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Nexus between nature-based solutions, ecosystem services and urban challenges

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ABSTRACT

Nature-based Solutions (NBS) are increasingly promoted to support sustainable and resilient urban planning. However, design and planning urban NBS targeted at the needs of the local context require knowledge about the causal relationships between NBS, ecosystem services (ES) and urban challenges (UC) This paper aims at contributing to this knowledge, by systematically identifying nexuses (i.e. qualitative links) between UC, ES and NBS, and describing plausible causal relationships. A conceptual UC-ES-NBS criteria framework was built, and used to guide a two-step systematic literature review on current UC and on the supply of ES by urban NBS. This was followed by a non-systematic literature review, which complemented the previous one by unveiling knowledge gaps on the biophysical and social processes and attributes on which specific ES classes depend. The non-systematic review was also used to identify additional NBS. The UC review identified 18 UC and 58 sub-challenges, and illustrated which UC were more studied, according to the type of literature and environmental and socio-economic attributes of urban contexts. The ES review led to the development of an urban NBS classification, and supported the identification of UC-ES and ES-NBS nexuses, which were analysed and classified into four groups of causal relationship. For the nexuses identified as direct plausible causal relationship, the main processes and attributes on which the supply of specific ES depend were pointed out. Relationships between UC, ES, NBS, processes, and attributes were represented in the form of network diagrams. Our results can be used to support urban policies aimed at mainstreaming NBS and as a basis to further understand UC-ES-NBS relationships.

1. Introduction

The global trends of increasing urbanisation, urban population and their associated environmental impacts are expected to continue over the coming decades (Keivani, 2009). These trends are likely to intensify existing urban challenges (UC) for sustainability and resilience, as well as generate new ones. In terms of sustainability, UC include all factors that limit the capacity of urban areas to protect and conserve the environment, minimise environmental impacts and enhance resource-efficiency, human health, social inclusiveness and equality, as well as harness the productivity of local economies and value-added activities (United Nations, 2017). In terms of resilience, UC relate to those factors that limit the capacity of urban areas (including their inhabitants, institutions and inner systems) to resist and adapt to environmental, social or economic chronic stresses, and acute shocks (Meerow et al., 2016; Marron Institute of Urban Management, 2018). In many cases, UC for sustainability and UC for resilience (hereafter referred generically to as UC) overlap and also share limiting factors. The nature of these limiting factors, can be biophysical (e.g. a lack of woody vegetation can contribute to the presence of heat islands), technological (e.g. insufficient technological development for achieving universal access to certain goods or services), human-social (e.g. the current human, institutional or social structure act as barriers for adapting to new situations), and/or financial (e.g. limited amount of money

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restricts access to products of a certain quality). UC can therefore be determined by many types of limiting factor, which need to be understood before strategies and interventions can be developed to mitigate or address those UC.

Mitigation strategies and interventions should acknowledge that urban areas have the potential to buffer their own impacts and enhance the quality of life of their inhabitants, since they are capable of fostering not only local, but also global sustainability and resilience (Elmqvist et al., 2015; Luederitz et al., 2015). Framing such strategies and interventions with specific solutions, requires a good understanding of the local environmental, social and economic conditions of urban contexts. Its acquisition would provide information about the suitability of the proposed solutions and the adequacy of their transfer and replicability in other urban contexts. As potential solutions, those that use natural systems and rely on concepts such as natural capital (Guerry et al., 2015), ecosystem services and green infrastructure are becoming increasingly popular among built-environment professionals, policymakers and researchers (Cortinovis and Geneletti, 2018; Geneletti et al., 2020; Nesshover et al., 2017; Pauleit et al., 2017). Among these concepts that of nature-based solutions (NBS) has emerged recently.

NBS are defined by the European Commission (EC) as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions" (European Commission, 2016). Further supported by several scholars (Faivre et al., 2017; Raymond et al., 2017a,b; Dorst et al., 2019), an expert report for the EC emphasises that NBS are able to address multiple challenges simultaneously, as well as to provide additional co-benefits (European Commission, 2015). Similarly, the International Union for Conservation of Nature (IUCN) defines NBS as "actions to protect, sustainably manage, and restore (create) natural or modified ecosystems that address societal challenges (including urban ones) effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016).

EC, IUCN and many other scholars relate NBS to the concept of ecosystem service (ES) and natural capital (Cohen-Shacham et al., 2016; Eggermont et al., 2015; European Commission, 2015; Maes and Jacobs, 2017; Nesshover et al., 2017; Potschin et al., 2016). For example, Eggermont et al. (2015) classify three types of NBS: i) better use of ecosystems; ii) sustainable and multifunctional management of ecosystems; and iii) design and management of new ecosystems. These types are organised based on their contribution to an increased supply of ES (i.e. linking ES and NBS) and the level of engineering to be applied to ecosystems to achieve this supply. ES are considered the outputs (flows) derived from natural capital stocks (Dominati et al., 2010). They are accounted for to estimate the contribution of natural capital to human well-being from a social, economic and environmental point of view (Turner et al., 2016). As implied by IUCN and EC, and stated by other authors (Albert et al., 2019; Bush and Doyon, 2019), NBS contain natural capital stocks or are actions to maintain and enhance the flow of ES. Hence, as part of urban planning strategies and interventions addressing different UC, NBS can help to operationalise the concepts of natural capital and ES (Potschin et al., 2016).

In terms of conceptualisation, several authors propose framing NBS as an umbrella concept under which other ecological concepts such as ecological engineering, ecosystem-based approaches, green infrastructure or ecological restoration could be integrated (Cohen-Shacham et al., 2016; Dorst et al., 2019; Nesshover et al., 2017; Pauleit et al., 2017). Compared to these other ecological concepts, NBS emphasise the value of nature to address societal (urban) challenges (Kabisch et al., 2016), the connection to policy and the relevance of implementation aspects (Pauleit et al., 2017). However, NBS is still a very open concept (Potschin et al., 2016) and this vagueness hampers its mainstreaming into urban planning strategies and interventions (Dorst et al., 2019). Then, to facilitate its operationalisation, the concept itself and the added value of NBS (i.e. the fact that they provide multiple benefits) compared to other solutions needs to be easily understood by practitioners and decision-makers.

In practical terms, practitioners and decision makers need further studies relating specific urban NBS to particular benefits (e.g. Cortinovis and Geneletti, 2019; Frantzeskaki et al., 2019; Keeler et al., 2019). For this, first they need a clear NBS classification shared among different professionals. They also need to know when specific NBS are not suitable due to the specificity of the context (Albert et al., 2019), or when are not enough as a stand-alone solution, e.g. to address social related UC (Haase et al., 2017; Kotsila et al., 2020). More research also needs to show which attributes of urban NBS affect the supply of specific ES, to consider those during their planning and design. There are previous systematic reviews on factors influencing ES supply (e.g. Bordt and Saner, 2019; Smith et al., 2017). However, these are mainly focused on spatial levels such as entire ecosystem or landscape mosaics, rural contexts, and in general factors (e.g. population dynamics), which might not help to define individual urban NBS. In synthesis, there is a need i) to define and classify urban NBS in a form that is suitable for scientists, decision-makers and built-environment professionals; ii) to understand the causal relationships between different types of NBS, ES and UC; and iii) how the attributes of NBS and the contexts where these are placed influence the provision of ES.

This paper aims to identify the nexuses between UC, ES and NBS, discuss their plausible causal relationships, and how these relationships can be affected by urban context conditions. Accordingly, the term "nexus" is understood as a qualitative link identified between a UC and an ES, as well as between a specific NBS and an ES. These nexuses are disclosed through a two-step systematic review plus a complementary non-systematic review. The identification of the nexuses is followed by a critical analysis of the collected evidence in order to assess which nexuses can be considered plausible causal relationships. We refer to "plausible" (i.e. likely) causal relationships according to a precautionary principle, because through a literature review a causal relationship cannot be confirmed with full certainty. In order to fulfil the aim, the following objectives are established:

- identify and classify UC, ES, NBS and their relationships based on the current scientific, policy and urban planning literature;
- determine attributes of NBS (e.g. soil properties, height of vegetation)and their contexts influencing social and biophysical processes, which lead to the generation of specific ES relevant for mitigating or addressing UC;
- identify similarities and differences in the UC, ES and NBS emphasised across urban case studies due to their specific socio-economic and environmental conditions.

Ultimately, the identification of nexuses as well as the discernment of plausible causal relationships was guided by the conceptual framework presented in Section 2.

2. Characteristics of the conceptual framework

The proposed framework aims to relate UC, ES and NBS in a simple form as outlined in Fig. 1, which illustrates the overall structure and characteristics guiding the establishment of plausible causal relationships. A detailed description about the type of UC-ES-NBS causal relationships found is provided in Section 4.3.

First, specific nexuses are identified through their reiterated occurrence in the empirical results of the works included in the different literature reviews. Then, further analysis is required to understand if those nexuses are in fact plausible causal relationships. In particular, the analysis takes into consideration that urban areas are hybrid systems where natural and artificial components, as well as social and ecological processes are blurred and interconnected (Albertí et al.,

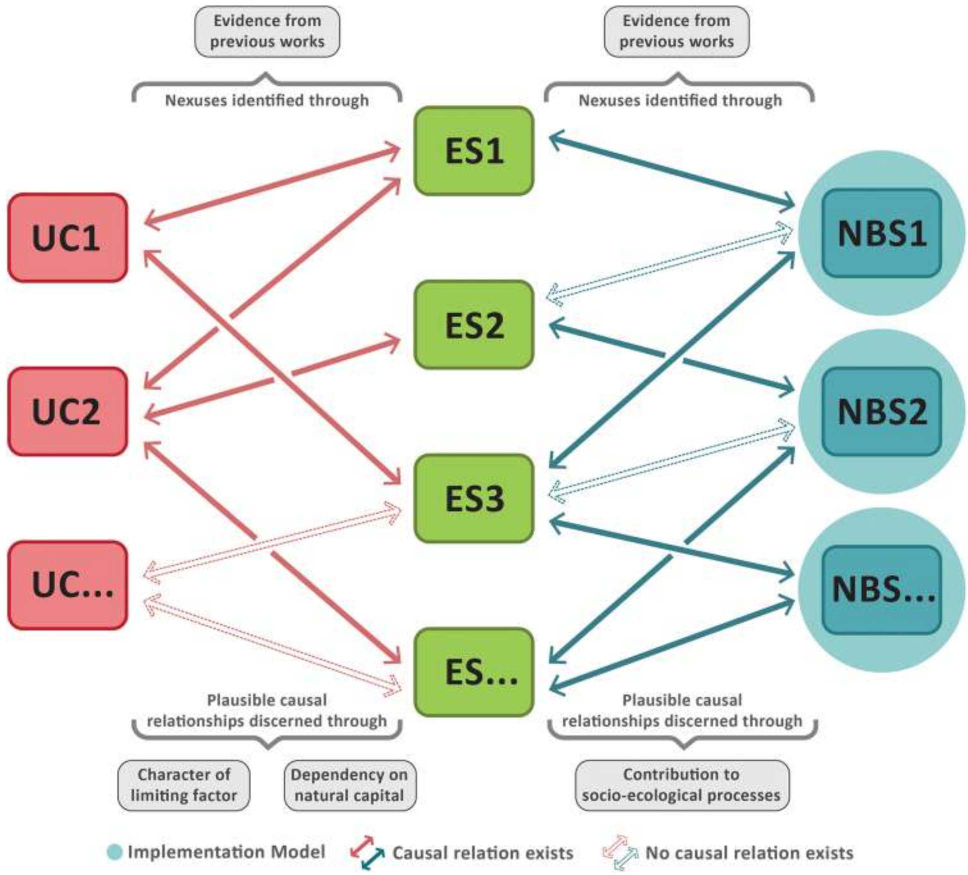

Fig. 1. Conceptual diagram for the identification of UC-ES-NBS nexuses and plausible causal relationships, making explicit the factors, attributes and processes that define the latter; UC = Urban Challenge(s); ES = Ecosystem Service(s); NBS = Nature-based solution(s).

2017).

Regarding the UC-ES nexuses, not all UC are rooted in biophysical limiting factors or could be mitigated with natural capital, and consequently their mitigation might not be achieved by increasing ES provision. In these cases, plausible causal relationships between UC-ES do not exist or they are not relevant enough to be acknowledged.

In terms of ES-NBS nexuses, each NBS provides only a specific set of ES. Then, a plausible causal relationship between NBS and ES does not exist when the NBS does not contribute to the socio-ecological processes that generate the specific ES. In the case of NBS that are biophysical structures (i.e. created ecosystems), the contribution occurs if the abiotic and biotic attributes of the NBS are involved in the socio-ecological processes. In the case of NBS as actions applied on ecosystems (e.g. management and restoration actions), the contribution occurs if these actions modify positively the attributes of the ecosystems involved in the socio-ecological processes. In addition, the extent to which a particular ES-NBS plausible causal relationship not only exists, but it is relevant enough to be acknowledged also depends on the role of the abovementioned attributes in the performance of the socio-ecological processes, i.e. the lesser or greater generation of that ES. Besides the NBS itself, its implementation model (i.e. the combination of governance, business, and financial models under which the NBS is planned, developed and managed) might also influence its capacity to provide ES, and mitigate UC.

