **greening** actions. Greening may be understood as often aesthetics-based interventions, e.g., the planting of trees, or the provisioning of green spaces, e.g., through the greening of vacant lots (Hunter et al., 2019). Consequently, we consider greening as an entity that may correspond to different types of actions: First, an implementation action, in case of greening to establish new green spaces/green-blue infrastructure elements; or second, a restoration action, in case of greening as an intervention for the (aesthetic) improvement of existing green-blue infrastructure elements.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

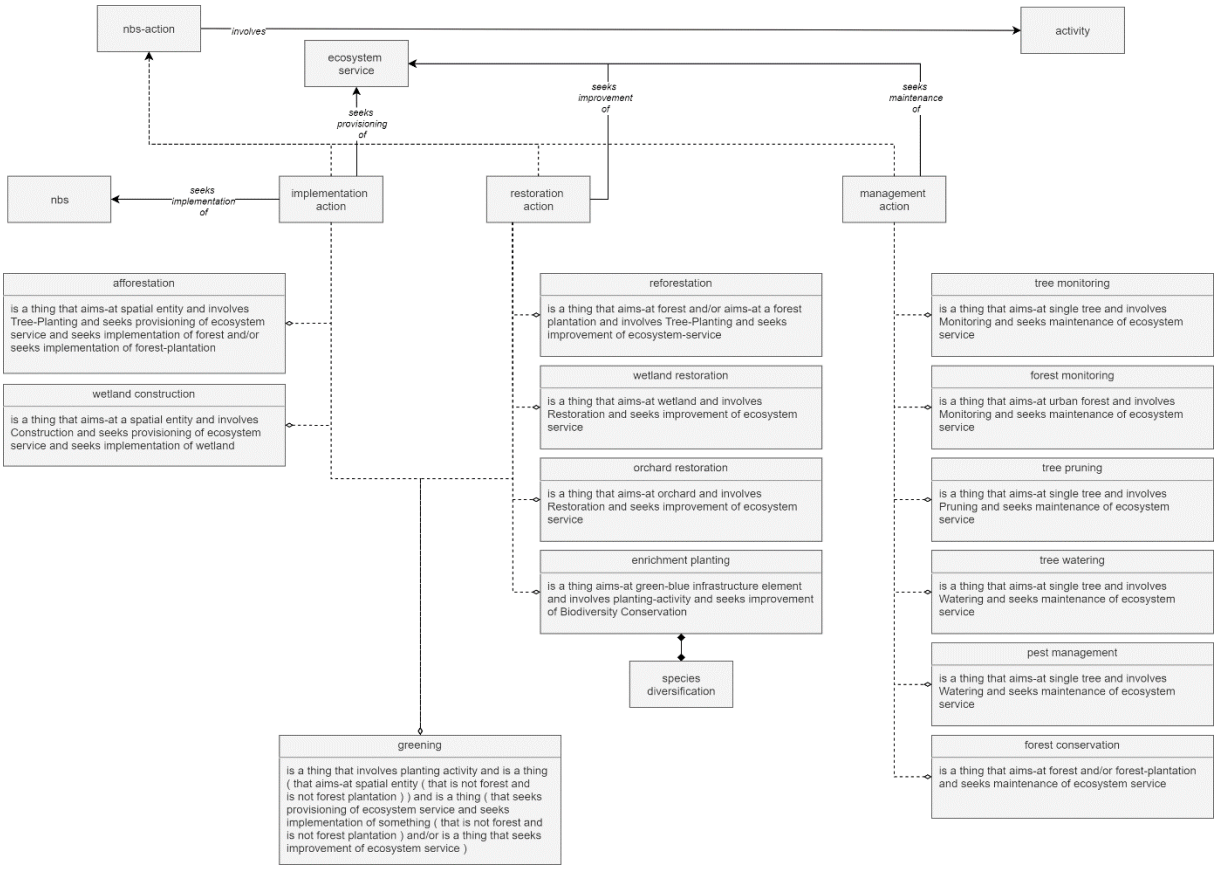

Figure 22. Formalization of actions as types of nature-based solutions.

3.2.5 Formalization of NBS and UF-NBS

3.2.5.1 Elements of the green-blue infrastructure as NBS

Based on the definitions outlined in section 1.3.1, we consider a NBS any entity that provides at least *two* **`ecosystem service`**. The proposed typology defines a transitive character for the object properties `is composed of` and `provides ecosystem service`, i.e., if some entity **`X`** `is composed of` **`something`** that `provides ecosystem service` **`Y`**, then **`X`** `provides ecosystem service` **`Y`**. Hence, GBI elements are conceptualized to provide ecosystem service(s) due to their composition and are thus considered **`NBS`**.

Included in this definition of NBS are thus also **`engineered element`**, i.e., entities that represent rather technical solutions *inspired by nature*, that are designed to provide specific ecosystem services, e.g., **`permeable pavement`**.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

3.2.5.2 Actions as NBS

Through the object properties seek provisioning of, seek improvement of, and seek maintenance of, the different types of **nbs-action** are associated with the **ecosystem service** concept. More specifically, it has been described previously that the object property has intended outcome links a given action to a desired ecosystem service as benefit. This object property is in turn conceptualized to include the roles of each of the aforementioned properties. Thence, the relationship provides ecosystem service is declared to include the role of has intended outcome, i.e., we argue that the intended meaning of both terms is identical in that each term establishes a link to an intended benefit. Hence, in so doing, under the definition of **nbs** as described above, the **nbs-action** concept assumes the role of a nature-based solution.

3.2.5.3 Urban Forests as Nature-Based Solutions

As elicited earlier, the concept of urban forest[7] is understood by Endreny (2018) as the totality of urban trees. Consequently, we devise a class **urban forest** to formalize this concept (Figure 23). This class embraces **tree**—i.e., we consider all individual trees to be part of the urban forest—and compositions of tree(s), i.e., an entity that is composed of **tree**, or that is composed of **something** that itself is composed of **tree**, and/or is composed of **row of tree**, and/or is composed of **group of tree**.

Urban forests as nature-based solutions are finally defined in the class **uf-nbs** as the intersection of the classes **NBS** and **urban forest**. (cf. Figure 1 and Figure 23).

[7] as opposed to urban forest in terms of an urban forest stand

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

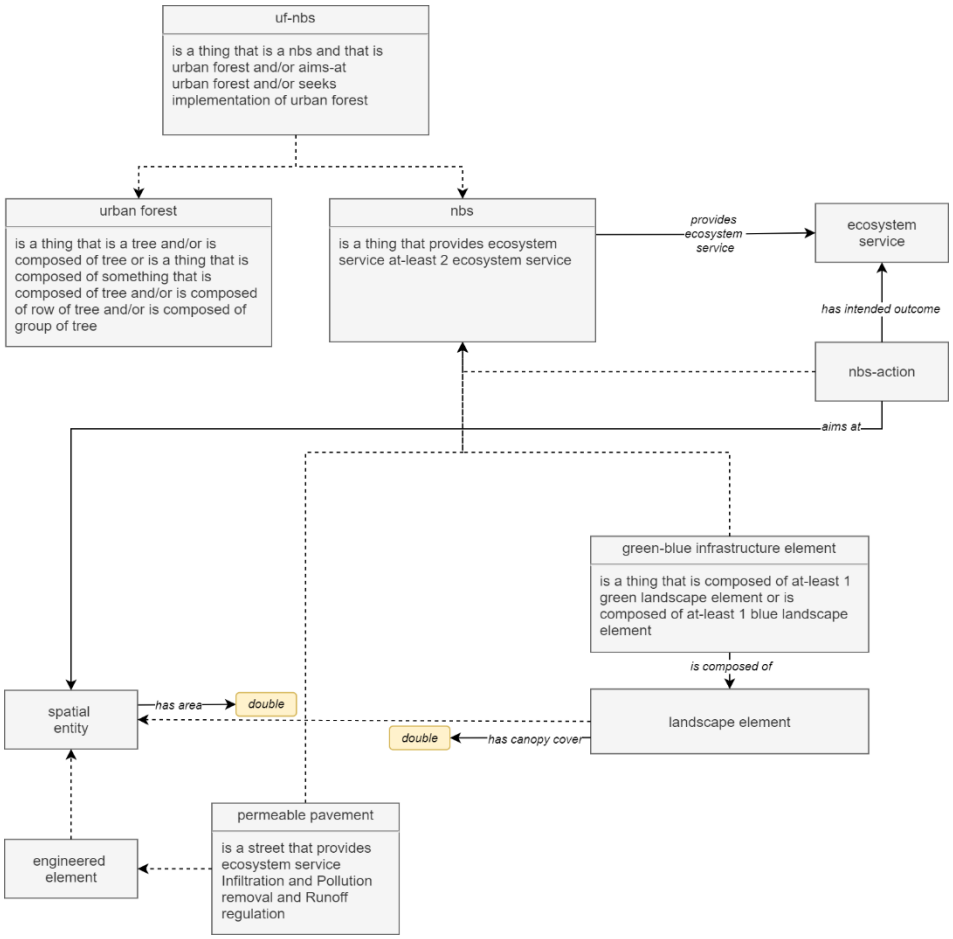

Figure 23. Formalization of nature-based solutions, and urban forests as nature-based solutions, and their relationship with actions as nature-based solutions, green-blue infrastructure elements, and engineered solutions.

3.3 Evaluation

Formalized expressions of UF-NBS knowledge were tested simultaneous to the implementation of the respective OWL classes through defining test cases in the form of OWL individuals. For example, when urban parks were formalized as a class, simultaneously, an OWL individual was created expressing the relevant conceptual assumptions of the urban park class and queried against the formalized knowledge to ensure the intended meaning. The corresponding assumptions were in turn evaluated in discussions with project partners, through expert knowledge, and validated through the review of scientific knowledge, including existing typologies. Moreover, the approach to knowledge formalization was discussed in form of an online workshop (M1.2).

A more meaningful evaluation of formalized knowledge is the testing against real-world knowledge—in contrast to the abovementioned test cases—collected through the CLEARING HOUSE case studies. However, time constraints did not allow such an in-depth evaluation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

4 Discussion

The CLEARING HOUSE typology formalizes urban forests as nature-based solutions. As (UF-)NBS, the typology conceptualizes, first, relevant types of green-blue infrastructure elements, for example, forests and urban green areas. These entities are described through a set of grouping principles, that include morphology (form) and physical properties such as location, function, and governance and institutional aspects such as accessibility and entitlements. Second, different types of actions for the implementation of green-blue infrastructure elements, the improvement of degraded areas, or of their management are considered (UF-)NBS. Their formalization linked relevant GBI elements and ecosystem services to these actions. Third, also engineered elements are embraced by the (UF-)NBS definition.

It has been shown that the common and necessary criterion for these entities to be considered a nature-based solution is their provisioning of two or more ecosystem services, i.e., of economic, environmental, and societal benefits. Using semantic principles, this common ground, the various devised entities, and their relationships are formalized in an internally coherent taxonomy of concepts. Through the semantic formalization of green-blue infrastructure elements on the basis of their morphological, physical, functional and institutional properties to capture defining traits of GBI elements, the CLEARING HOUSE typology advances textual knowledge representations and attempts to provide a coherent, logical and systematic way for a compartmentalized description of green-blue features, i.e., their composition as well as their spatial contexts.

From a research perspective, to further the understanding of urban-ecological systems, research has emphasized that in such complex and intertwined human-dominated systems, many different factors, particularly landscape and urban patterns/urban morphology, affect ecological functions, conditions and ecosystem service provisioning at multiple spatiotemporal scales, thus necessitating research on the nature of these interactions, for example for the improvement of ecosystem service assessment and GBI planning (Alberti, 2005; Alberti & Marzluff, 2004; Bierwagen, 2005; Holt et al., 2015; Koc et al., 2016; Pan & Du, 2020; Wang et al., 2019; Whitford et al., 2001). To support this research, the CLEARING HOUSE typology provides the basic expressiveness necessary to describe UF-NBS in the context of their composition and urban form.

From a technical perspective, through the semantic codification of concepts, particularly in comparison to textual knowledge representations, the CLEARING HOUSE typology excels in enabling a querying of and reasoning upon the formalized knowledge. Consequently, descriptions of compositions and their spatial context can be evaluated against the codified knowledge, and corresponding type(s) of GBI and relevant overarching concepts, i.e., NBS or UF-NBS, can be inferred. In this context, the presented typology conceptualizes UF-NBS as the intersection of two neighbouring concepts: First, nature-based solutions (in terms of GBI elements, actions, or engineered elements); and second, the concept of urban forest as the entirety of forests and, more generally, trees within an urban area (Endreny, 2018; Davies et al., 2017; Konijnendijk, 2003; Patarkalashvili, 2017). In so doing, the typology emphasizes the “polymorphism” of GBI elements, i.e., the fact that a given class of GBI element may assume different compositions and contexts and may thus represent different or additional kinds of entities (Figure 24). We argue that it is such “polymorphism” that is difficult to express in non-semantic typologies.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Figure 24. Two realizations of green verges to exemplify that composition is crucial. Both examples are considered green-blue infrastructure elements. The left example is furthermore considered an NBS. The example on the right is additionally part of the urban forest, and thus also an UF-NBS.

However, clear-cut distinguishing traits may not always be easily identifiable for different types of the green-blue infrastructure. For example, Cvejić et al. (2015) define different types of parks, such as large urban parks, small to medium-sized urban parks, and pocket parks. Whilst these concepts pose a subset of a more general urban park class, a sharp separation between them proves difficult (cf. also Nature4Cities, 2018). Consequently, the proposed typology may still feature a comparatively limited, or more restricted expressiveness regarding certain types of the green-blue infrastructure. This also includes a limited expressiveness regarding the grouping principles used to define characteristic traits of UF-NBS. They require refinement, e.g., in case of species diversity, that should be more closely linked to context, and/or require a further evaluation and extension as needed, e.g., regarding physical processes, or governance or institutional attributes. Here, for example, aspects of scale as well as ownership are not yet formalized, and concepts to consider temporal dynamics need advancement.

Other aspects needing review include thresholds used to formalize selected concepts, e.g., size and canopy cover, that are often context-dependent (Wang et al., 2019), and thus difficult to generalize, possibly limiting transferability. Context-dependence of definitions of (UF-)NBS and GBI may also manifest itself in regard to the provenance of concepts, and the concomitant relevancy for Europe and/or China. In this regard, it shall be emphasized that first and foremost, semantic modelling seeks to capture a common understanding, here established through the exchange with and input of project partners. Thus, it is argued that the present typology captures those concepts most-relevant for the conceptualization of UF-NBS for both, Europe and China.

Moreover, in its current form, the typology characterizes actions as types of NBS and spatial entities through relationships with spatial entities, ecosystem services as intended outcomes, and activities conducted as part of the action. In so doing, concepts such as tree monitoring and forest monitoring are only distinguishable through the entity the action is aimed at, i.e., a single tree in the former case, and the conceptual urban forest in the latter case. However, in regard to the monitoring of such different spatial scales, also different monitoring methods—e.g., sampling vs. remote sensing—will usually be required. However, at this moment, methods are not formally expressed in the typology.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

To address shortcoming, we propose iterative refinements of the typology as previously described. In addition, information and data pertaining to the performances of specific tree genera or tree species related to distinct ecosystem (dis-)services may be integrated. At present, the typology only foresees such further linkages, e.g., to tree databases, through the formalization of tree traits (Helletsgruber et al., 2020), but does not implement these linkages more specifically.

5 Re-usability and relationship to CLEARING HOUSE

5.1 Relationship to other tasks within the CLEARING HOUSE project

The presented typology incorporates findings from the identification and mapping of UF-NBS (T1.1), and from the collation of evidence on intended outcomes and unintended impacts of UF-NBS through the rapid review of the knowledge repository (T1.2). The CLEARING HOUSE typology has been introduced and discussed during a web conference (T1.1, M1.2).

The typology will be fed into the Sino-European co-design event (T3.1, M3.2), and into the development of the analytical framework (T1.5). Furthermore, it provides the grounding knowledge for the comparative case study analysis to be conducted by CLEARING HOUSE (T2.2), serves as a basis for the development of UF-NBS scenarios, and may be utilized and further refined for/during the development of the CLEARING HOUSE benchmarking tool (T4.2).

5.2 Re-usability aspects

The formal, codified knowledge that poses the CLEARING HOUSE typology may be re-used in manifold avenues for research, within the CLEARING HOUSE project as outlined in section 5.1, and beyond. For example, this includes re-using the typology to implement semantically-backed inventories of GBI and (UF-NBS), e.g., for selected case study cities. As such inventories would be machine-interpretable, and could thus be used for reasoning and inference, comparative analysis may be supported through the identification of common features and traits (e.g., T2.2). Moreover, through enabling querying, decision-making and planning may be supported, for example through the identification of GBI elements or actions suitable to achieve specific purposes. A re-use of the CLEARING HOUSE typology may also be feasible for remote-sensing and GIS-based land-use/land-cover classification applications, and for the development of semantically-enabled applications for the evaluation of green-blue infrastructures. Through establishing and implementing linkages regarding the performances of specific tree species as outlined above, we could furthermore envision a simultaneous assessment of ecosystem services within such applications that are embedded within the expressiveness of the typology, e.g., the assessment of the total provisioning of ecosystem services provided by specific UF-NBS classes. In this sense, it can be linked to municipal cadastral data, inventories and other city-specific databases as well as to existing tree (traits) databases such as iTree or CiTree.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

6 Access to the typology and Versioning

The implemented UF-NBS typology can be accessed under doi 10.5281/zenodo.4649961. Additional information including documentation is made available on the project website at http://clearinghouseproject.eu/.