3. Methods

The method is composed of three main steps, namely a two-step systematic literature review on UC and ES, a complementary non-systematic review and *a posteriori* integrated analysis of the data (Fig. 2). The systematic review adapts the review protocol of Luederitz et al. (2015) and Brink et al. (2016). Operationally, the review was conducted by:

i) identifying an initial list of articles based on a broad search string that encompasses UC and ES topics;
ii) preselecting the articles if their abstracts meet specific criteria (as reported in Fig. 2, Data screening & cleaning);
iii) selecting the articles and conducting a critical analysis if their complete text fulfils the screening criteria (see Fig. 2, Article appraisal & Analysis).

3.1. Systematic literature review

For the two-step systematic literature review, the search of peer-review papers was limited to the last 20 years, from 1998 to early 2019. The concept of NBS and similar concepts (e.g. green infrastructure), as well as the study of ES in regard to them, are very recent, making it unnecessary to account for a longer time period. In addition, UC evolve over time, hence limiting the temporal extent of the search ensures that only currently-relevant challenges are included in the analysis.

The papers were retrieved from Web of Science at the end of February 2019 using the search strings included in Fig. 3. The screening phase (see the criteria in Fig. 2) was performed to retain only papers describing an assessment of ecosystem services or ecosystem functions in urban contexts.

The literature review of UC for sustainability and resilience included peer-reviewed papers, reports from international public institutions (e.g. United Nations, FAO) and local urban planning documents, thus integrating science, policy and local urban planning perspectives. The collection of policy reports and urban planning documents was completed in February 2019. The policy reports were selected from a pre-

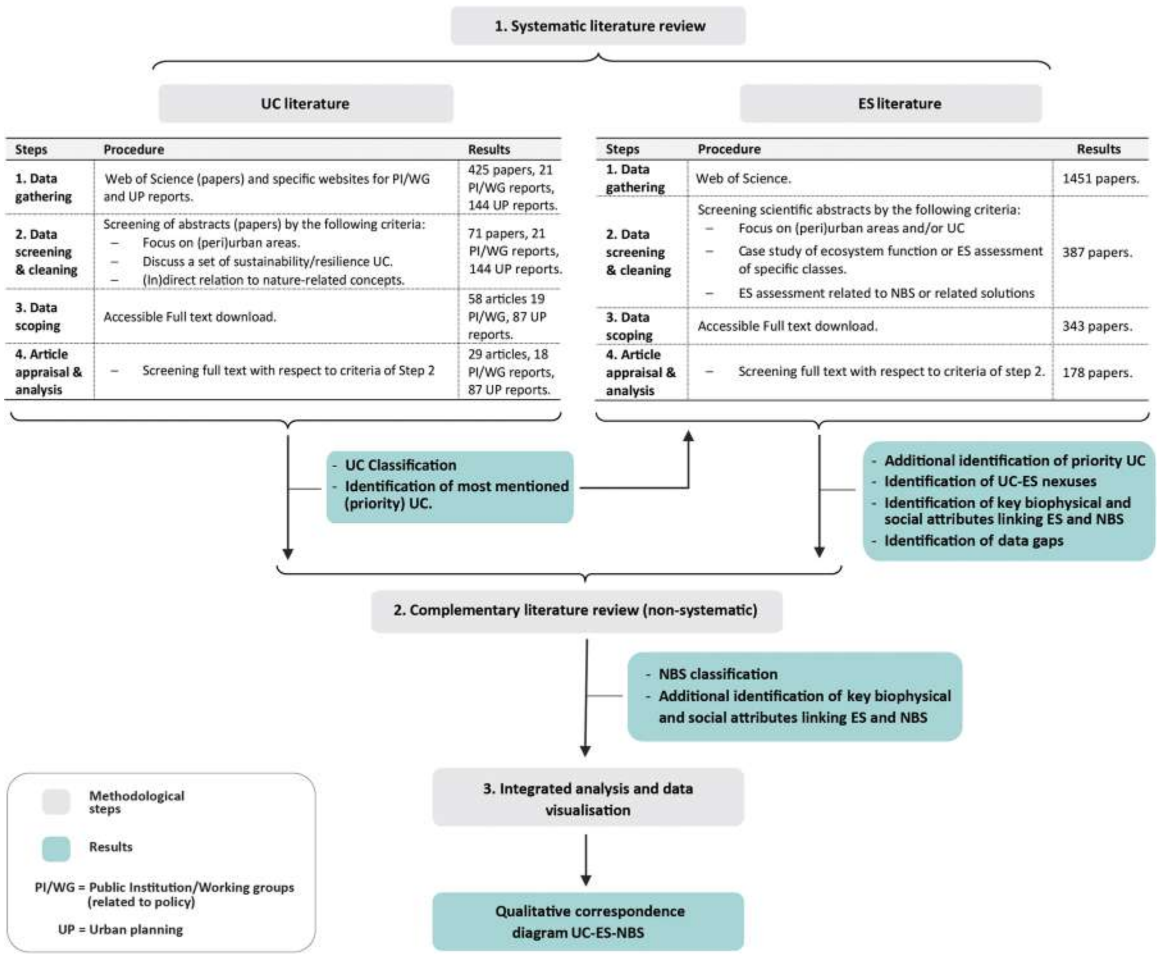

Fig. 2. Methodological steps of the literature review including the criteria that the selected documents fulfilled to be kept in the review.

established list of well-known international institutions and related initiatives (Supplementary Material A). The local urban planning documents were reports selected from various global inter-city scale initiatives, such as Emerging and Sustainable Cities (Inter-American Development Bank), 100 Resilient Cities Initiative (Rockefeller Centre) and the C40 Cities. These initiatives include a comprehensive list of cities around the world that prove to be active in sustainable and resilient urban planning (Supplementary Material A). In the case of public institutions and local urban planning reports, the stages of data gathering, screening and scoping were done simultaneously.

The lack of a recognised exhaustive classification of UC in the literature made it necessary to develop an original one based on existing frameworks. The UC, and their sub-challenges, obtained from the selected literature were organised by combining the classifications of UC proposed in the Emerging and Sustainable Cities Initiative, the Reference Framework for Sustainable Cities and the EKLIPSE report (RFSC, 2016; Raymond et al., 2017a,b; IADB, 2019). These classifications well complement each other well and are already used in Latin America and Europe. New sub-challenges mentioned in the papers reviewed and not considered in the original classifications were also incorporated into the UC classification (See Supplementary Material B for a description of the classification). In the reviewed literature, multiple terms were used for the same UC or sub-challenge. This made a harmonisation of the terms necessary as part of the development of the classification system. In addition, when a paper or document referred to a UC or a sub-challenge using a vague terminology, and there was no

UC literature review

TS=("urban challeng*" OR "urban priorit*" OR "urban sustainability issu*" OR "urban resilence issu" OR "urban strateg*") Refined by: DOCUMENT TYPES: (ARTICLE OR REVIEW) AND LANGUAGES: (ENGLISH) Timespan=1998-2018

Indexes=SCI EXPANDED, SSCI, A&HCI; ESCI

ES literature review

TS=(("urban*") AND ("assess*") AND ("ecosystem servic*" OR "landscape servic*" OR ("ecosystem functio*" OR "landscape functio*" OR "ecosystem structur*" OR "landscape structur*" OR "nature-based solution*")) Refined by: DOCUMENT TYPES: (ARTICLE OR REVIEW) AND LANGUAGES: (ENGLISH) Timespan=1998-2018

Indexes=SCI EXPANDED, SSCI, A&HCI; ESCI

Fig. 3. Search string for the UC and ES literature review.

definition and/or clear description to help its classification, this non-distinguishable UC or sub-challenge was disregarded from the review.

The papers of the UC review were analysed making use of nine categories that included the type of UC, type of source (science, policy, local urban planning) and contextual attributes that characterise specific socio-economic and environmental conditions. The contextual attributes included location, continent, climatic conditions, average elevation, population (size of urban areas), population density and gross national income (GNI) classes of the referenced cities (see Supplementary Material C for details on each category). Specific classes were defined for each of the contextual attributes (further description in Section 3.3).

The papers of the ES review included only peer-reviewed papers. The ES classification of reference used in this review is CICES v5.1. It categorises ES in three main sections: “provisioning services”, “regulation and maintenance services” and “cultural services” (Haines-Young and Potschin, 2018). CICES is recognised internationally, it has a more detailed classification, especially for cultural ES that are relevant in cities, and it is used in the initiative Mapping and Assessment of Ecosystems and their Services (MAES) of the EC. The authors acknowledge the existence of other ES classification systems (e.g. FEGS-CS, TEEB), which all have their strengths and special attributes, but a choice formulated on the basis of a detailed comparison was considered out of the scope in the present paper. Further information on the differences and complementary features of ES classification systems can be found in La Notte et al. (2017) and McDonough et al. (2017).

The ES papers were analysed based on 16 categories, incorporating the nine used in the UC literature (see Supplementary Material C for detail on each category). The additional categories included ES sections, ES classes, key social and biophysical attributes, key social and ecological processes, types of NBS or similar solutions, and the spatial level of the assessment. The analysis helped to identify the most frequent UC mentioned in the ES literature, the most frequent ES classes and the NBS that were investigated more in urban areas. It also helped to justify relationships between i) specific UC and ES classes, ii) specific ES classes and social and biophysical processes; and iii) these processes and attributes of some types of NBS (those with a biophysical structure) or the urban contexts where they are placed.

3.2. Non-systematic literature review

A complementary non-systematic review was performed to help establish the classification of NBS types. It was also used to fill gaps in the identification of social and biophysical processes and attributes involved in the generation of ES already identified. This was necessary because many papers from the systematic literature review did not clearly identify the factors influencing the supply of specific ES classes, as also raised by Luederitz et al. (2015) in their review.

The non-systematic review was supported by land management and ecological restoration handbooks, papers on NBS types and their assessment (e.g. Xing et al., 2017a) and handbooks of ES process-based models (process-based models as defined by Santos-Martin et al., 2018). The handbooks on land management techniques (Morgan, 2013; Triest et al., 2016) and types of restoration ecology interventions (Hobbs et al., 2009; van Andel and Aronson, 2012v) complemented the identification of NBS that were less studied in the urban ES studies. The papers and ES process-based model handbooks were identified making use of a snow-balling approach (Badampudi et al., 2015), starting from the references of the systematic literature review. Only papers clearly stating the biophysical and social attributes influencing the supply of specific ES classes were included.

The classification of NBS types modifies the one proposed by IUCN (Cohen-Shacham et al., 2016). In fact, the classification of IUCN is also an adaptation of the three NBS types of Eggermont et al. (2015). The classification also makes use of three categories (i.e. ecosystem types, dominant media and spatial levels), as summarised in Fig. 4. In terms of conceptualisation, NBS is assumed as an umbrella concept for other ecological concepts, and the definitions of IUCN and EC are respected. Therefore, NBS included in the classification are actions applied to enhance living solutions or which are formed of them that protect, sustainably manage, restore or create (natural, modified or novel) ecosystems (Cohen-Sacham, 2016; European Commission, 2016).

In this paper, NBS Type 1 are considered solutions that permit not only a better use, but also a better management (i.e. non-physical modifications) of existing natural or naturalistic ecosystems. Making better use of an ecosystem implies a change in its management or in the management of surrounding ecosystems (indirect change). It could also imply changes in how the resources obtained from the ecosystem are exploited. In this sense, from the authors' perspective, it is not possible to distinguish between “a better use” and “a better management” as two different NBS types. With this modification NBS Type 2 include only solutions and procedures to restore ecosystems. These are further differentiated into reclamation and restoration categories. Following the adaptation of IUCN, NBS Type 3 are maintained as solutions that involve creating novel ecosystems. These also include solutions that involve the extensive (i.e. a large percentage of area) and intensive (i.e. high degree) modifications of existing ecosystems. This would be the case of converting a highly artificialized urban green area into a highly naturalised one.

Regarding the categories, the three types of NBS refer to actions applied to ecosystems in one way or another, thus necessitating the organisation of NBS according to ecosystem types. The ecosystem type classification of the MAES initiative (J Maes et al., 2013) was selected as the most appropriate one because of its detailed categorical resolution and correspondence with EUNIS and CORINE classifications. MAES ecosystem type classification is also the one used in Europe and promoted by the European Commission for ES assessment. Using the MAES classification can therefore facilitate in the future an exchange of information and harmonisation with other studies on ES and NBS. The identification of ecosystem types can also help to understand the dominant media (on the left in Fig. 4) per each ecosystem type, which may constrain the specific NBS that can be implemented. References to (semi)natural and artificial ecosystems were included in the conceptualisation of NBS types (in the centre of Fig. 4) as auxiliary elements. These ecosystems are the biophysical support on which NBS Types 1, 2 and 3 can be developed and define the initial ES supply that should be enhanced (see the y axis in Fig. 4) by the implementation of NBS.