This deliverable describes Version 1 of the UF-NBS typology. As additional knowledge is created within the CLEARING HOUSE project and with corresponding revisions of the typology conducted as feasible, the CLEARING HOUSE UF-NBS typology that is linked under doi 10.5281/zenodo.4649961 will be updated to newer versions as they are released.

CONCLUSION

Unlike typologies such as the one developed by Cvejić et al. (2015), the CLEARING HOUSE typology proposes the definition and conceptualization of (UF-)NBS not on the basis of textual representations of knowledge, but through a description of characteristic and defining traits of (UF-)NBS elements in regard to their composition, morphology, and form in combination with their physical, functional and institutional traits. To do so, methodically, the proposed typology is implemented in the form of an ontology using semantic modelling, i.e., knowledge is structured and expressed in a formal way. This ontology is, technically, implemented using the Web Ontology Language, a standardized, machine-readable and machine-interpretable language, that provides a systematic and inherently coherent vocabulary for the description of (UF-)NBS elements.

From a research perspective, focusing on aspects of composition, form, function, and spatial context of UF-NBS and thereby going beyond more descriptive representations of UF-NBS elements, the CLEARING HOUSE typology seeks to provide the grounding knowledge necessary for furthering the research on urban-ecological systems, particularly, regarding the interaction of urban form and the biophysical functions and benefits provided by UF-NBS that are embedded in such urban contexts. From a technical perspective, the implementation of knowledge in form of an ontology allows a wide re-use, including the building of software-supported UF-NBS inventories or decision-support systems.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

BIBLIOGRAPHY

Abgeordnetenhaus von Berlin (2018). Antrag: Urban Gardening in der Stadt verwurzeln.

Alberti, M. (2005). The Effects of Urban Patterns on Ecosystem Function. International Regional Science Review, 28(2), 168–192.

Alberti, M., & Marzluff, J. (2004). Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. Urban Ecosystems, 7, 241–265.

Allemang, D., & Hendler, J. (2008). Semantic Web for the Working Ontologist. Modelling in RDF, RDFS and OWL. Burlington (MA).

Almenar, J., Elliot, T., Rugani, B., Philippe, B., Gutierrez, T., Sonnemann, G., & Geneletti, D. (2021). Nexus between nature-based solutions, ecosystem services and urban challenges. Land Use Policy, 100, 104898.

Antoniou, G., & van Harmelen, F. (2004). A Semantic Web Primer. Cambridge (MA), London.

Arlt, G., Hennersdorf, J., Lehmann, I., & Thinh, N. (2005). Auswirkungen städtischer Nutzungsstrukturen auf Grünflächen und Grünvolumen. Leibniz-Institut für ökologische Raumentwicklung, IÖR-Schriften, 47, Dresden.

Atkinson, C., Gutheil, M., & Kiko, K. (2006). On the relationship of ontologies and models. In S. Brockmans, J. Jung, & Y. Sure (Eds.), Meta-modelling and ontologies. Proceedings of the 2nd international workshop on meta-modelling WoMM 2006, October 12–13th, 2006. Karlsruhe.

Baader, F., Horrocks, I., & Sattler, U. (2004). Description logics. In S. Staab, & R. Studer (Eds.), Handbook on ontologies. International handbook on information systems (pp. 3–28). Heidelberg.

Bierwagen, B. (2005). Predicting ecological connectivity in urbanizing landscapes. Environment and Planning B: Planning and design, 32, 763–776.

Boyle, J., Tappeiner II, J., Waring, R., & Smith, C. (2016). Sustainable Forestry: Ecology and Silviculture for Resilient Forests. Reference Module in Earth Systems and Environmental Sciences, doi: 10.1016/B978-0-12-409548-9.09761-X.

Breed, M. F., Cross, A. T., Wallace, K., Bradby, K., Flies, E., Goodwin, N., Jones, M., Orlando, L., Skelly, Ch., Skelly, Ch., Weinstein, P., & Aronson, J. (2020). Ecosystem Restoration: A Public Health Intervention. EcoHealth, https://doi.org/10.1007/s10393-020-01480-1.

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.) (2016). Nature-Based Solutions to Address Global Societal Challenges. Gland.

Cvejić, R., Eler, K., Pintar, M., Železnikar, Š., Haase, D., Kabisch, N., & Strohbach, M. (2015). A typology of urban green spaces, eco-system services provisioning services and demands. EU FP7 (ENV.2013.6.2-5-603567) GREEN SURGE project (2013–2017), available online: http://www.e-pages.dk/ku/1334/html5/. Accessed January 20, 2020.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Chandrasekaran, B., Josephson, J. R., & Benjamins, V. R. (1999). What are ontologies, and why do we need them? IEEE Intelligent Systems, 14(1), 20–26.

Davies, H., Doick, K., Hudson, M., Schreckenberg, K. (2017). Challenges for tree officers to enhance the provision of regulating ecosystem services from urban forests. Environmental Research, 156, 97–107.

Eisenberg, B., & Polcher, V. (2019). Nature Based Solutions – Technical Handbook. EU Horizon 2020 research and innovation programme, grant No 730052, available online: https://unalab.eu/en/documents/ unalab-technical-handbook-nature-based-solutions. Accessed August 30, 2020.

Endreny, T.A. (2018). Strategically growing the urban forest will improve our world. Nature Communications, 9(1), 1160.

European Commission (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". Luxembourg.

Evans, J. (2004). Plantation silviculture. Encyclopedia of Forest Sciences, doi: 10.1016/B0-12-145160-7/00212-X.

FAO (Food and Agricultural Organization of the United Nations) (2018). Global Forest Resources Assessment 2020: Terms and Definitions. Forest Resources Assessment Working Paper, 188. Rome.

Fayle, T., Turner, E., Basset, Y., Ewers, R., Reynolds, G., & Novotny, V. (2015). Whole-ecosystem experimental manipulations of tropical forests. Trends in Ecology & Evolution, 30(6), 334–346.

Foster, C., Neumann, J., & Holloway, G. (2019). Linking mesoscale landscape heterogeneity and biodiversity: gardens and tree cover significantly modify flower-visiting beetle communities. Landscape Ecology, 34, 1081–1095.

Gašević, D., Djurić, D., & Devedžić, V. (2006). Model driven architecture and ontology development. Heidelberg.

Gómez-Pérez, A., Fernández-López, M., & Corcho, O. (2004). Ontological engineering with examples from the areas of knowledge management, e-commerce and the semantic web. London.

Gori, A., Ferrini, F., & Fini, A. (2019). Reprint of: Growing healthy food under heavy metal pollution load: Overview and major challenges of tree based edible landscapes. Urban Forestry & Urban Greening, 45, 126292.

Hanson, H., Wickenberg, B., & Olsson, J. (2020). Working on the boundaries—How do science use and interpret the nature-based solution concept? Land Use Policy, 90, 104302.

Helletsgruber, C., Gillner, S., Gulyás, Á., Junker, R. R., Tanács, E., & Hof, A. (2020). Identifying Tree Traits for Cooling Urban Heat Islands—A Cross-City Empirical Analysis. Forests, 11(19), 1064.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Hitzler, P., Krötzsch, M., Parsia, B., Patel-Schneider, P. F., & Rudolph, S. (2012). OWL 2 Web Ontology Language Primer (Second Edition), available online: https://www.w3.org/TR/2012/REC-owl2-primer-20121211/, accessed September 01, 2020.

Holt, A., Mears, M., Maltby, L., & Warren, P. (2015). Understanding spatial patterns in the production of multiple urban ecosystem services. Ecosystem Services, 16, 33–46.

Hunter R., Cleland C., Cleary A., Droomers M., Wheeler B., Sinnett D., Nieuwenhuijsen M., & Braubach M. (2019). Environmental, health, wellbeing, social and equity effects of urban green space interventions: A meta-narrative evidence synthesis. Environment International, 104923.

Janssen, I., & Rosu, A. (2015). Undeveloped green space and free-time physical activity in 11 to 13-year-old children. u International Journal of Behavioral Nutrition and Physical Activity, 12:26, doi: 10.1186/s12966-015-0187-3.

Kalfoglou, Y. (2001). Exploring ontologies. In S. K. Chang (Ed.), Handbook of software engineering and knowledge engineering (pp. 863–887). Singapore.

De Keyser, P. (2012). Indexing. From Thesauri to the Semantic Web. Oxford, Cambridge.

Koc, C., Osmond, P., & Peters, A. (2016). A Green Infrastructure Typology Matrix to Support Urban Microclimate Studies. Procedia Engineering, 169, 183–190.

Konijnendijk, C. (2003). A decade of urban forestry in Europe. Forest Policy and Economics, 5(2), 173–186.

Lehmann, I., Mathey, J., Rößler, S., Bräuer, A., & Goldberg, V. (2014). Urban vegetation structure types as a methodological approach for identifying ecosystem services – Application to the analysis of micro-climatic effects. Ecological Indicators, 42, 58–72.

Liu, C., Kuchma, O., Krutovsky, & K. V. (2018). Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. Global Ecology and Conservation, 15, e00419.

MA (Millennium Ecosystem Assessment) (2005). Ecosystems and Human Well-Being: Synthesis. Washington DC.

Martin-Smith, K. (2004). Aquatic Habitats in Forest Ecosystems. Encyclopedia of Forest Sciences, doi: 10.1016/B0-12-145160-7/00024-7.

Margueira, J., Holl, K., & Rodrigues, R. (2019). Enrichment planting to restore degraded tropical forest fragments in Brazil. Ecosystems and People, 15:1, 3–10.

Motik, B., Patel-Schneider, P. F., & Parsia, B. (2012). OWL 2 Web Ontology Language Structural Specification and Functional-Style Syntax (Second Edition), available online: https://www.w3.org/TR/owl2-syntax/, accessed September 01, 2020.

Nature4Cities (2018). D1.1 – NBS multi-scalar and multi-thematic typology and associated database. EU Horizon 2020 research and innovation programme, grant No 730468, available online:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

https://9e99b973-33ae-43f5-b05a-fbba8e8b1314.filesusr.com/ugd/55d29d_8813db2df690497e80740537b6a8a844.pdf. Accessed January 20, 2020.

Nikolaidis, N., Lilli, M., Kolokotsa, D., Somarakis, G., Stagakis, S., & Lemaitre, F. (2019): Classification of nature-based solutions, in: Somarakis, G., Stagakis, S., & Chrysoulakis, N. (Eds.), ThinkNature Nature-Based Solutions Handbook. ThinkNature project funded by the EU Horizon 2020 research and innovation programme under grant agreement No. 730338. doi:10.26225/ jerv-w202.

Nissen, S. (2008). Urban Transformation From Public and Private Space to Spaces of Hybrid Character. Czech Sociological Review, 44(6), 1129–1149.

Pan, W., & Du, J. (2020). Towards sustainable urban redevelopment: urban design informed by morphological patterns and ecologies of informal settlements, in: Verma, P., Singh, P., Singh, R., & Raghubanshi, A., Urban Ecology – Emerging Patterns and Social-Ecological Systems, Amsterdam, pp. 377–411.

Patarkalashvili, T. (2017). Urban forests and green spaces of Tbilisi and ecological problems of the city. Annals of Agrarian Science, 15(2), 187–191.

Pawar, K. V., Rothkar, R. V., 2015. Forest Conservation & Environmental Awareness. Procedia Earth and Planetary Sciences, 11, 212–215.

Scheuer, S., Haase, D., & Meyer, V. (2013). Towards a flood risk assessment ontology - Knowledge integration into a multi-criteria risk assessment approach. Computers, Environment and Urban Systems. 37, 82-94.

Science for Environment Policy (2015). Ecosystem Services and the Environment. In-depth Report 11 produced for the European Commission, DG Environment by the Science Communication Unit, UWE, Bristol, available online: http://ec.europa.eu/science-environment-policy. Accessed January 20, 2020.

Senatsverwaltung für Umwelt, Verkehr und Klimaschutz (2019). Kleingärten in Berlin. Kleingartenentwicklungsplan 2030 - Entwurf.

Shafiq, M. & Kim, R. (2017). Retrofitting the Low Impact Development Practices into Developed Urban areas Including Barriers and Potential Solution. Open Geosciences, 9, 240–254.

Smith, A. C., Berry, P. M., & Harrison, P. A. (2016). Sustainable Ecosystem Management, in: Potschin, M. & K. Jax (Eds), OpenNESS Ecosystem Services Reference Book. EC FP7 Grant Agreement no. 308428, available online: www.openness-project.eu/library/reference-book. Accessed February 05, 2020.

Somarakis, G., Stagakis, S., & Chrysoulakis, N. (Eds.) (2019). ThinkNature Nature-Based Solutions Handbook. ThinkNature project funded by the EU Horizon 2020 research and innovation programme under grant agreement No. 730338. doi:10.26225/jerv-w202.

Suppakittpaisarn P., Jiang B., Slavenas M., & Sullivan W.C. (2019). Does density of green infrastructure predict preference? Urban Forestry and Urban Greening, 40, 236–244.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Torquebiau, E. (2000). A renewed perspective on agroforestry concepts and classification. Comptes Rendus de l'Académie des Sciences - Series III - Sciences de la Vie, 323(11), 1009–1017.

Wang, J., Xu, C., Pauleit, S., Kindler, A., & Banzhaf, E. (2019). Spatial patterns of urban green infrastructure for equity: A novel exploration. Journal of Cleaner Production, 238, 117858.

Whitford, V., Ennos, A., & Handley, J. (2001). City form and natural process-indicators for the ecological performance of urban areas and their application to Merseyside, UK. Landscape and Urban Planning, 57, 91–103.

Vlaamse Land Maatschappij (2019). Green and Blue Infrastructure for Grey Peri-Urban Landscapes, available Online: https://green4grey.be/en. Accessed January 1, 2021.

Zhang, D., & Stanturf, J. (2008). Forest Plantations. Encyclopedia of Ecology, 2nd ed., doi: 10.1016/B978-0-444-63768-0.00331-0.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

APPENDIX

Glossary of terms

Table 5. Glossary of technical terms.

Term	Description	Example
Annotation	Annotations are used to associate additional information with the ontology, or the entities defined in it. Annotations are typically referred to include human-readable labels and descriptions, e.g., of classes.	
Axiom	An axiom refers to a statement about what is true in the domain described by an ontology. Axioms may be understood as restrictions (see restriction, class axioms).	
Cardinality restriction	Cardinality restrictions require that for a class X, regarding a property P, a cardinality constraint must be met. Cardinality constraints include a minimum cardinality (at least n), a maximum cardinality (at most n), or a specific cardinality value (exactly n).	A minimum cardinality restriction may be used to imply that to be considered UF-NBS, something must provide at least one ecosystem service.
Class	Classes denote sets (collections) of individuals (objects), correspond to concept expressions, and are roots of various taxonomic trees (classes may be subclasses of other classes, so-called superclasses). Classes may be explicitly named, or may be derived from property restrictions, be intersections, unions or a complement of classes, or an enumeration.	Entities typically correspond to (named) classes. Classes may be UF-NBS, ecosystem service, green-blue infrastructure element, green landscape element, etc.
Class axioms	Class axioms make statements about (taxonomic) relationships of concepts. They express, e.g., subclass relationships, equivalency, or that classes are pairwise disjoint.	
Controlled Natural Language (CNL)	Controlled natural language is a language restricted in terms of vocabulary and grammar in order to allow automatic analysis and interpretation (e.g., related to the fields of	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

	computational natural language learning and computational linguistics).	
Datatype property	Datatype properties relate classes (and their instances, i.e., objects) to data types as range, such as text or numerical values.	A datatype property may be "has canopy cover", where X has canopy cover Y, with Y being a share (%) expressed through a numerical value (a data type).
Domain	In regard to an ontology, domain refers to the subject of the knowledge formalized in the ontology. In regard to a property, domain refers to the left-hand side of the property.	The CLEARING HOUSE ontology has the domain urban forest. The object property "provides ecosystem service" has UF-NBS as its domain, i.e., ecosystem services are provided by UF-NBS.
Entity	Element or concept that refers to a real-world object/a real-world phenomenon.	A tree, a garden, a large park, institutional accessibility, etc.
Existential restriction (existential quantification)	An individual is an instance of domain X if it holds true that at least one pair (x,y) belongs to property P. The restriction indicates that at least one value of P must be a member of Y.	An existential restriction may be imposed on the object property "is composed of", so that for something to be considered a green-blue infrastructure element, there must be at least one property defined for X that states that X is composed of a green landscape element Y.
Individual	Individuals correspond to instances of classes, and thus to objects of the real-world (see entity).	Park is a class, whereas "Treptower Park" is an individual of that class that corresponds to the real-world park located in Berlin.
Individual value restriction	An individual value restriction explicitly defines the value for a property.	
Inheritance	Inheritance refers to the fact that subclasses inherit (have the same) properties (characteristics) as their superclasses.	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Object property	Object properties relate classes (and their instances) to other classes as range.	An object property may be "provides ecosystem service", where X provides ecosystem service Y, with Y being a specific type of ecosystem service (an object). Another object property may be "is composed of", where X is composed of Y.
Ontology	A formal description (as a series of statements of facts, i.e., axioms) of the kinds of entities of relevance within a domain in question (a subject), and their relations (see axiom).	
OWL	See Web Ontology Language.	
Property	A property is a characteristic (an attribute) of a class, i.e., a directed binary relation between a domain X (a class) and the range Y (e.g., another class). Properties can be distinguished into object and datatype properties (see datatype property, object property), and may be restricted in regard to values or cardinality (see value restriction, cardinality restriction).	
RDF	RDF (Resource Description Framework) is, similar to the Web Ontology Language (OWL), a means to express facts about resources (e.g., entities from a domain). It is less expressive than OWL, however, OWL is built upon RDF.	
Restriction	Core concept of OWL that describes classes by the values allowed for specific properties (see Property, Value restriction, Cardinality restriction).	
Semantic modelling	Semantic modelling refers to the process of organizing and formalizing (unstructured) information (i.e., modelling), e.g., to express and depict relationships that exist among concepts or values of data (their semantics). Formalization is done by means of a semantic language, such as the Web Ontology Language (OWL; see Web Ontology Language).	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Taxonomy	Hierarchical tree structure of the classes of entities, i.e., superclass-subclass relationships (where, for example, superclasses may serve as "umbrella terms").	The expression that a "historical park" is a special kind of "parks and gardens" denotes that "historical park" is a subclass of "parks and gardens".
Trait	Here, a trait corresponds to a distinguishing quality or feature related to the grouping principles of the typology, i.e., regarding morphology, or function.	Object grouping, i.e., whether an object appears solitary or in a clustered group, is a trait.
Universal restriction (universal quantification)	The restriction indicates that all values Y of P for X are members of Y. Conversely, all individuals for which the value of P is Y belong to class X.	A universal restriction may be applied to the object property "provides ecosystem service", so that all values for this property must be nothing but ecosystem service(s). No other concepts shall be allowed as values.
Value restriction	Local class definitions that restrict the range of properties (see universal restriction, existential restriction, individual value restriction).	
Web Ontology Language	The Web Ontology Language is a formal, declarative language to express ontologies. It allows expressing detailed constraints between concepts.	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Table 6. Glossary of grouping principles terms.