Finally, to make the classification relevant for urban planners and decision-makers, urban NBS also need to be organised according to the spatial level at which they should be implemented (on the right in Fig. 4). The spatial level indicates the range of required space for each specific NBS, and consequently its adequacy for different types of urban strategies and interventions.

3.3. Integrated analysis and visualisation of the outputs

The outputs from the UC and ES literature review were analysed making use of the categories described in Section 3.1. The contextual attributes of the case studies were analysed in order to understand the similarities and differences in the UC, ES and NBS depending on the specific socio-economic and environmental conditions of their urban contexts. First, the location of the case studies was used to georeference them. Second, data associated with the remaining contextual attributes (e.g. population, climate) were collected making use of existing databases. Data on population and population density were extracted from Angel et al. (2011), which provide an informational database for 3646 urban agglomerations worldwide. For urban agglomerations not included in Angel et al. (2011), the data were collected from databases found one by one on specific municipal, metropolitan or regional websites. The updated Köppen-Geiger climate classification world map (Kottek et al., 2006) was used to assign regional climatic classes to each

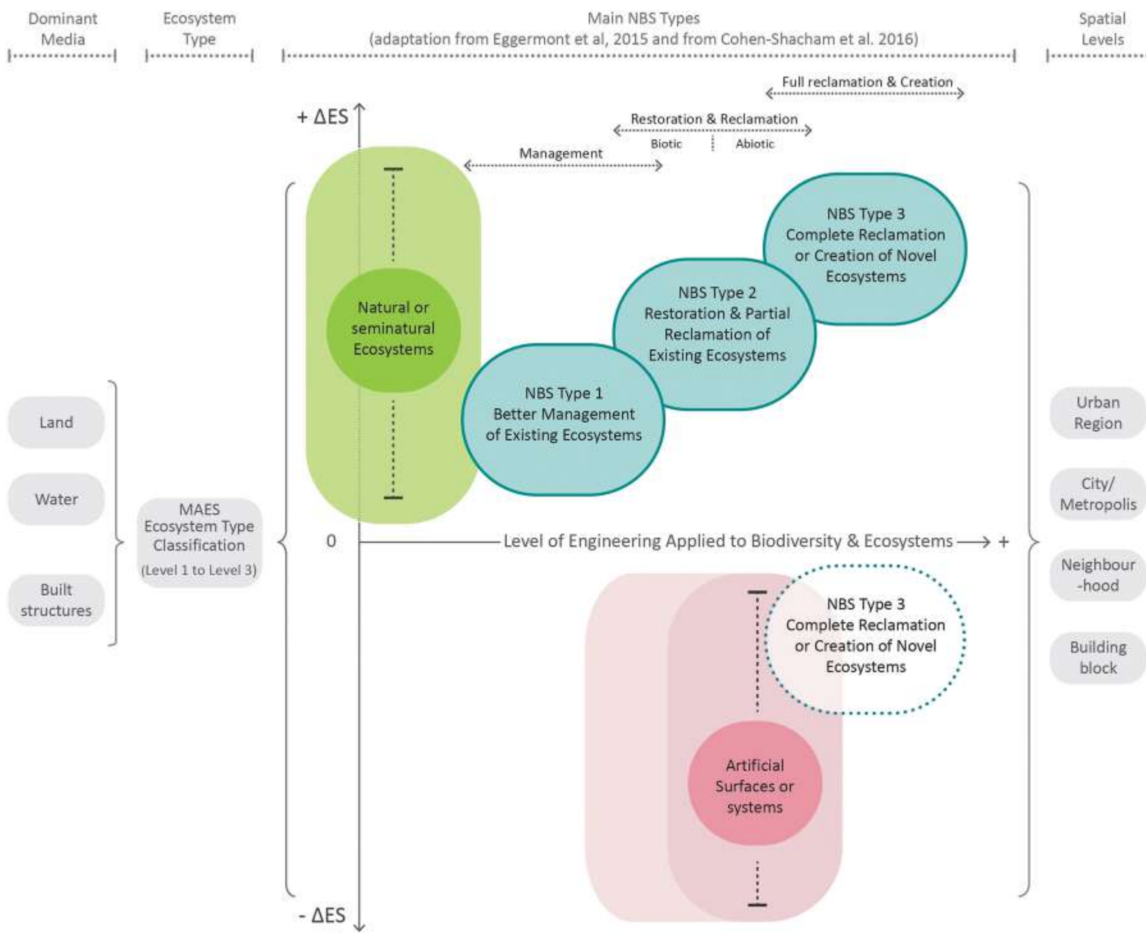

Fig. 4. Conceptualisation of NBS types. Elements and their positioning in an X-Y diagram built on the framework of Eggermont et al. (2015) and IUCN (2016).

case study. The one-kilometre resolution map of the GLOBE project (Hastings and Dunbar, 1993) was applied to differentiate urban areas with low-lying elevation. Third, per each contextual attribute, qualitative classes were established to make easier the differentiation between urban contexts with similar contextual conditions. In terms of urban size, the cities were classified according to their population making use of OECD (2019) classes. Regarding inhabitants' income capacity, the GNI classes proposed by the World Bank (2019) were used.

The visualisation of the data for each UC with respect to the type of document and urban contextual conditions was done using an ordinal ranking approach supported on conditional tables. The same procedure was used for the visualisation of the most widely studied ES and NBS, UC-ES nexuses and ES-NBS nexuses (only links appearing more than three times were kept in the visualisation), but with a graph-based approach (Bastian et al., 2009). For the discernment of UC-ES plausible causal relationships, the nature of the limiting factors of the UC were analysed as well as if they could be overcome with increased natural capital (as stated in Fig. 1). Similarly, for the discernment of ES-NBS plausible causal relationships, the conditions of the framework in Fig. 1 were followed based on the identified social and biophysical attributes and socio-ecological processes. The names of these attributes and processes were harmonised to avoid repetitions and overlaps and the related information populated in a table. In the case of attributes and processes, the nexuses were not ranked because the objective was only to identify them and not to illustrate the most acknowledged ones. Finally, a qualitative correspondence diagram was constructed to depict potential plausible causal relationships among the most frequently mentioned UC, ES and NBS. The diagram also includes the association of UC with specific urban contextual classes and the attributes and processes linking ES and NBS.

4. Results & discussion

The two-step systematic review examined 312 documents, 178 from the ES review and 134 from the UC review (further details in Fig. 2). These documents included 374 case studies (i.e. several papers have more than one case study). As Fig. 5 shows, the highest number of cases are located in Europe (166), America (109) and Asia (58), while only few documents investigated case studies in Africa (14) and Oceania (8). Among the selected documents, some also focused on the global context (18). In terms of the ES review, most of the case studies are from North America, Europe and Asia, which is consistent with the results of precedent reviews (Dobbs et al., 2019; D. Haase et al., 2014; Keeler et al., 2019; Luederitz et al., 2015). No difference emerged in the UC, ES, and NBS addressed in the studies based on average elevation and population density. In addition, due to the relatively low number of African and Oceanian case studies, these were not taken into consideration when looking for similarities and differences between continents. Likewise, only four climatic classes (Tropical Savannah with dry winter (Aw); Temperate without dry season and with hot summer (Cfa); Temperate without dry season and with warm summer (Cfb) and Mediterranean hot summer (Csa)) and three GNI classes (high income, upper-medium income and lower medium income) were considered, since the number of studies for other classes was negligible.

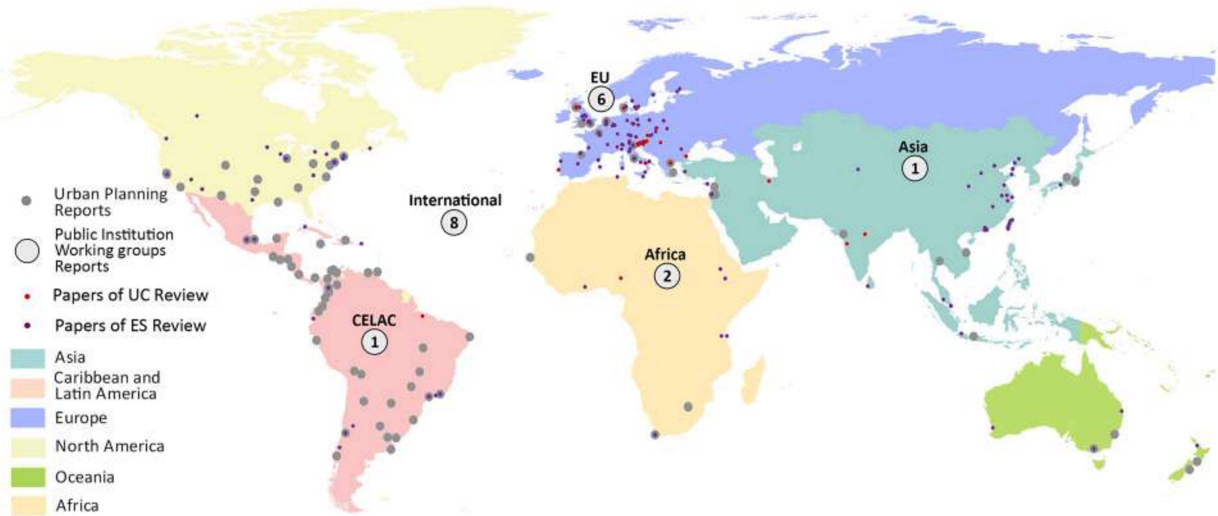

Fig. 5. Location of the case studies in the reviewed documents.

4.1. Classification of urban challenges by type of document and contextual attributes

Based on the UC review, we identified 18 UC for urban sustainability and resilience and 58 associated sub-challenges. Table 1 shows the occurrence of UC and sub-challenges in the reviewed literature per type of document. At least 50 % of all reviewed literature on UC focuses on *built-environment issues*, *physical health*, *green and circular economy,* and *material & solid waste management*. Public institution reports and urban planning documents mention *water management* and *mobility* in at least 50 % of the documents. Around half of public institution reports consider *energy* and *governance*. Similarly, only urban planning documents consider *social vulnerability* and *climate change* in at least 50 % of the cases. In fact, urban planning documents is the only type of literature where a sub-challenge (*vulnerability to human/natural disasters*) is present in at least half of the documents.

The review of the most frequently mentioned UC and sub-challenges (i.e. those present in at least 15 % of the UC literature) across urban contextual classes (e.g. medium size urban areas) helps us to understand similarities and differences among specific urban contexts (Table 2). Regarding similarities, the *green and circular economy* is the only UC mentioned in at least 50 % of the case studies in every contextual class. Other UC, such as *social vulnerability*, *built environment*, *mobility*, *water management*, *material & solid waste management* and *physical health*, show a frequency close to 50 % in most of the contextual classes. When looking for differences, some UC and sub-challenges appear to be of higher interest in urban areas sharing certain conditions. For example regarding continents, *solid waste management*, *governance* and the sub-challenge of *vulnerability to human/natural disasters*, are only present in around 50 % of the cases of urban areas belonging to the Community of Latin America and Caribbean States (CELAC), whilst *energy* and the sub-challenge of *employment (job) development* are mainly taken into consideration in European contexts. Also, more than 50 % of all cases in the review (bold numbers in Table 2) identifying *wastewater management, expenditure and debt management,* and the sub-challenge *urban violence and insecurity* come from CELAC urban areas. In terms of urban size, *socio-spatial equity*, *climate change* and the sub-challenge *flooding risk*, are mostly studied in large metropolitan areas. Moreover, more than 50 % of all cases in the review for the sub-challenges of *ageing and inadequate infrastructure* and *urban heat island effect, sea level rise,* and *vulnerability to disease outbreak* correspond to large metropolitan areas. Climate classes constitute a particular case, where the sub-challenge *energy efficiency* appears to be of interest only in urban contexts in the climatic class Cfb.

The different prioritisation of UC according to particular contextual conditions (e.g. urban size, continent) suggests that the presence of some UC might be more likely where specific social and biophysical contextual factors occur. We are not able to identify if causal relationships exist or not, and in this case only nexuses are identified. In the future, in-depth studies of UC in regard to contextual classes can help us understand whether these links are causal relationships or not. For example, the UC *socio-spatial equity* appears to be closely associated with large metropolitan areas, and therefore it might be worth investigating whether there is a causality associated with urban size. Future studies could also inform us whether lessons learnt from other urban contexts regarding the mitigation of UC through the ES supplied by NBS are transferable or not.

Part of our results on UC across urban contextual classes (Table 2) have also been stressed in the review of Dobbs et al. (2019). Their review emphasises *governance* and *vulnerability to human/natural disasters* as UC intrinsic to CELAC countries. As implied by these authors, these UC are triggered by a combination of social, political and biophysical factors specific to CELAC countries. Consequently, in their opinion, global urban ES lessons extracted predominantly from studies in northern developed countries and applied directly to advise on urban strategies and policies in CELAC countries could generate socially, environmentally and economically mismatched decisions (Dobbs et al., 2019). Instead, win-win situations could arise if policy-makers and urban planners of municipalities with similar contextual conditions and UC collaborate and exchange knowledge about their research and experiences on urban ES or policies, strategies and interventions on NBS. Consistently, scholars argued that NBS should not be copied from one place and applied exactly as they are to others (Dorst et al., 2019; A. Haase, 2017). NBS should be sensitive both to the socio-spatial context in which they are applied, as well as to the specific UC that they aim to tackle, in order to be considered "solutions"(Dorst et al., 2019; A. Haase, 2017).

4.2. Identification of ecosystem services and nexuses with urban challenges

In the ES literature, the most frequently mentioned UC and sub-challenges (right-hand column of Table 1) are *physical health* (39 % of the papers), *mental health* (29 %), *climate change* (29 %), *water management* (22 %) and the sub-challenge *urban heat island and heatwaves* (15 %). In contrast, several UC are not explicitly mentioned in the ES articles (e.g. *mobility, digital connectivity, governance*), which could be interpreted as a lack of direct causal relationship between ES and UC, and therefore NBS. In addition, for some UC (e.g. *social cohesion, green*

Table 1
Urban Challenges and sub-challenges considered in the literature review. (For interpretation of the references to colour in this Table legend, the reader is referred to the web version of this article).

Urban Challenges and sub-challenges	**UP**	**SA-UC**	**PI/WG**	**SA-ES**
Total Number of Documents	87	29	18	178
Socio-spatial Equity	42	10	7	8
Socio-spatial Segregation	7	3	0	0
Lack of Gender Equity	2	0	1	0
Lack of Age Equity	1	0	1	0
Lack of Racial Equity	6	0	0	0
Lack of Income Class Equity	11	0	0	2
Social Cohesion	29	6	7	3
Lack of Inclusion of Immigrants and Refugees	3	1	3	0
Lack of Community-Building	8	3	0	0
Lack of Public Spaces for Social Interaction	6	1	0	0
Social Vulnerability	65	5	5	11
Vulnerability to Human/Natural Disasters	49	1	3	10
Vulnerability to Disease Outbreak	19	0	0	0
Vulnerability to Terrorism	7	0	0	0
Urban Violence & Insecurity	28	1	2	1
Demographic Dynamics	15	7	3	1
Increasing Population	9	4	0	1
Decreasing Population	1	3	1	0
Population Displacement	3	0	0	0
Ageing Population	5	1	2	0
Built Environment	48	15	11	5
Preservation of the Cultural Heritage and Identity	8	2	2	0
Affordable Housing	17	3	5	0
Lack of Liveable and Adaptable Public Spaces	16	4	5	4
Urban Sprawl	6	6	3	0
Informal Settlements	2	4	1	0
Mobility	55	10	11	0
Inadequate Public Transport	11	0	0	0
Ageing & Inadequate Infrastructure	30	5	3	0
Inadequate Non-Motorised Transport Systems	6	1	0	0
Physical Health	46	19	9	66
Lack of Air Quality	22	8	5	8
Lack of Soil Quality	2	1	0	3
Lack/Deficient Sanitation Systems & Water Quality	26	9	2	11
Mental Health	33	9	5	50
Urban Stress & Lack of Psychological Relaxation	4	0	1	3
Lack of Education and Training	24	8	3	0
Lack of Cultural & Leisure Opportunities	1	1	1	1

>≈50% <10%

Papers per type of document

(*continued on next page*)

Table 1 (*continued*)

Urban Challenges and sub-challenges	UP	SA	PI/WG	SA-ES
Total Number of Documents	87	29	18	178
Green and Circular Economy	58	15	12	2
Economic Efficiency and Competitiveness	14	1	1	0
Lack of Economic Diversification	8	1	1	0
Employment (Job) Development	31	10	8	0
Innovation and Green Entrepreneurship	16	0	0	0
Climate Change	52	13	8	52
Greenhouse Gas Emissions	4	2	0	1
Urban Heat Island & Heatwaves	21	6	0	31
Sea Level Rise & Coastal Resilience	16	0	1	1
Water Management	59	11	9	45
Flooding Risk	27	3	0	32
Freshwater Shortage	33	7	2	11
Wastewater Management	26	4	3	11
Material & Solid Waste Management	43	16	9	6
Raw Material Shortage	8	2	0	0
Food Shortage	16	4	3	4
Solid Waste Management	31	10	5	2
Energy	31	9	9	10
Energy Efficiency	9	5	2	3
Increased Energy Demand	7	2	1	2
Lack of Diversification of Energy sources (Renewable Energy)	12	0	1	0
Biodiversity	16	9	4	18
Loss and Degradation of Habitats	10	3	2	7
Lack of Ecological Integrity and Connectivity	4	0	0	1
Digital Connectivity	21	3	5	0
Unreliable Digital Infrastructure	3	0	0	0
Insufficient Public Access to Open Data	2	0	0	0
Public Participation	31	4	3	0
Empowerment of Communities in Decision-making	14	0	0	0
Promotion of Stakeholder Involvement	16	1	1	0
Governance	39	5	10	0
Transparency	11	1	1	0
Relationship Private Stakeholders - Government	7	1	0	0
Collaborative Multi-level Governance	6	2	1	0
Empowerment of Local Representatives	3	0	1	0
Expenditure	23	0	4	0
Expenditure & Debt Management	17	0	1	0
Use of Taxes & Financial Autonomy	12	0	1	0

Notes: UP = Urban Planning Reports; SA-UC = Scientific Articles from UC review; PI/WG = Public Institution and Working Groups Reports; SA-ES = Scientific Articles from ES review.

and circular economy) either no sub-challenges are specified in the papers or it was difficult to distinguish them (e.g. *energy* sub-challenges) due to the use of vague terminology.

In terms of ES, regulation services are the most frequently assessed (131 papers), followed by cultural services (73 papers) and provisioning services (41 papers). This is consistent with previous literature reviews (Ziter 2016, Luederitz et al., 2015; Haase et al., 2014). The analysis of ES studies by urban contextual classes does not present major differences and therefore this aspect is not discussed. In addition, several ES classes of CICES v5.1 are not identified (e.g. *visual screening* and *smell reduction*) or appear very rarely (e.g. *noise attenuation*, *weathering processes*). A few of these ES classes, such as *smell reduction*, are not identified as independent classes either in CICES before version 5.1 or in other classifications (e.g. TEEB), which could explain the lack of related case studies. Furthermore, the assessment of some ES classes (e.g. *bioremediation*) is quite specific (i.e. pollutant by pollutant) and technically complex (e.g. analyses that require several years of experimentation in the field and lab testing). The lack of identification of these ES classes might also indicate that they have minor or no relevance to address UC or that urban NBS do not have the capacity to supply them. For the remaining ES, the review suggests multiple links occurring with UC for each ES, as visualised in Fig. 6. The above results might help policy-makers to frame their urban agendas, prioritising the supply of those ES classes for which at least a nexus with a UC has been identified reiteratively by academic papers.

The visualisation of the UC-ES nexuses shows that *physical health* and *mental health* are not only the most frequently mentioned UC, as shown in Table 1, but also are the ones with the highest number of links to different ES, including classes from all ES sections. The UC *climate change* and the sub-challenges *urban heat island effect* and *heatwaves* are

Table 2
Urban (sub)challenges most frequently assessed per contextual class in the UC literature review. Bold numbers in a cell indicate that more than 50 % of the case studies including a specific (sub)challenge come from that specific class. (For interpretation of the references to colour in this Table legend, the reader is referred to the web version of this article).

Urban Challenges and sub-challenges	No.	Climate Classes*				Continents*				Size of Urban Areas					GNI Classes*		
		Aw	Cfa	Cfb	Csa	R.Am	Asia	CELAC	Eur	LMA	MA	MC	SC	VSC	HI	UMI	LMI
Cases per Contextual Class		16	21	39	9	20	18	45	47	49	30	20	17	10	77	42	11
Socio-spatial Equity	59	10	9	7	1	15	7	21	7	23	11	7	6	0	26	17	5
Social Cohesion	47	1	6	12	4	11	4	6	18	16	10	5	5	1	**29**	6	2
Lack of Inclusion of Immigrants and Refugees	7	0	2	1	0	3	0	0	**4**	3	1	0	0	0	**4**	0	0
Social Vulnerability	75	10	15	12	4	14	10	33	6	33	16	10	8	2	33	27	7
Vulnerability to Natural Disasters	53	9	11	7	4	7	7	**28**	3	24	14	6	6	0	20	22	6
Vulnerability to Disease Outbreak	19	1	7	5	2	2	4	5	4	**13**	3	2	1	0	**11**	6	1
Reduction of Urban violence & insecurity	31	7	4	2	2	6	2	**20**	1	14	5	5	4	1	9	15	4
Demographic Dynamics	26	1	5	7	2	2	5	1	8	12	1	4	2	0	**14**	3	2
Built Environment	85	11	11	16	6	12	13	25	25	31	16	12	7	2	36	27	9
Affordable Housing	25	1	5	4	1	9	4	2	6	11	2	3	2	0	**17**	3	1
Lack of Liveability & Adaptability of Public Spaces	35	1	6	13	2	6	2	5	**20**	14	6	7	3	0	**24**	6	1
Urban Sprawl	15	0	1	2	1	0	4	4	4	7	1	0	1	1	2	7	2
Mobility	83	10	11	18	5	14	12	29	18	24	18	8	8	10	36	28	6
Ageing & Inadequate Infrastructure	38	3	6	4	5	11	11	4	6	**20**	6	2	3	1	19	8	5
Physical Health	81	9	14	16	4	10	15	24	22	28	15	7	5	9	39	20	10
Lack of Air Quality	42	4	6	13	3	6	5	12	17	16	5	2	3	9	**23**	10	3
Lack/Deficient Sanitation Systems & Water Quality	44	5	6	12	2	5	9	14	13	16	7	4	4	9	**24**	11	6
Mental Health	62	6	9	23	2	9	6	18	25	13	15	11	7	8	38	14	5
Improved Education & Training	47	5	7	18	1	8	4	14	21	9	12	9	4	8	**30**	12	3
Green and Circular Economy	97	12	11	26	6	11	12	27	33	28	17	14	9	10	50	23	6
Enhancement of Economic Efficiency & Competitiveness	16	7	0	2	1	0	1	**13**	1	1	6	3	2	2	2	**10**	2
Employment (Job) Development	61	8	6	21	3	8	4	14	28	15	11	10	5	9	37	10	4
Innovation and Green Entrepreneurship	16	0	**9**	4	0	3	5	4	2	**10**	4	2	0	0	**12**	3	1
Climate Change	81	7	12	22	3	15	8	18	27	34	11	7	8	9	49	15	6
Urban Heat Island & Heatwaves	28	0	9	5	4	6	5	4	9	**19**	3	1	3	0	**19**	6	2
Sea Level Rise & Coastal Resilience	17	1	7	2	1	5	3	2	3	**11**	2	2	1	0	**11**	2	2

Urban Challenges and sub-challenges	No.	Climate classes*				Continents*				Size of Urban Areas					GNI Classes*		
		Aw	Cfa	Cfb	Csa	R.Am	Asia	CELAC	Eur	LMA	MA	MC	SC	VSC	HI	UMI	LMI
Cases per Contextual Class		16	21	39	9	20	18	45	47	49	30	20	17	10	77	42	11
Water Management	85	10	17	13	3	12	15	29	18	35	17	13	8	1	41	27	9
Flooding Risk	36	2	11	9	3	9	6	7	14	25	5	6	3	1	**28**	10	2
Freshwater Shortage	42	5	6	5	2	5	9	15	5	20	11	3	4	0	17	13	8
Wastewater Management	33	7	4	3	2	4	4	**19**	3	12	9	5	5	0	11	14	5
Material Solid Waste	81	7	11	21	5	9	9	23	24	26	13	10	9	9	42	20	6
Food Shortage	28	0	5	8	3	6	2	1	10	12	4	4	3	0	**19**	2	1
Solid Waste Management	53	7	7	13	3	5	8	22	13	16	9	6	7	9	24	17	5
Energy	56	1	7	18	4	8	8	7	22	20	7	3	5	10	**34**	8	1
Enhance Energy Efficiency	23	0	2	**12**	1	4	3	1	**12**	6	3	1	2	8	**16**	2	1
Biodiversity	42	2	4	18	5	5	7	5	**21**	11	5	5	5	10	**29**	5	3
Digital Connectivity	36	5	4	12	3	5	5	8	15	7	5	5	5	9	**20**	6	4
Public Participation	45	5	7	15	4	6	7	13	16	14	10	5	4	9	**27**	11	3
Empower Communities in Decision-making	14	4	3	2	2	2	4	6	1	4	5	1	3	1	5	**7**	1
Promote Stakeholder Involvement	18	0	3	3	4	4	4	4	4	**9**	4	2	1	1	**11**	4	1
Governance	59	10	5	8	3	8	4	25	13	13	14	9	11	0	23	17	6
Expenditure	27	7	5	2	0	3	1	**20**	1	3	11	4	4	1	7	**14**	2
Expenditure & Debt Management	18	4	4	1	0	2	0	**15**	0	3	**9**	1	3	1	5	**9**	2
Digital Connectivity	36	5	4	12	3	5	5	8	15	7	5	5	5	9	**20**	6	4

>≈50% <10%

Case studies per contextual class

Notes: Aw = Tropical Savannah with dry winter; Cfa = Temperate climate without dry season and with hot summer; Cfb = Temperate climate without dry season and with warm summer; Csa = Mediterranean hot summer; CELAC = Community of Latin American and Caribbean States; R.Am = Rest of America; Eur. = Europe; LMA = large Metropolitan Areas (> 1.5 Million inhabitants); MA = Metropolitan Areas (500.000 – 1.5 Million inhabitants); MC = Medium Cities (200.000–500.000 inhabitants); SC = Small Cities (200.000 – 50.000 inhabitants); HI = Higher income class country; UMI = Upper-medium income class country.
*As stated in Section 4, not all the classes of each contextual attribute are included because in some cases the number of studies was considered too low to be relevant.