Term	Description
Morphological attribute (form)	Describes (non-)grouping of elements (as in solitary tree, row of trees, or group of trees
Physical attribute	Describes the canopy cover, the physical location related to a building or other support structures for greening (e.g. ground-based, on a roof etc.), and spatial/topological relationships (adjacency, containment etc.) to further describe location and setting
Functional attribute	Describes the provision with ecosystem service provisioning by individual elements such as (a specific genus/species of) tree, or compositions of such elements, i.e., GBI elements.
Institutional attribute	Describes the management of GBI elements, the governance arrangements and mechanism of their implementation, planning and maintenance, and captures aspects of institutional accessibility and property regimes (private, semi-public, public).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Non-commented NCL version of the UF-NBS typology

```
Title: 'CLEARING HOUSE UF-NBS TYPOLOGY'.
Namespace: 'http://clearinghouseproject.eu/typology/elements'.
Author: 'Sebastian Scheuer, Jessica Jache, Thilo Wellmann, Dagmar Haase, Manuel Wolff'.


Comment:'http://purl.org/dc/terms/title'::: 'CLEARING HOUSE Typology on Urban Forests As Nature-Based
Solutions'.

Comment:'http://purl.org/dc/elements/1.1/creator'::: 'The CLEARING HOUSE project. This project has
received funding from the European Union's Horizon 2020 Research and Innovation Program under Grant
Agreement 821242.'.

Comment:'http://purl.org/dc/terms/abstract'::: 'This deliverable outlines the CLEARING HOUSE typology
of urban forests as nature-based solutions (UF-NBS). The typology thus conceptualizes entities relevant
to UF-NBS. To do so, elements of the green-blue infrastructure (GBI) are defined in the typology.
Contrary to purely textual representations of knowledge, CLEARING HOUSE proposes a definition of GBI
elements through traits, i.e., characteristic and defining morphological, physical, functional, and
institutional attributes, including for example the composition, spatial grouping and topology of (UF-
)NBS elements, and the ecosystem services and benefits provided them. CLEARING HOUSE proposes a
semantic approach to express this knowledge, i.e., a formalization of knowledge as an ontology using
the Web Ontology Language. Such ontologies are machine-interpretable series of statements of facts to
define a taxonomy (a vocabulary). The definitions of GBI elements are embedded within a formalization
of overarching concepts, particularly, of urban forest, nature-based solutions (NBS), and of UF-NBS.
Here, urban forest is conceptually understood as the entirety of trees within an urban-ecological
system. NBS are perceived in CLEARING HOUSE as an overarching concept that embraces natural and semi-
natural elements of the GBI such as forests, engineered solutions such as permeable pavements, as well
as actions inspired by nature. UF-NBS are then conceptualized as the intersection of the two previous
entities, i.e., as the intersection of urban forest and NBS, and thus include any tree-related NBS. The
proposed typology will provide the grounding knowledge of the comparative case study analysis to be
conducted by CLEARING HOUSE, and will serve as a basis for the development of the CLEARING HOUSE
benchmarking tool.'.

Comment:'http://purl.org/ontology/bibo/status'::: 'MARCH 2021'.

Part-1: 'GROUPING PRINCIPLES'.
Every grouping-principle is something.
Every morphological-attribute is a grouping-principle .
Every physical-attribute is a grouping-principle .
Every functional-attribute is a grouping-principle .
Every institutional-attribute is a grouping-principle .

Part-2: 'MORPHOLOGY AND FORM'.
Every object-grouping is a morphological-attribute .
If X has-grouping Y then X "<->" Y .
Every-single-thing has-grouping nothing-but object-grouping .
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Every zero-dimensional-grouping is an object-grouping .
Every one-dimensional-grouping is an object-grouping .
Every two-dimensional-grouping is an object-grouping .

Solitary is a zero-dimensional-grouping .
Linear-Group is an one-dimensional-grouping .
Clustered-Group is a two-dimensional-grouping .
Irregular-Pattern is a two-dimensional-grouping .

Every regular-patterns is a two-dimensional-grouping .
Regular-Grid is a regular-patterns .
Regular-Pattern is a regular-patterns .

Every species-diversity is a morphological-attribute.
If X has-species-diversity Y then X "<->" Y.
Low-Or-Monoculture is a species-diversity.
Average is a species-diversity.
Elevated is a species-diversity.

Part-3: 'PHYSICAL ATTRIBUTES'.

Part-4: 'SEALING'.
Every tree has-planting-condition nothing-but sealings.
Every sealing is a physical-attribute.
Paved is a sealing.
Unpaved is a sealing.

Part-5: 'CANOPY COVER'.
Every canopy-cover is a physical-attribute.
Every value-of has-canopy-cover is something (some real value).

Part-6: 'LOCATION'.
Every-single-thing has-physical-location nothing-but physical-location.
If X has-physical-location Y then X "<->" Y.
Every location-not-associated-with-a-support-structure is a physical-location.
Every location-on-support-structure is a physical-location.
Every location-on-building is a physical-location.
Every ground-based-location is a location-not-associated-with-a-support-structure.
Ground-Based is a ground-based-location.
On-Pergola is a location-on-support-structure.
On-Building-Facade is a location-on-building.
On-Balcony is a location-on-building.
On-Building-Roof is a location-on-building.

Part-7: 'PROCESS PHENOMENA'.
Every process-phenomenon is something.
Every physical-process-phenomenon is a process-phenomenon.
Every physical-process-phenomenon is a physical-attribute.
Every physical-location is a physical-attribute.
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Flooding is a physical-process-phenomenon.
Shading is a physical-process-phenomenon .
Transpiration is a physical-process-phenomenon .
Evaporation is a physical-process-phenomenon .
Photosynthesis is a physical-process-phenomenon .
Evapotranspiration is a physical-process-phenomenon .

Every-single-thing that contributes-to Transpiration and contributes-to Evaporation contributes-to
Evapotranspiration .
Every-single-thing that contributes-to Shading provides-ecosystem-service Regulation-Of-Air-
Temperature-And-Humidity .
Every-single-thing that contributes-to Transpiration provides-ecosystem-service Regulation-Of-Air-
Temperature-And-Humidity .
Every-single-thing that contributes-to Evaporation provides-ecosystem-service Regulation-Of-Air-
Temperature-And-Humidity .
Every-single-thing that contributes-to Photosynthesis provides-ecosystem-service Carbon-Sequestration .
Every-single-thing that contributes-to Photosynthesis provides-ecosystem-service Carbon-Storage .

Part-8: 'TOPOLOGY'.
If X is-adjacent-to Y then X "<->" Y.
X is-adjacent-to Y if-and-only-if Y is-adjacent-to X.
If X is-part-of Y then X "<->" Y.
If X has-part Y then X "<->" Y.
X has-part Y if-and-only-if Y is-part-of X.
If X is-enclosed-by Y then X "<->" Y.
If X is-fully-enclosed-by Y then X "<->" Y.
Every-single-thing is-adjacent-to nothing-but things .
Every-single-thing is-enclosed-by nothing-but things .
Every-single-thing is-fully-enclosed-by nothing-but things .
Every-single-thing is-part-of nothing-but things .
Every-single-thing is-affected-by nothing-but things .
X is-affected-by Y if-and-only-if Y contributes-to X.

Part-9: 'COMPOSITION'.
If X is-composed-of Y then X "<->" Y.

Part-10: 'FUNCTION ATTRIBUTES'.

Part-11: 'ECOSYSTEM SERVICES AS BENEFITS'.
Every ecosystem-service is a functional-attribute.
If X provides-ecosystem-service Y then X "<->" Y.
If X is-composed-of something that provides-ecosystem-service Y then X provides-ecosystem-service Y.

Part-12: 'SUPPORTING SERVICES'.
Every supporting-service is an ecosystem-service.
Habitat-Provisioning is a supporting-service.
Biodiversity-Conservation is a supporting-service.

Part-13: 'PROVISIONING SERVICES'.
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Every provisioning-service is an ecosystem-service.
Food-Production is a provisioning-service.
Timber-Production is a provisioning-service.
Non-Timber-Forest-Products is a provisioning-service.
Plant-Propagation is a provisioning-service.

Part-14: 'REGULATION AND MAINTENANCE SERVICES'.
Every regulation-and-maintenance-service is an ecosystem-service.
Every pollution-removal is a regulation-and-maintenance-service.
Water-Purification is a pollution-removal.
Air-Purification is a pollution-removal.
Regulation-Of-Air-Temperature-And-Humidity is a regulation-and-maintenance-service.
Every water-flow-regulation is a regulation-and-maintenance-service.
Infiltration is a water-flow-regulation.
Runoff-Regulation is a water-flow-regulation.

Every carbon-sequestration-and-storage is a regulation-and-maintenance-service .
Carbon-Sequestration is a carbon-sequestration-and-storage .
Carbon-Storage is a carbon-sequestration-and-storage .

Part-15: 'CULTURAL SERVICES'.
Every cultural-service is an ecosystem-service.
Heritage-Value is a cultural-service.
Aesthetical-Value is a cultural-service.
Social-Cohesion is a cultural-service .
Place-Attachment is a cultural-service .
Every recreation is a cultural-service.
Passive-Recreational-Use is a recreation.
Active-Recreational-Use is a recreation.
Mixed-Recreational-Use is a recreation.
Every interaction-with-nature is a cultural-service.
Scientific-Value is an interaction-with-nature.
Education is an interaction-with-nature.

Every-single-thing that provides-ecosystem-service Infiltration provides-ecosystem-service Water-