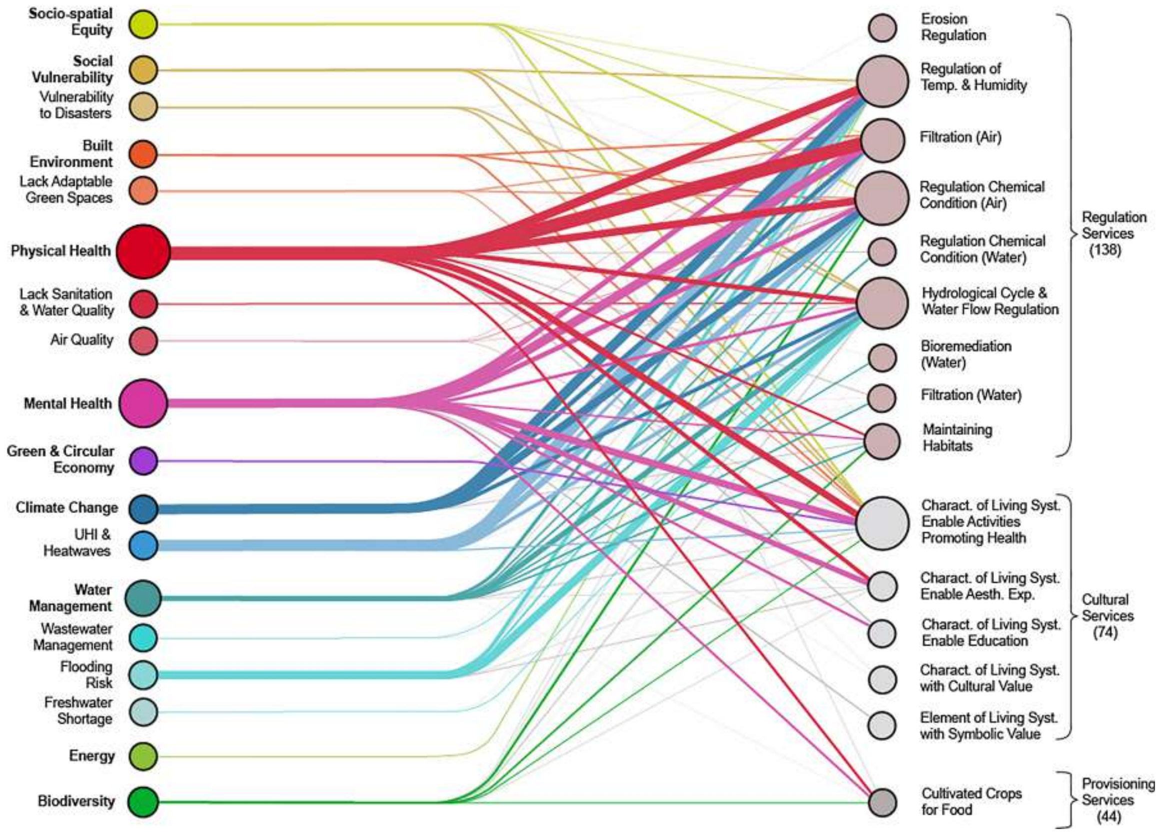

Fig. 6. Visualisation of UC-ES nexuses by edges (links weighted by number of cases) and nodes (circles weighted by the number of ES and cases per ES). Urban challenges are written in bold.

the only ones for which nexuses are mostly concentrated in few regulating ES. Overall, the most frequently mentioned UC show numerous links with the *regulation of chemical condition of the atmosphere*, *regulation of temperature and humidity*, *hydrological cycle and water flow regulation* and *filtration/sequestration/storage of pollutant* (air or water). Additionally, *physical* and *mental health, biodiversity, built environment, lack of adaptable and green spaces, social vulnerability, vulnerability to disasters and socio-spatial equity* appear several times in relation to the *characteristics of living systems that enable activities promoting health*.

Cause-effect relationships underpinning the identified UC-ES nexuses are in many cases evident and can be easily understood. For example, this is the case for the relationship between *characteristics of living systems that enable activities promoting health* (ES class belonging to the ES section of "cultural services") and the mitigation of *physical health* or *mental health* issues (see UC in Table 1). Similarly, the relationship between the above ES class and the UC *socio-spatial equity* can also be easily explained once it is known that several case studies describe a lack of adequate distribution of living systems (and therefore their associated *characteristics promoting health*) in urban areas. This is why the study of this ES class in regard to *socio-spatial equity* is recurrent in the ES papers reviewed. In fact, this outcome is consistent with several papers on environmental justice focused on urban inequity derived from the distribution of green areas (Anguelovski et al., 2018; B. Lin et al., 2015; Shen et al., 2017; Wu et al., 2018). In contrast, for other UC-ES nexuses, such as *characteristics of living systems that enable activities promoting health* (ES) and *biodiversity* (UC), the direct causality is not evident. However, it might be that an indirect causal relationship exists due to synergies and trade-offs between the supply of this ES and the supply of other ES related directly to the UC *biodiversity*. For example, Lin et al. (2018) show that an increase in the *maintenance of habitats and gene pool reserve* might also increase the presence of the *characteristics of living systems that enable activities promoting health* and mitigate *biodiversity* decline.

4.3. Limiting factors and UC-ES-NBS causal relationship groups

The results from the above sections, together with the characterisation of the nature of limiting factors (e.g. biophysical, technological) driving specific UC provide the basis to differentiate groups of UC-ES-NBS relationships (Fig. 7), identifying when direct plausible causal relationship between UC-ES-NBS exist.

In the first group of UC-ES-NBS (upper left, Fig. 7) neither direct nor indirect plausible causal relationships occur. This is the case of *digital connectivity* and *mobility*, which are both limited by human and technology limiting factors, rather than biophysical ones. The enhancement of ES would neither be able to compensate for the limitations and nor mitigate or address these UC. For example, an NBS could make a road infrastructure more pleasant, or protect it against flooding, but it cannot overcome mobility issues due to infrastructure limitations. Nevertheless, these UC would not jeopardise either the implementation of NBS or their perception by people.

In the second group (upper right Fig. 7), the limiting factors of UC are of human-social nature, such as decision-making issues (*governance, public participation and expenditure)* or changes in socio-economic trends (*demographic dynamics*), which cannot be compensated by ES. Some of these UC are relevant to several urban contexts (as shown in Table 2). In contrast to the first group, the planning and implementation of NBS in those urban contexts might need to tackle these UC or adapt to the consequences resulting from them to ensure the subsequent wide acceptance/use of the NBS implemented by society. For example, in the case of *demographic dynamics,* when related to an ageing population, NBS will not be able to mitigate this issue. However, if the ageing issue

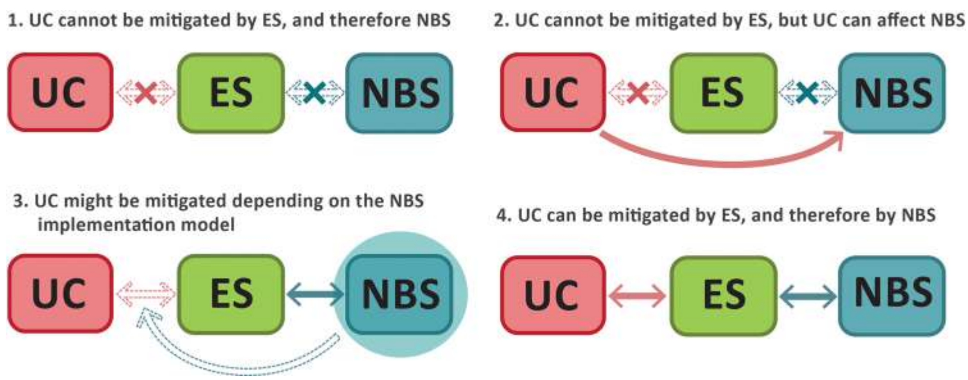

Fig. 7. Scheme of the four types of causal relations among UC, ES and NBS; UC = Urban Challenge(s); ES = Ecosystem Service(s); NBS = nature-based solution(s).

exists in an urban context, it might need to be considered when planning or designing NBS for mitigating other UC. This would be the case of a municipality with ageing issues that implements urban forests to increase (in the long term) nature-based recreation with the aim of enhancing the physical health conditions of its citizens. In that case, to ensure that the accessibility and usability of the urban forests is adequate for an elderly population might be more relevant than in other contexts. As another example, to mitigate UC related to decision-making issues, representatives of different political parties, levels of governance, private partnerships and citizens need to be included early on in the planning and implementation phases of NBS and consensual planning should be followed to avoid failure or non-implementation due to citizens' opposition or changes in the government representatives. In the same sense, Dorst et al. (2019) state that the multifunctionality of NBS can be hampered by *governance* issues such as fragmentation (or lack of consensus) in the decision-making process.

In the third group (lower left Fig. 7), the UC (*socio-spatial equity, social cohesion, social vulnerability, green and circular economy*) are partially driven by limiting biophysical factors and/or their enhancement might contribute to the mitigation of UC. However, the mitigation of UC depends on *how*, *where*, and *for whom* (i.e. the interests of which social groups are considered) NBS are implemented. For example, in terms of *how* to move towards *a green and circular economy*, business and financial mechanisms need to be considered in the implementation of NBS. This will ensure the economic exploitation of their products and services (Chen and Warren, 2011; TECNALIA et al., 2018; Toxopeus and Polzin, 2017). Concerning *where* and *for whom*, in order to address *socio-spatial equity* factors such as location of NBS with respect to existing recreational areas (i.e. *where*), public accessibility, inclusion of different social groups in the plan, design, and implementation stages (i.e. *for whom*) and potentially governance aspects (e.g. to prevent green gentrification) need to be considered (Almohamad et al., 2018; Haase et al., 2017; Park and Kim, 2019). In this sense, as already illustrated by other scholars through empirical cases (Haase et al., 2017; Kotsila et al., 2020), NBS per se do not solve social cohesion issues. In order to tackle social and economic UC, the specific NBS implementation model chosen, including governance, finance and business mechanisms, is also relevant.

The fourth group (lower right Fig. 7) occurs when the UC (or one of its sub-challenges) is driven by limiting biophysical factors or could be overcome by processes depending on biophysical attributes, which influence the ES supply. These are mainly the cases where the nexuses between UC and ES are evident or can be easily explained, as illustrated at the end of Section 4.2. For example, in cities suffering from the *urban heat island effect*, the solution requires the *regulation of temperature and humidity* through the enhancement of biophysical processes such as evapotranspiration and/or shading (see Zardo et al., 2017). Section 4.6 describes the identified social and biophysical attributes and processes, on which the supply of the most frequently mentioned ES (of this review) depend, are described. The network diagram described in Section 4.7 and in the Supplementary Material E and F focus on this group.

4.4. Classification and identification of NBS types

In the systematic and non-systematic literature reviews, solutions based on (or applied to) nature or living features were often framed under different ecological concepts: green infrastructure, urban green (and blue) spaces, services providing units, services providing elements, sustainable urban drainage systems and ecosystem-based adaptation. As already stated in Section 3.2, these ecological concepts and their specific solutions could be assimilated under the umbrella of NBS. For example, ecosystem-based adaptation refers to the protection, management and restoration of the spatial structures (Munang et al. 2013, Geneletti and Zardo 2016) corresponding to NBS Type 1 and 2. As another example, green infrastructure types, urban green (and blue) spaces, services providing units and sustainable urban drainage systems correspond to biophysical structures and in many cases are equivalent to specific MAES Ecosystem types (and NBS Type 3). Hence, following the NBS conceptualisation (Fig. 4), specific solutions framed under these ecological concepts were included in the three main types of urban NBS, leading to the detailed classification of NBS types shown in Figs. 8a and b.

In the systematic literature, only urban case studies referring to (semi)natural ecosystems and NBS Type 3 are found. This illustrates a clear prevalence of physical solutions in urban ES studies, although the underlying reason is not entirely clear. It could be because there is still a strong need to bring back natural structures into cities before solutions focused on managing and restoring them (NBS Type 1 and 2) become relevant. It could also mean that the extensive and intensive modification of existing urban ecosystems and the creation of new ones are perceived as more effective solutions for addressing UC. Alternatively, the lack of Type 1 and 2 urban NBS in our review may be due to the difficulty of assessing them independently from the physical structures on which they are applied. For example, for the assessment of the individual contribution of NBS Type 1 to ES supply it might be necessary to compare changes in the supply of ES by the same physical structure before and after an NBS Type 1 or 2 was applied. Furthermore, urban environmental management and urban ecological restoration might not usually be framed in the research area of ES and therefore these related studies were not captured in our review.

The most frequently studied NBS Type 3 per type of media are green roofs, green walls, woodland-like structures, urban grasslands and meadows, urban scrubland and heathland, horticultural gardens, vegetated filter strips, swales, constructed wetlands, natural(ised) wetlands, natural(ised) ponds and bioretention basins (Fig. 9). Similar to previous reviews, woodland-like structures appear as the most frequently studied supplier of ES (Haase et al., 2014; Keeler et al., 2019;

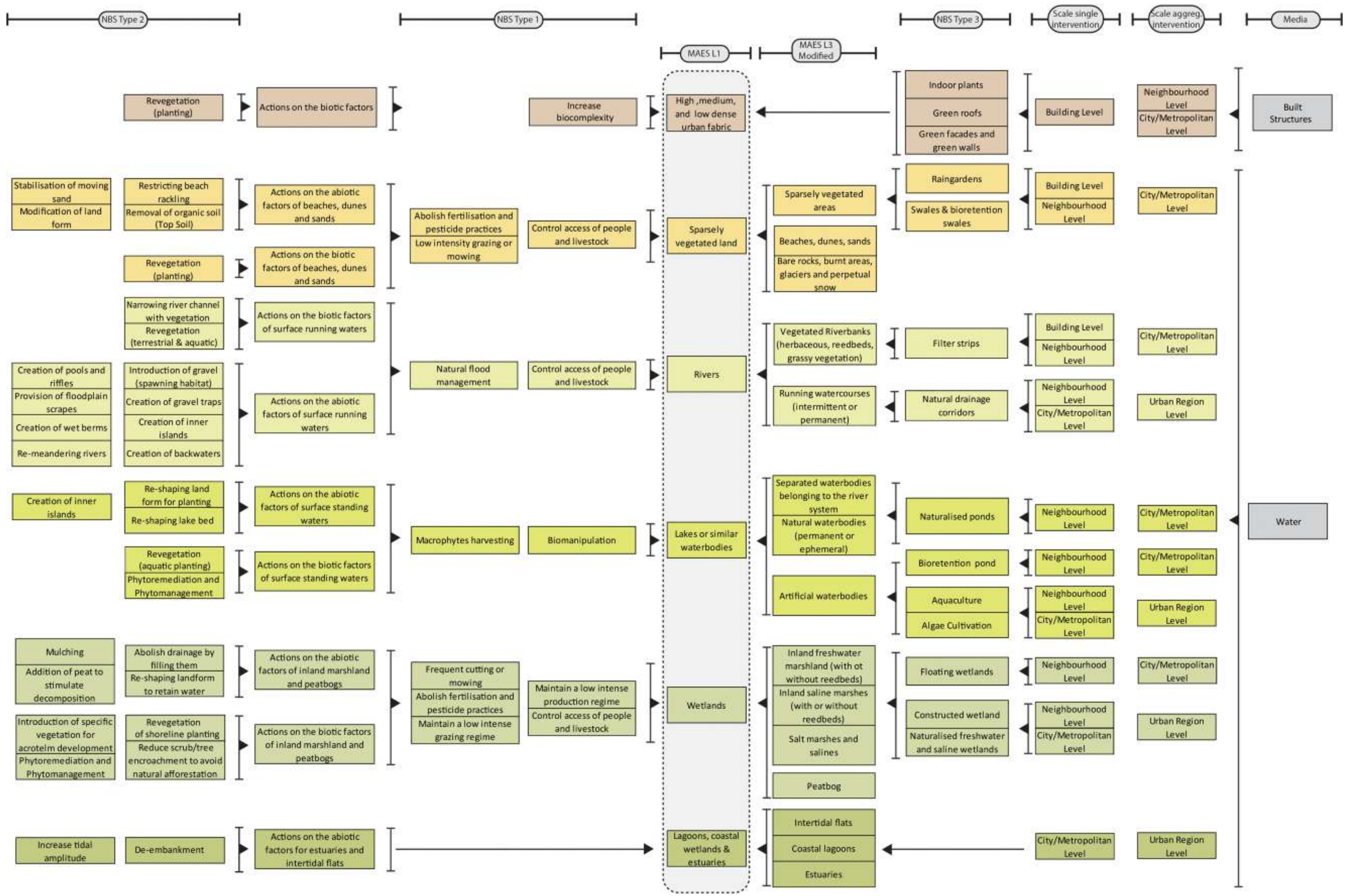

Fig. 8. a) Built structure and water NBS Types 1, 2 and 3 (as described in Fig. 4) corresponding to MAES Level 1 ecosystem types. NBS Type 2 are differentiated in actions that apply to the abiotic and the biotic factors of NBS. The spatial scales refer only to NBS Type 3. b) Land NBS Types 1, 2 and 3 (as described in Fig. 4) corresponding to MAES Level 1 ecosystem types. NBS Type 2 are differentiated in actions that apply to the abiotic and the biotic factors of NBS. The spatial scales refer only to NBS Type 3.

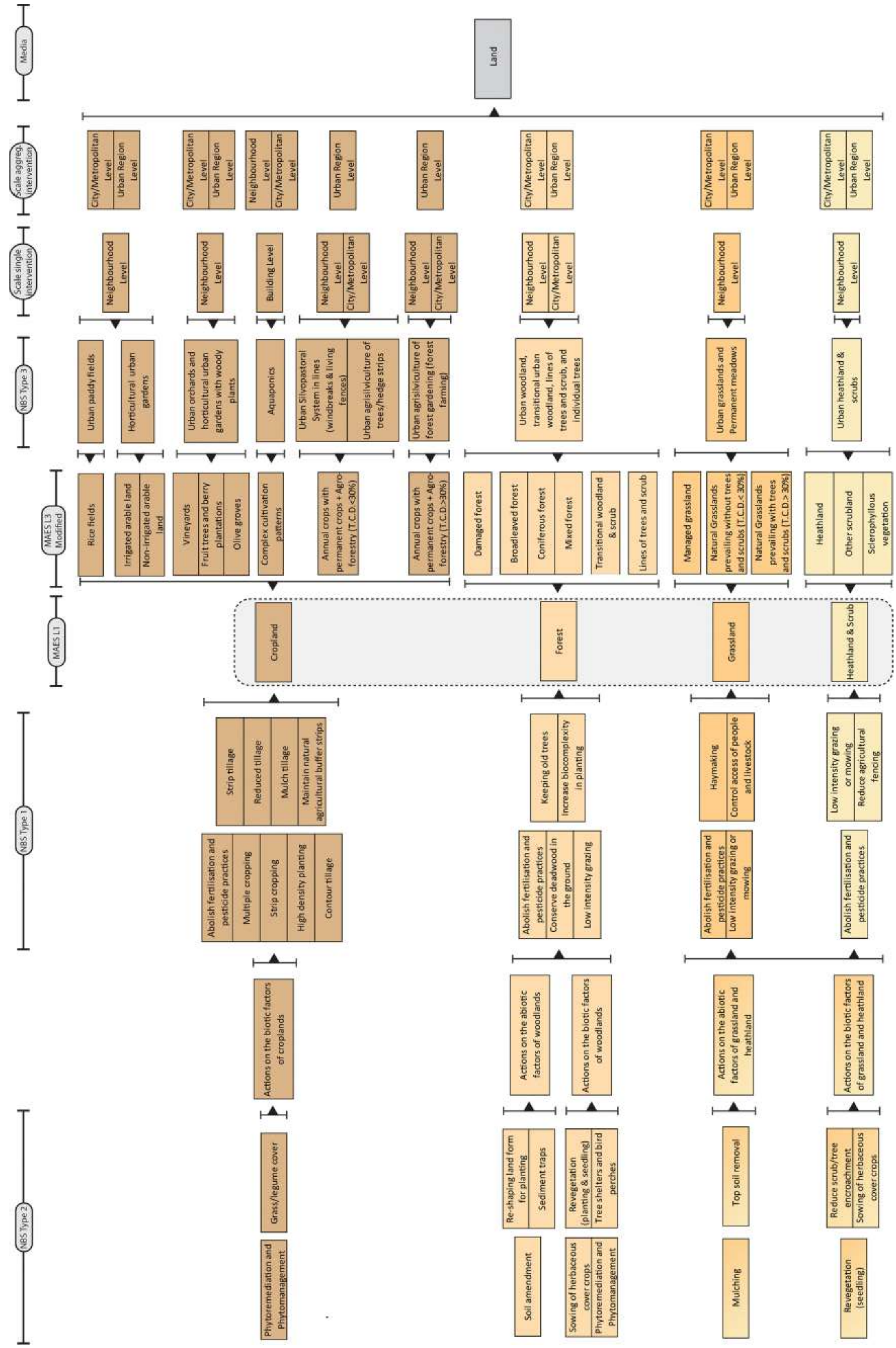

Fig. 8. (*continued*)

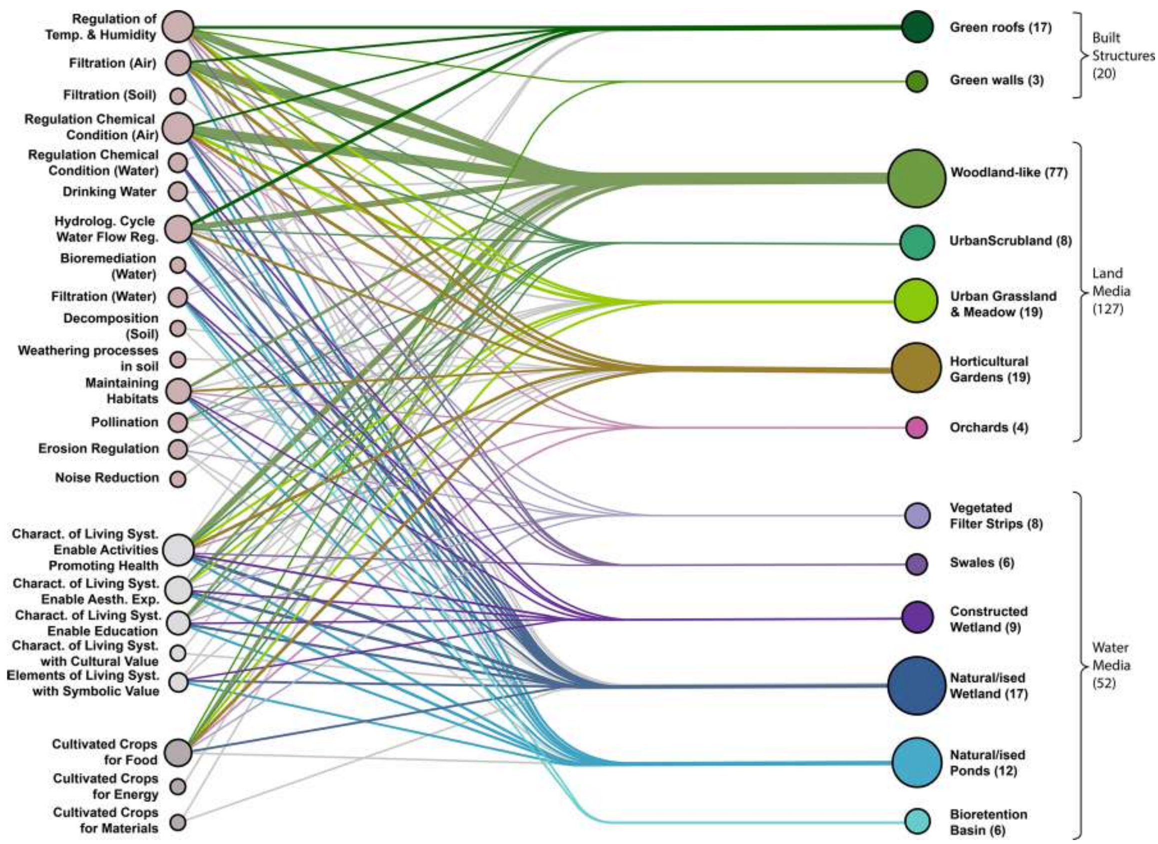

Fig. 9. NBS (Type 3)-ES links identified in the ES review. Edges (links weighted by number of case studies) and Nodes (circles weighted by number of ES (or NBS) and number of case studies per ES).