Purification and provides-ecosystem-service Runoff-Regulation.
Every-single-thing that provides-ecosystem-service Active-Recreational-Use and provides-ecosystem-
service Passive-Recreational-Use provides-ecosystem-service Mixed-Recreational-Use.

Part-16: 'GOVERNANCE AND INSTITUTIONAL ATTRIBUTES'.

Part-17: 'MANAGEMENT'.
Every management-intensity is an institutional-attribute.
If X has-management-intensity Y then X "<->" Y.
High is a management-intensity.
Low is a management-intensity.
Not-Managed is a management-intensity.
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Part-18: 'ACCESSIBILITY'.
Every institutional-accessibility is an institutional-attribute .
If X has-institutional-accessibility Y then X "<->" Y .
Public is an institutional-accessibility.
Semi-Public is an institutional-accessibility .
Selective is an institutional-accessibility.
Private is an institutional-accessibility.

Temporally-Restricted-Access is an institutional-accessibility .
Temporally-Unrestricted-Access is an institutional-accessibility .

Part-19: 'ENTITLEMENTS'.
Every entitlement-of-use is an institutional-attribute .
If X has-entitlement Y then X "<->" Y .
Unrestricted-Public is an entitlement-of-use .
Restricted-Collective is an entitlement-of-use .
Restricted-Private is an entitlement-of-use .

Part-20: 'OVERARCHING CONCEPTS AND LANDSCAPE ELEMENTS - FRAMING CONTEXT'.
Something is a spatial-entity if-and-only-if-it has-area (some real value).

Part-21: 'LANDSCAPE ELEMENTS'.
Every landscape-element is something.
Every landscape-element is a spatial-entity.

Every green-landscape-element is a landscape-element.
Every blue-landscape-element is a landscape-element.
Every grey-landscape-element is a landscape-element.

Every green-blue-infrastructure-element is something.
Every green-landscape-element is a green-blue-infrastructure-element.
Every blue-landscape-element is a green-blue-infrastructure-element.

Part-22: 'GBI, URBAN FOREST CONCEPT, NBS, AND UF-NBS '.
Something is a green-blue-infrastructure-element if-and-only-if-it is a thing that is-composed-of at-
least one green-landscape-element and-or is-composed-of at-least one blue-landscape-element.
Something is a urban-forest if-and-only-if-it is a thing that is a tree and-or is a thing that is-
composed-of a tree and-or is a thing that is-composed-of something that is-composed-of a tree and-or
is-composed-of a row-of-tree and-or is-composed-of a group-of-tree.

Every engineered-element is something .
Every engineered-element is a spatial-entity.

Something is a nbs if-and-only-if-it is a thing that provides-ecosystem-service at-least two ecosystem-
service.
Every nbs provides-ecosystem-service nothing-but ecosystem-service.
Every green-blue-infrastructure-element is a nbs.
Every nbs-action is a nbs.
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Something is a uf-nbs if-and-only-if-it is a thing that is a nbs and is a thing that is a urban-forest
and-or aims-at a urban-forest and-or seeks-implementation-of urban-forest.

Part-23: 'GREEN LANDSCAPE ELEMENTS - TYPES OF VEGETATION, INCLUDING TREES AS CORE ENTITIES'.
Every type-of-vegetation is a green-landscape-element.
Something is a edible-plant if-and-only-if-it is a type-of-vegetation that provides-ecosystem-service
Food-Production .
Every woody-vegetation is a type-of-vegetation.
Every non-woody-vegetation is a type-of-vegetation.

Every type-of-vegetation contributes-to Transpiration .
Every type-of-vegetation contributes-to Shading .
Every type-of-vegetation contributes-to Photosynthesis .

Comment: 'Trees, including forest and non-forest trees, and fruit trees'.
Every tree is a woody-vegetation.
Every fruit-tree is a tree.
Every fruit-tree provides-ecosystem-service Food-Production.
Every forest-tree is a tree.
Something is a forest-tree if-and-only-if-it is a tree that has-mature-height greater-than 5.0.
Every non-forest-tree is a tree.
Something is a non-forest-tree if-and-only-if-it is a tree that has-mature-height lower-or-equal-to
5.0.
No non-forest-tree is a forest-tree.

Comment: 'Tree traits'.
Every tree has-mature-height nothing-but (some real value).
Every tree has-height nothing-but (some real value).
Every tree has-trunk-circumference nothing-but (some real value).
Every tree has-crown-area nothing-but (some real value).
Every tree has-crown-base nothing-but (some real value).
Every tree has-crown-volume nothing-but (some real value).
Every tree has-leaf-area-index nothing-but (some real value).
Every tree has-leaf-area-density nothing-but (some real value).
Every tree is-of-genus nothing-but tree-genera .
Every tree is-of-species nothing-but tree-species .

Comment: 'Shrubs'.
Every shrub is a woody-vegetation.
No shrub is a tree.

Comment: 'Hedge'.
Something is a hedge if-and-only-if-it is a thing (that is-composed-of a tree and has-management-
intensity High and-or is-composed-of a shrub) and has-grouping Linear-Group.
Every hedge is a woody-vegetation.

Comment: 'Grasses'.
Every grass is a non-woody-vegetation.
Something is a lawn if-and-only-if-it is a thing that is a grass and has-management-intensity High.
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Every lawn provides-ecosystem-service Aesthetical-Value and provides-ecosystem-service a recreation.
Something is a meadow if-and-only-if-it is a thing that is a grass and has-management-intensity Low.
Every meadow provides-ecosystem-service Habitat-Provisioning and provides-ecosystem-service
Biodiversity-Conservation.

Comment: 'Derivatives of trees, and elements composed of trees in specific arrangements'.
Something is a single-tree if-and-only-if-it is a tree that has-grouping Solitary.
Every single-tree is a green-landscape-element.

Something is a group-of-tree if-and-only-if-it is a thing that is-composed-of a tree and has-grouping
Clustered-Group.
Something is a row-of-tree if-and-only-if-it is a thing that is-composed-of a tree and has-grouping
Linear-Group.
Every group-of-tree is a green-landscape-element.
Every row-of-tree is a green-landscape-element.

Something is a single-street-tree if-and-only-if-it is a single-tree that has-physical-location a
ground-based-location and is-adjacent-to a street.
Every single-street-tree is a green-blue-infrastructure-element.
Every single-street-tree is a street-green.

Something is an ornamental-tree if-and-only-if-it is a single-tree that provides-ecosystem-service
Aesthetical-Value.
Every ornamental-tree is a green-blue-infrastructure-element.

Something is a tree-alley if-and-only-if-it is a thing that is-composed-of at-least two row-of-tree and
has-physical-location a ground-based-location and is-adjacent-to a street.
Every tree-alley is a green-blue-infrastructure-element.
Every tree-alley is a street-green.

Something is a veteran-tree if-and-only-if-it is a single-tree that provides-ecosystem-service Habitat-
Provisioning.
Every veteran-tree is a green-blue-infrastructure-element.

Something is a survivor-tree if-and-only-if-it is a single-tree that provides-ecosystem-service
Heritage-Value.
Every survivor-tree is a green-blue-infrastructure-element.

Something is a grove if-and-only-if-it is a group-of-tree that has-physical-location a ground-based-
location.
Every grove is a green-blue-infrastructure-element.

Part-24: 'BLUE LANDSCAPE ELEMENTS'.
Every blue-landscape-element contributes-to Evaporation .

Every permanent-standing-water is a blue-landscape-element.
Every pond is a permanent-standing-water.
Every lake is a permanent-standing-water.
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Every watercourse is a blue-landscape-element.
Every river is a watercourse.
Every canal is a watercourse.
Every stream is a watercourse.

Every wetland is a blue-landscape-element.

Part-25: 'GREY LANDSCAPE ELEMENTS'.
Every network-infrastructure-element is a grey-landscape-element.
Every path is a network-infrastructure-element.
Every street is a network-infrastructure-element.
Every square is a network-infrastructure-element.

Every track is a network-infrastructure-element.
Tram-Track is a track.
Railroad-Track is a track.

Every building is a grey-landscape-element.
Every private-house is a building.
Every multistorey-building is a building.

Every object-feature is a grey-landscape-element.

Every grave is an object-feature.
Every bench is an object-feature.
Every sports-field is an object-feature.
Every playground is an object-feature.
Every fitness-equipment is an object-feature.
Every skate-park is an object-feature.

Every bench provides-ecosystem-service Passive-Recreational-Use.
Every playground provides-ecosystem-service Active-Recreational-Use.
Every sports-field provides-ecosystem-service Active-Recreational-Use.
Every fitness-equipment provides-ecosystem-service Active-Recreational-Use.
Every skate-park provides-ecosystem-service Active-Recreational-Use.

Part-26: 'NATURAL AND SEMI-NATURAL AREAS'.

Part-27: 'TREED AREAS'.
Something is a treed-area if-and-only-if-it is a thing that has-physical-location a ground-based-
location and is a thing (that is-composed-of a tree (that has-grouping a two-dimensional-grouping)) and
is a thing that has-canopy-cover greater-than 50.
Every treed-area is a green-blue-infrastructure-element.
Every treed-area is a wood .
Every wood is a treed-area .

Part-28: 'FOREST'.
Something is a forest if-and-only-if-it is a treed-area that has-area greater-than 5000.
Every forest is a green-blue-infrastructure-element.
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Every forest provides-ecosystem-service Timber-Production.
Every forest provides-ecosystem-service Non-Timber-Forest-Products.
Every forest provides-ecosystem-service a recreation.

Part-29: 'RIPARIAN FOREST/FLOODPLAIN FOREST'.