Luederitz et al., 2015). In contrast to previous reviews, studies of ES supplied by green roofs have increased. For many other solutions, it is difficult to draw parallels with previous reviews due to a lack of common NBS classification and because not all of the previous reviews analysed solutions relating to nature (e.g. urban fabric, land use mixture and infrastructure appear as ES suppliers in Haase et al. (2014)). This outcome also illustrates the importance of an agreed-upon NBS classification, so as to allow comparison among studies and facilitate transfer of information to support urban policies, strategies and interventions.

4.5. Identification of links between ecosystem services and nature-based solutions

Green roofs, woodland-like, urban grasslands and meadows, horticultural gardens, (natural(ised) wetlands and natural(ised) ponds have links to a higher number of ES classes than other NBS (Fig. 9).

Regarding the specific ES-NBS nexuses, all the highlighted NBS except vegetated filter strips, green roofs and green walls appear to be strongly associated with *characteristics of living systems that enable activities promoting health*. In addition, green roofs (built structures media) are mostly linked to regulation services (i.e. *regulation of temperature and humidity, filtration, sequestration, storage of air pollutants and regulation of the hydrological cycle and water*). Urban woodland-like environments, urban grasslands and horticultural gardens (land media) are also often associated with the *regulation of temperature and humidity*, *regulation of chemical condition of the atmosphere, filtration, sequestration and storage of air pollutants, regulation of hydrological cycle and water flow* and *cultivated terrestrial plants for nutritional purposes*. Natural(ised) wetland, constructed and natural(ised) ponds (water media) prove to be relevant not only for regulation services but also for cultural ones, being mostly linked to the *regulation of chemical conditions* (water), *regulation of hydrological cycle and water, filtration (water), sequestration and storage of water pollutants, characteristics of living systems enabling aesthetics experiences,* and *education and symbolic value*.

As with the visualisation of the UC-ES nexuses (Fig. 6), Fig. 9 shows that the ES classes *smell reduction, erosion regulation* and *bioremediation* are not mentioned in connection with NBS or seem to have low momentum in urban studies. Fig. 9 also presents ES classes rarely assessed in the case studies, which do not appear in Fig. 6 (i.e. *drinking water, pollination, filtration (soil), decomposition (soil), weathering processes, noise reduction, cultivated crops for manufacturing purposes and cultivated crops for energy*). The differences between both figures occur because 55 of the 170 papers in the ES literature review do not clarify the specific UC that could be addressed by the specific ES studied therein. Consequently, links with UC are not established for all the ES classes identified in the literature review. The review of Haase et al. (2014) also shows the scarce consideration of many of the abovementioned ES classes in urban studies, making it less likely that this outcome is the result of an unnoticed bias in the current review. It might be that the roles of those ES classes in urban areas are not clear enough. A reason that could also explain why in this review clear connections with specific UC are not found for many of those ES classes.

Similarly to the results outlined in Fig. 6 for the UC-ES nexuses, multiple links between specific ES classes and NBS do also occur. This is unsurprising given that NBS are described as solutions capable of addressing multiple challenges and providing multiple benefits (see Section 1). To investigate the causality underpinning these nexuses, the processes and factors responsible are discussed below. However, in some cases, especially for cultural services, these processes and factors were difficult to identify. For example, in *characteristic of living systems that enable education* or *with symbolic values* or *resonant in cultural values*, the attributes are very subjective and it was not possible to identify the ones that were reiterated several times in the case studies and that did

Table 3
Processes and factors per ES class identified in the systematic and non-systematic literature review. Blue cells identify processes already described in an upper ES or an ES that influences the ES class analysed (references per process included in a simplified table in Supplementary Material D). (For interpretation of the references to colour in this Table legend, the reader is referred to the web version of this article)

ES Section	ES Classes	Related Processes (conditions and other ES)	Related Attributes and Associated Processes
Regulation	Regulation of temperature and humidity	Shading	**Vegetation growth**, Tree canopy coverage, Dimension of trees, Leaf area index
		Alteration of wind movement	**Vegetation growth**, Shape of the open space, Shape of the buildings
		Evapotranspiration	**Vegetation growth**, Land cover type, Temperature, Precipitation, Tree canopy coverage, Leaf area index, Root depth and distribution, Soil (vegetation) cover, Soil permeability, Soil texture, Soil moisture, *Shape of vegetated area*
		Insulation (buildings)	Soil depth, Thermal capacity of soil substrate (and building materials)
		Vegetation growth	Temperature, Precipitation, Growing season, Land cover type, Vegetation composition and density, Plant health condition, Light conditions, Landscape (vegetation) management, Soil texture, Soil nutrients, Soil depth, Dimension of tree & Wood density (only for trees)
	Regulation of hydrological cycle and water flow	Interception	**Vegetation growth**, Precipitation, Tree canopy coverage, Leaf area index, Plant vegetation composition and density
		Detention	Precipitation, Land surface slope, Roughness of land surface
		Infiltration	**Vegetation growth, Detention, Soil storage**, Precipitation, Soil permeability, Soil moisture, Root distribution & depth
		Soil storage	**Infiltration**, **Evapotranspiration**, **Percolation**, Depth of depression storage, Soil texture, Soil depth
		Evapotranspiration	-
		Water run-off	**Infiltration**, **Soil Storage**, Precipitation, Land slope, Roughness of land surface
		Groundwater lateral flow	**Not identified**
		Percolation (deep infiltration)	**Infiltration, Storage**, *Soil permeability, Soil moisture*
		Vegetation growth	-
	Regulation of chemical composition of the atmosphere	Carbon uptake (by vegetation and soil)	**Vegetation growth, Soil respiration**, Dimension of trees, Species wood density, *Carbon fraction of dry biomass (species specific)*, Landscape (vegetation and soil) management.
		Organic matter decomposition	***Soil respiration, Vegetation growth****, Degradation rates of organic matter types, Land management, Temperature*
		Soil respiration	*Soil texture, Soil moisture, Landscape management, Organic matter inflow, Percentage of humus, Microbiological activity, Temperature*
		Vegetation growth	-
	Filtration, sequestration, storage, accumulation by microorganisms, algae, plants (air)	Dry deposition (on vegetation)	**Vegetation growth**, Tree canopy coverage, Vegetation composition & density, Canopy height, Leaf area index, Shape of leaves, Roughness of leaves (due to hair, Exudates), Phenology of Plant, Plant Diversity, Concentration of air pollutants, Deposition velocity, Distance from emission source
		Re-suspension	*Wind speed, PM amount in the leaf surface*
		Washing-off	*PM amount in the leaf surface*, ***dry deposition of PM****, Precipitation*
		Pollutants' plant uptake	**Vegetation growth**, Leaf area, Soil moisture, Growing season, Light condition, Health of trees, Stomatal resistance, *Aerodynamic resistance, Quasi-laminar boundary layer resistance, Canopy resistance (stomatal resistance, mesophyll resistance, cuticular resistance and soil resistance), Concentration of CO2*
		Biological emission of particulates (including pollen)	**Vegetation growth**, Total leaf biomass, Plant diversity, Plant composition, Type of pollination, Duration of pollen season, Height of plant
		Vegetation growth	-
	Filtration, sequestration, storage, accumulation by microorg., algae, plants (water) / Regulation of the chemical condition of freshwaters by living processes	*Dry deposition (on water)*	*Deposition velocity*
		Settling (sedimentation)	Roughness of land surface
		Adsorption by sediments	**Not identified**
		Re-suspension (from water)	**Not identified**
		Nitrification	*Temperature, Soil moisture*
		Denitrification	*Temperature*, Dissolved oxygen, *Water saturation, Dissolved and particulate organic carbon, Soil depth, Soil permeability, pH, Soil cover*
		Ammonification	*Temperature, pH, C/N ratio, Available nutrients, Soil texture, Soil permeability*
		Mineralisation	*Temperature, Soil moisture*

(*continued on next page*)

Table 3 (*continued*)

ES Section	ES Classes	Related Processes (Conditions and other ES)	Related Attributes
Regulation	Filtration, sequestration, storage, accumulation by microorganisms, algae, plants (water) / Regulation of the chemical condition of freshwaters by living processes	Plant & microbial uptake (and immobilisation)	**Vegetation growth**, Plant capacity to absorb inorganic nitrogen (N), Rate of conversion of N into biomass, Bioavailability of N, *Temperature, Soil moisture*
		Organic matter decomposition	-
		Leaching	**Plant & microbial uptake, Adsorption, Soil sorption, Infiltration**, Soil depth, Soil nutrients
		Volatilisation	**Not identified**
		Soil sorption	*Amount of organic matter, Degradability of the pollutant, Temperature, Precipitation*
		Vegetation growth	-
		Erosion regulation (ES)	-
		Water run-off	-
		Groundwater lateral flow	-
		Infiltration	-
		Percolation (deep infiltration)	-
	Bioremediation by microorganisms, algae, plants and animals	*Phytoextraction (plant & microbial uptake)*	***Vegetation growth, Soil storage**, Hyperaccumulation capacity of plant, Plant biomass, Planting density, Cropping period, Compartmentalisation of pollutants in biomass, Rooting depth, Plant's resistance trait to the specific pollutant, Landscape management, Soil aeration, Presence of macronutrients, Soil microbiological activity, Soil pH*
		Phytodegradation	**Not identified**
		Rhizofiltration	***Vegetation growth**, Microbiological activity, Rooting depth, Exhudation*
		Phytostabilisation	*Microbiological activity*
		Phytovolatilisation	***Vegetation growth, Plant uptake, Evapotranspiration***
		Evapotranspiration	-
		Leaching	***Phytodegradation, Rhizofiltration, Phytostabilisation, Phytovolatilisation***
		Adsorption by soil	-
		Soil sorption	-
		Infiltration	-
		Vegetation growth	-
	Maintaining nursery populations and habitats	Conservation of habitat	*Vegetation patches: abundance, richness, distribution& area (single patches)*
		Movement of species	*Dimension of vegetation patches, Number of vegetation patches, Distances between vegetation patches, Presence of barriers, Suitability of surrounding patches for movement*
Cultural	Characteristics of living systems enabling activities promoting health or enjoyment	Accessibility (visual, physical, legal)	Presence of barriers (e.g. fences, dense vegetation), Public access allowance, *Proximity*
		Provision of recreational infrastructure	Footpaths and cycling routes, *Plant diversity adjacent to paths, Lighting along paths*, Sport facilities, Benches, Pleasant views, *Existence of forests, Water features, Parking lots*
		Perception of safety	*Lack of traffic, Availability of footpaths*
		Social characteristics	People's age, Health, Level of education
		Aesthetics (ES)	-
	Characteristics of living systems enabling aesthetic experiences	Sensorial perception	Number of view axes, Presence & view of landmarks, Ratio between open spaces and forests, Existence of (mature) forests, Existence of fruit trees, Amount of natural vegetation, Amount of naturalised waterbodies, Diversity of natural features, Landscape management, Number of disturbing elements, *Shape diversity, Patch and edge attributes and Seasonal changes in vegetation & water* features
Provision	Plants cultivated for food purposes	Vegetation growth	-
		Pollination (ES)	*Abundance and distribution of pollinators, Availability of forage and nesting habitat, Landscape management*

Note: Words in italics are for processes, factors and references identified through the non-systematic review.

not rely on human agreements, such as the application of a legal protection status.

4.6. Interpretation of the links between ecosystem services and nature-based solutions

The main social and biophysical attributes and processes identified in the reviews, which influence the most frequently studied ES classes, are summarised in Table 3.