Something is a riparian-forest if-and-only-if-it is a forest (that is-adjacent-to a river and-or is-adjacent-to a stream) and is a forest that is-affected-by Flooding.
Every riparian-forest is a floodplain-forest .
Every floodplain-forest is a riparian-forest .
Every riparian-forest is a green-blue-infrastructure-element.

Part-30: 'URBAN FOOD FOREST, NURSERIES, AND FOREST PLANTATIONS'.

Part-31: 'NURSERY, E.G., TO DERIVE TREE NURSERIES'.
Something is a nursery if-and-only-if-it is a thing that is-composed-of at-least one type-of-vegetation and provides-ecosystem-service Plant-Propagation.
Every nursery is a green-blue-infrastructure-element.

Part-32: 'FOREST PLANTATION/PLANTATION FOREST'.
Something is a forest-plantation if-and-only-if-it is a thing (that is-composed-of a tree (that has-grouping a regular-patterns)) and is a thing that has-physical-location a ground-based-location and has-species-diversity Low-Or-Monoculture and has-management-intensity High.
Every forest-plantation provides-ecosystem-service Timber-Production.
Every forest-plantation is a green-blue-infrastructure-element.
Every forest-plantation is a plantation-forest .
Every plantation-forest is a forest-plantation .

Part-33: 'ORCHARD'.
Something is an orchard if-and-only-if-it is a thing (that is-composed-of a fruit-tree and has-grouping a two-dimensional-grouping) and is a thing that has-physical-location a ground-based-location.
Every orchard is a green-blue-infrastructure-element.
Every orchard is a urban-food-forest.

Part-34: 'URBAN GREEN AREAS'.

Part-35: 'PARKS-AND-GARDENS'.
Something is a parks-and-gardens if-and-only-if-it is a thing that has-physical-location a ground-based-location and is a thing (that is-composed-of a green-blue-infrastructure-element and is-composed-of a grey-landscape-element) and-or is a thing that is a treed-area that has-area lower-or-equal-to 5000.
Every parks-and-gardens provides-ecosystem-service a recreation.

Part-36: 'RIVERBANK GREEN'.
Something is a riverbank-green if-and-only-if-it is a thing that is-adjacent-to a watercourse and has-physical-location a ground-based-location and is-composed-of a green-blue-infrastructure-element.
Every riverbank-green is a green-blue-infrastructure-element.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Part-37: 'URBAN PARK, IRRESPECTIVE OF SIZE'.
Something is a urban-park if-and-only-if-it is a parks-and-gardens (that is-composed-of at-least one
lawn) and has-institutional-accessibility Public and has-entitlement Unrestricted-Public .
Every urban-park is a green-blue-infrastructure-element .

Part-38: 'BOTANICAL GARDENS AND ARBORETA'.
Something is a botanical-garden if-and-only-if-it is a parks-and-gardens that provides-ecosystem-
service Education and has-species-diversity Elevated and has-management-intensity High.
Every botanical-garden is a green-blue-infrastructure-element .

Part-39: 'HISTORICAL PARK/GARDEN'.
Something is a historical-park if-and-only-if-it is a parks-and-gardens ( that has-management-intensity
High and provides-ecosystem-service Heritage-Value ) .
Every historical-park is a green-blue-infrastructure-element .
Every historical-park is a historical-garden.
Every historical-garden is a historical-park.

Part-40: 'ALLOTMENT GARDEN'.
Something is an allotment-garden if-and-only-if-it is a thing that has-physical-location ground-based-
location and is-composed-of edible-plant and is-composed-of grey-landscape-element and has-
institutional-accessibility Semi-Public and has-entitlement Restricted-Private .
Every allotment-garden is a green-blue-infrastructure-element .

Part-41: 'COMMUNITY GARDENS'.
Something is a community-garden if-and-only-if-it is a thing that is-composed-of edible-plant and has-
entitlement Restricted-Collective .
Every community-garden is a green-blue-infrastructure-element .

Part-42: 'NEIGHBOURHOOD GREEN SPACE'.
Something is a neighbourhood-green-space if-and-only-if-it is a thing that is-composed-of green-blue-
infrastructure-element and is-adjacent-to a multistorey-building and has-institutional-accessibility
either Public or Semi-Public .
Every neighbourhood-green-space is a parks-and-gardens.
Every neighbourhood-green-space is a green-blue-infrastructure-element.

Part-43: 'HOUSE GARDEN'.
Something is a house-garden if-and-only-if-it is a thing that has-physical-location ground-based-
location and is-composed-of green-blue-infrastructure-element and is-adjacent-to private-house and has-
institutional-accessibility Private and has-entitlement Restricted-Private .
Every house-garden provides-ecosystem-service Aesthetical-Value .
Every house-garden is a parks-and-gardens.
Every house-garden is a green-blue-infrastructure-element.

Part-44: 'COURTYARD GREEN'.
Something is a courtyard-green if-and-only-if-it is a thing that has-physical-location ground-based-
location and is-composed-of green-blue-infrastructure-element and is-composed-of grey-landscape-element
and is-enclosed-by multistorey-building and has-institutional-accessibility either Selective or Private
and has-entitlement either Restricted-Collective or Restricted-Private .
Every courtyard-green is a green-blue-infrastructure-element .
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Part-45: 'OTHER TYPES OF GBI'.

Part-46: 'CEMETERIES'.
Something is a cemetery if-and-only-if-it is a thing that is-composed-of a grave.
Every cemetery that is-composed-of at-least one green-blue-infrastructure-element is a green-blue-
infrastructure-element.

Part-47: 'ARBORETUM'.
Something is an arboretum if-and-only-if-it is a thing that has-physical-location a ground-based-
location and is-composed-of a tree and has-species-diversity Elevated and provides-ecosystem-service
Education.
Every arboretum is a green-blue-infrastructure-element .

Part-48: 'GBI ASSOCIATED WITH BUILDINGS AND SUPPORT STRUCTURES'.

Part-49: 'GREEN ROOFS - NO FURTHER DISTINCTION USED'.
Something is a green-roof if-and-only-if-it is a thing that has-physical-location On-Building-Roof and
is-composed-of at-least one green-landscape-element.
Every green-roof is a green-blue-infrastructure-element.

Part-50: 'GREEN WALLS. NO FURTHER DISTINCTION USED.'.
Something is a green-wall if-and-only-if-it is a thing that has-physical-location On-Building-Facade
and is-composed-of at-least one green-landscape-element.
Every green-wall is a green-blue-infrastructure-element.

Part-51: 'BALCONY GREEN'.
Something is a balcony-green if-and-only-if-it is a thing that has-physical-location On-Balcony and is-
composed-of at-least one green-landscape-element.
Every balcony-green is a green-blue-infrastructure-element.

Part-52: 'ATRIUM'.
Something is an atrium if-and-only-if-it is a thing that is-fully-enclosed-by nothing-but building and
is-composed-of at-least one green-landscape-element.
Every atrium is a green-blue-infrastructure-element.

Part-53: 'VEGETATED PERGOLAS AS PARTS OF THE GBI'.
Something is a vegetated-pergola if-and-only-if-it has-physical-location On-Pergola and is-composed-of
at-least one green-landscape-element.

Part-54: 'PART OF BUILDING TO BUILDING-ASSOCIATED GREEN'.
Every-single-thing that is-enclosed-by nothing-but building and-or has-physical-location On-Building-
Roof and-or has-physical-location On-Building-Facade is-part-of a building.

Part-55: 'ACTIONS AS FORMS OF NBS'.
Something is a nbs-action if-and-only-if-it aims-at a spatial-entity and involves activity and has-
intended-outcome ecosystem-service.

Comment: 'Define object properties to describe action outcomes, i.e., intended ecosystem services'.
If X has-intended-outcome Y then X "<->" Y .
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
If X aims-at Y then X "<->" Y .

If X seeks-implementation-of Y then X "<->" Y .
If X seeks-provisioning-of Y then X "<->" Y .
If X seeks-improvement-of Y then X "<->" Y .
If X seeks-maintenance-of Y then X "<->" Y .

If X seeks-provisioning-of Y then X has-intended-outcome Y .
If X seeks-improvement-of Y then X has-intended-outcome Y .
If X seeks-maintenance-of Y then X has-intended-outcome Y .

Every-single-thing has-intended-outcome nothing-but ecosystem-service .
Every-single-thing seeks-provisioning-of nothing-but ecosystem-service .
Every-single-thing seeks-improvement-of nothing-but ecosystem-service .
Every-single-thing seeks-maintenance-of nothing-but ecosystem-service .

If X has-intended-outcome Y then X provides-ecosystem-service Y .

Comment: 'Implementation actions'.
Every implementation-action is a nbs-action.
Every implementation-action seeks-provisioning-of an ecosystem-service .
Something is an implementation-action if-and-only-if-it seeks-implementation-of nbs and seeks-
provisioning-of ecosystem-service .

Comment: 'Restoration actions'.
Every restoration-action is a nbs-action.
Every restoration-action seeks-improvement-of an ecosystem-service.
Something is a restoration-action if-and-only-if-it seeks-improvement-of an ecosystem-service.

Comment: 'Management actions'.
Every management-action is a nbs-action.
Every management-action seeks-maintenance-of an ecosystem-service.
Something is a management-action if-and-only-if-it seeks-maintenance-of an ecosystem-service.

Comment: 'Activities are the entities that describe the action of an nbs-action, i.e., what is actually
done'.
Every activity is something .

Monitoring is an activity .
Pruning is an activity .
Watering is an activity .
Weed-Control is an activity .
Pest-Control is an activity .
Construction is an activity .
Restoration is an activity .

Every planting-activity is an activity .
Tree-Planting is a planting-activity .
Shrub-Planting is a planting-activity .
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

```
Grass-Planting is a planting-activity .

Every pest-control is an activity .
Biological-Pest-Control is a pest-control .
Application-Of-Pesticides is a pest-control .

Comment: 'Individuals of actions defines as classes would correspond to real-world actions taken, e.g., case studies'.

Comment: 'Implementation action'.
Something is an afforestation if-and-only-if-it is a thing that aims-at spatial-entity and is a thing that involves Tree-Planting and is a thing that seeks-provisioning-of ecosystem-service and seeks-implementation-of something ( that is a forest and-or is a forest-plantation ) .
Something is a wetland-construction if-and-only-if-it is a thing that aims-at a spatial-entity and is a thing that involves Construction and is a thing that seeks-provisioning-of ecosystem-service and seeks-implementation-of wetland .

Comment: 'Restoration action'.
Something is a reforestation if-and-only-if-it is a thing ( that aims-at a forest and-or aims-at a forest-plantation ) and involves Tree-Planting and is a thing that seeks-improvement-of ecosystem-service .
Something is a wetland-restoration if-and-only-if-it is a thing that aims-at a wetland and is a thing that involves Restoration and is a thing that seeks-improvement-of ecosystem-service .
Something is an orchard-restoration if-and-only-if-it is a thing that aims-at orchard and is a thing that involves Restoration and is a thing that seeks-improvement-of ecosystem-service .
Something is an enrichment-planting if-and-only-if-it is a thing that aims-at green-blue-infrastructure-element and involves planting-activity and is a thing that seeks-improvement-of Biodiversity-Conservation .
Every enrichment-planting is a species-diversification .
Every species-diversification is an enrichment-planting .

Comment: 'Management action'.
Something is a tree-monitoring if-and-only-if-it is a thing that aims-at single-tree and is a thing that involves Monitoring and is a thing that seeks-maintenance-of ecosystem-service .
Something is a forest-monitoring if-and-only-if-it is a thing that aims-at urban-forest and is a thing that involves Monitoring and is a thing that seeks-maintenance-of ecosystem-service .
Something is a tree-pruning if-and-only-if-it is a thing that aims-at single-tree and is a thing that involves Pruning and is a thing that seeks-maintenance-of ecosystem-service .
Something is a tree-watering if-and-only-if-it is a thing that aims-at single-tree and is a thing that involves Watering and is a thing that seeks-maintenance-of ecosystem-service .
Something is a pest-management if-and-only-if-it is a thing that aims-at green-blue-infrastructure-element and is a thing that involves pest-control and is a thing that seeks-maintenance-of ecosystem-service .

Comment: 'Some meta-classes'.
Something is a forest-conservation if-and-only-if-it is a thing ( that aims-at forest and-or aims-at forest-plantation ) and seeks-maintenance-of ecosystem-service .
Something is a greening if-and-only-if-it is a thing that involves planting-activity and is a thing ( that aims-at spatial-entity ( that is not forest and is not forest-plantation ) ) and is a thing ( that
```


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

seeks-provisioning-of ecosystem-service and seeks-implementation-of something (that is not forest and is not forest-plantation) and-or is a thing that seeks-improvement-of ecosystem-service) .

Part-56: 'ADDITIONAL ASSERTIONS'.

Part-57: 'STREET TREES'.
Something is a street-trees if-and-only-if-it is a single-street-tree and-or is a thing (that is-composed-of a tree and is-adjacent-to a street) and-or is a thing (that is-composed-of a row-of-tree and is-adjacent-to a street) and-or is a thing that is-composed-of a group-of-tree and is-adjacent-to a street .

Part-58: 'NETWORK-ASSOCIATED GREEN'.
Every green-blue-infrastructure-element that is-adjacent-to a network-infrastructure-element is a network-associated-green.

Part-59: 'BUILDING-ASSOCIATED GREEN'.
Every green-blue-infrastructure-element that is-part-of a building is a building-associated-green.

Part-60: 'GBI elements associated with networks'.
Part-61: 'RAILROAD BANK'.
Something is a railroad-bank if-and-only-if-it is a thing (that has-physical-location a ground-based-location) and is a thing (that is-composed-of green-landscape-element) and is a thing that is-adjacent-to Railroad-Track .
Every railroad-bank is a green-blue-infrastructure-element.

Part-62: 'GREEN VERGE'.
Something is a green-verge if-and-only-if-it is a thing (that has-physical-location a ground-based-location) and is a thing (that is-composed-of a grass and-or is-composed-of shrub and-or is-composed-of an ornamental-tree) and is a thing that is-adjacent-to network-infrastructure-element .
Every green-verge is a green-blue-infrastructure-element .
Every green-verge is a margin .
Every margin is a green-verge .

Part-63: 'ENGINEERED ELEMENTS AS TYPES OF NBS'.
Something is a permeable-pavement if-and-only-if-it is a street that provides-ecosystem-service Infiltration.
Every permeable-pavement is an engineered-element.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821242. The content of this milestone document does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).