In most cases, biophysical processes are partially dependent on attributes of NBS. For example, the amount of tree canopy coverage, which influences shading, and therefore *regulation of temperature and humidity,* relates to a biotic component (trees) of woodland-like NBS type. In other cases, such as for the sub-challenge *lack of water quality,* it is important to know which pollutants are generating the issue. This helps understanding whether regulation services that could mitigate the issue (e.g. *filtration, sequestration, storage and accumulation by plants, microorganisms and algae*) can be provided by the NBS or not. In some cases it is difficult to state the suitability of an NBS for supplying an ES class without a detailed analysis of the UC and related limiting factors. In the case of water-related ES, the reviewed literature focused mainly on processes specific to nitrogen and phosphorus compounds (e.g. Adhikari et al., 2011; Adyel et al., 2016; Liquete et al., 2016; Nocco et al., 2016; Olguin et al., 2017; Sun et al., 2017) and very few papers on processes specific to other pollutants (e.g. Krzeminski et al., 2019). Several reviewed papers also emphasise that physical attributes of the human-made contexts and/or their social characteristics (e.g. people's perception) are relevant to the supply of ES by NBS, especially in the case of cultural services (e.g. Andersson-Sköld et al., 2018; Brill et al., 2017; Fry et al., 2009; Ode et al., 2008; Szücs et al., 2015).

The abovementioned findings confirm the importance of making explicit which attributes of specific NBS, and the urban context, influence the processes underpinning the supply of a particular ES. It is necessary to state whether certain ES-NBS nexuses are plausible causal relationships or not. These reflections are also stressed by Keeler et al. (2019), who state i) that decision-makers need more applied information describing the conditions (of NBS and contexts) in which specific approaches and NBS are effective for some UC; and ii) that many NBS studies overlook the influence of social, ecological and technological factors when assessing their performance. For example, the *regulation of hydrological cycle and water flow* depends on infiltration, with several papers in this review indicating that it is influenced by root distribution and depth, among other attributes (Kim et al., 2016; Zölch et al., 2017a,b). However, root depth varies depending on whether we implement a horticultural garden or a woodland (two of the NBS indicated as suppliers of this ES class). It also varies inside the same NBS depending on attributes such as the plant species. Therefore, the contribution of NBS attributes should be carefully considered by policy-makers and urban planners when designing, implementing or assessing NBS with the aim of enhancing the supply of specific ES and, as a consequence, addressing a particular UC.

As another outcome, some ES share several processes and attributes, which implies that interdependencies occur in the supply of ES (Table 3), as shown by other scholars (Bennett et al., 2009; Lorilla et al., 2018). For example, as stated in several papers of this review, evapotranspiration is one of the main processes for *regulation of temperature and humidity*, as well as for *regulation of hydrological cycle* (Lundy and Wade, 2011; Nocco et al., 2016; Pappalardo et al., 2017; Reynolds et al., 2017; Skelton et al., 2011; Zardo et al., 2017). Evapotranspiration, more specifically transpiration, is also identified as an influence of several processes of *bioremediation by plants* (e.g. phytovolatilisation), since it affects the rate at which pollutants are taken up and expelled from plants (Pulford and Watson, 2003; Singh and Santal, 2015b). Moreover, Table 3 also illustrates that the supply of some ES classes might be indirectly influenced by other ES, or might prevent their demand in the first place, such as in the case of *erosion regulation* (De Troyer et al., 2016). Erosion dynamics influence the pollutants transported from one point to another, and therefore the input of pollutants to be filtrated, sequestrated or stored. Consequently, it seems necessary to study the supply of ES by NBS in bundles, defined as a set of ES that usually appear together (Yang et al., 2015), instead of individually. The importance of studying ES in bundles is also stressed in the review of Smith et al. (2017). Such an approach may further allow accounting for ES synergies and trade-offs, and should be recommended when planning/designing, assessing and monitoring the performance of NBS. The consideration of ES in bundles should also be recommended by policies and guidelines supporting the mainstreaming of NBS or establishing rules for their adequate implementation.

4.7. UC-ES-NBS framework

Our results were used to create a network diagram outlining all the UC-ES-NBS relationships observed. An illustrative example of this diagram is shown in Fig. 10 for the relationships of the UC *Built Environment*. Further information for the remaining UC-ES-NBS relationships is included in Supplementary Materials E and F. Supplementary material F includes two files containing the UC-ES-NBS network in the form of a set of graphs. These graphs are constructed in Gephi (Bastian et al., 2009), a graph-based software allowing a more complete visualisation of the network.

Based on the evidence of this review, the UC-ES-NBS network diagram obtained as the final outcome makes explicit the nexuses that are plausible causal relationships between NBS, ES and ultimately UC. The diagram confirms that NBS provide multiple benefits and adequately address multiple challenges, even if not all. In addition, nexuses between specific classes of contextual attributes and UC that were highly reiterated (i.e. in more than 50 % of the case studies including a specific class of contextual attribute) are also included. However, in the latter case plausible causal relationships were not studied.

The network diagram, in the two formats (html and Gexf) provided in the Supplementary Material F, can also be used by professionals of different backgrounds as a visual user-friendly output. The file in html format (accessible at https://mimes.list.lu/articles/network) allows an easy visualisation of the whole network and the detailed first order relationships without requiring any software. A more detailed visualisation (and manipulation) can be performed using the Gexf file, which shows relations of all the orders for each UC following the instructions included in the Supplementary Material F. Therefore, readers can use one of the three alternatives included (Figures of Supplementary Material E, html, and Gexf file) to see how specific UC can be addressed by means of ES, the processes on which the latter depend, and which attributes of NBS and their surrounding urban context mediate in those processes.

In combination with the NBS classification of Fig. 8, the diagram could be used to identify the specific NBS of interest for a particular situation, also taking into account the suitability of spatial levels and ecosystem types. It also highlights the NBS that need to be further studied in order to understand their capability for addressing specific UC through the supply of ES. In summary, the framework presented here has a double utility. First, it depicts a preliminary framework, in progress, that disentangles a wide set of UC-ES-NBS relationships in a qualitative form, which could inform urban policies, strategies and interventions. Second, in the longer term, this framework could be used as a basis to move towards broad quantitative “correspondence” tables that consider causal pathways and where each NBS is scored against every UC on the basis of the ES classes supplied and their amount. The relevance of the second point is also anticipated in Elliot et al. (2019), who review the integration of urban ES modelling within urban metabolism frameworks.

The usefulness of this framework is illustrated by the municipalities of São Paulo (Brazil) and Xalapa (Mexico), two cases that appear in the UC review. These urban areas share all the contextual attributes studied in the UC review (i.e. large metropolitan urban areas, Cfa climate, CELAC countries, upper-medium income countries). Both cities identify *built environment* (illustrative UC depicted in Fig. 10) as one of their main UC of concern in the reviewed urban planning documents. In a first instance, the framework presents policy-makers and urban planning professionals of both cities with the bundle of ES (third column Fig. 10) that they should prioritise to mitigate this UC. It also informs them about the underpinning biophysical and social processes to enhance those ES (fourth column Fig. 10) and how they relate to attributes of NBS and the urban context (fifth column Fig. 10). These details provide policy-makers and urban planners with supporting information to better frame policies, strategies and interventions, as well as monitoring them. Thus, policy-makers and urban planners could use the UC-ES-NBS network diagram and the NBS classification (Fig. 8) in combination to better understand which NBS Type 3 could be more relevant in their specific contexts. For example, they could prioritise a list of suitable NBS based on the dominant urban ecosystems of their municipalities, and spatial levels of proposed interventions. Moreover, in Fig. 8 they would be able to see non-physical solutions (NBS Type 1 and 2) applicable to selected NBS Type 3 or dominant natural ecosystems of their cities. Policy makers and urban planners might further investigate these non-physical solutions and if they find strong evidence of their value, include them as a complement in policies, strategies and interventions. This alternative might be especially relevant when the feasibility of extensive and intensive physical modifications is limited by space or budget.

5. Conclusion

This paper identifies and visualises the nexuses between urban

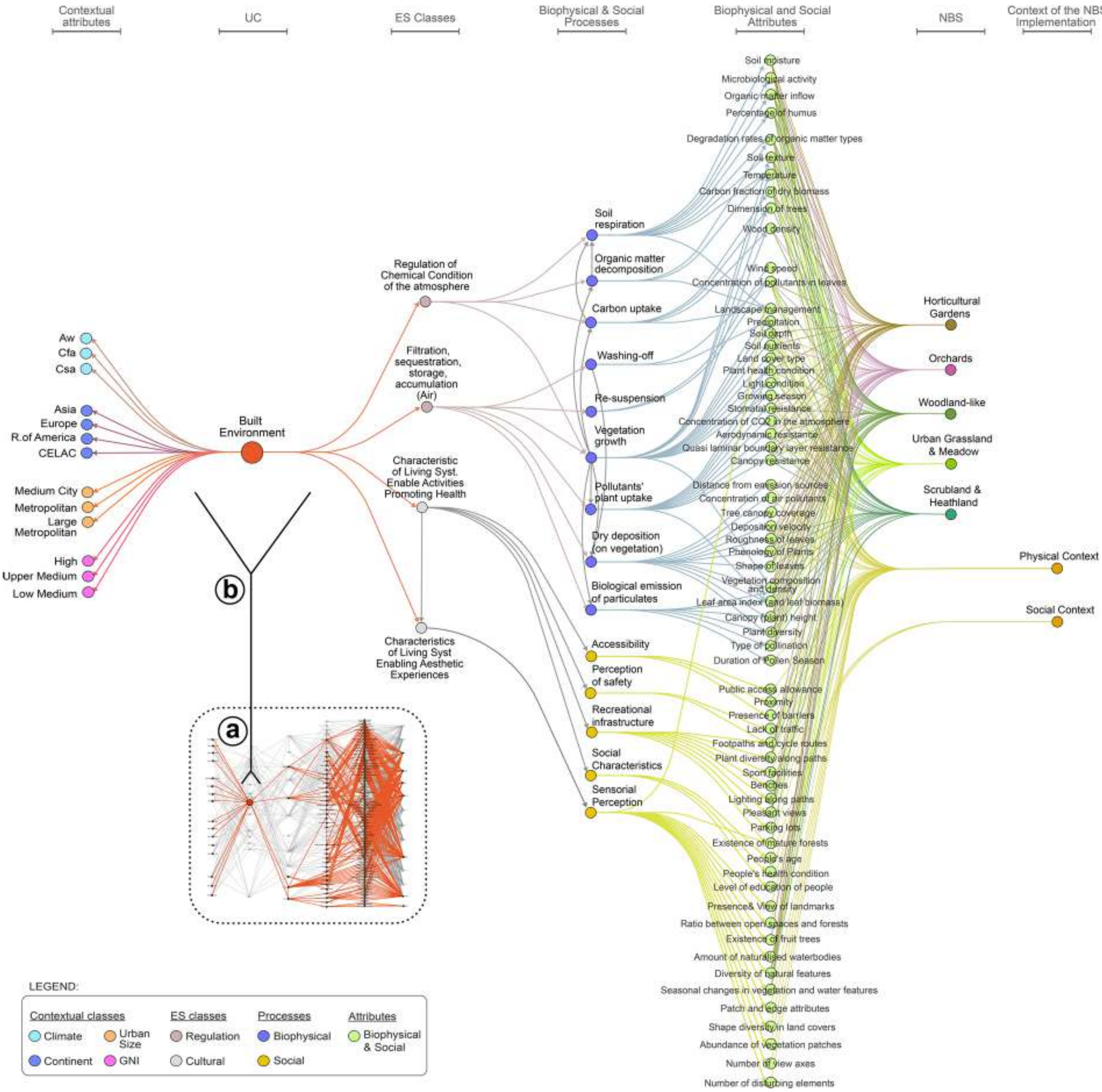

Fig. 10. Illustrative diagram of Contextual attributes-UC-ES-Process-Attributes-NBS Network for the UC *Built Environment. a)* Diagram of the complete network, only relationships of the *Built Environment* are in colour; b) Zoom to the *Built Environment* Network Diagram. Arrows are non-weighted to facilitate visualisation.

challenges (UC), ecosystem services (ES) and nature-based solutions (NBS), in order to support the mainstreaming of NBS in urban policies and sustainable and resilient urban planning interventions and strategies.

The review of UC literature from science, policy and local urban planning perspectives allowed us to identify and classify 18 UC and 58 sub-challenges for sustainability and resilience. This classification, and its equivalent for NBS, could be further improved and used as a basis for future studies aimed at identifying quantitative causal relationships among UC, ES and NBS. The results show that all the above-mentioned perspectives focus similarly on some UC in particular, namely *built environment issues, physical health, green and circular economy, climate change, water management, and material and solid waste*. The local urban planning literature is the one reiterating more social-led challenges (e.g. *social vulnerability*), showing more concern about this kind of UC. Additionally, several UC (e.g. *socio-spatial equi*ty) are stressed differently depending on the specific urban contextual classes (e.g. large metropolitan areas). In the future, further characterisation of UC with respect to their specific urban conditions can be useful for identifying which challenges arise mainly in urban areas sharing specific contextual attributes. By doing this, these cities can join forces when researching potential solutions and better understand whether certain contextual attributes drive the emergence of specific UC.

The reviews conducted in this paper have permitted us to advance in the classification of NBS types starting from the three broad types defined by Eggermont et al. (2015). More specifically, the overlap between specific NBS Types 1, 2 and 3 has been shown explicitly with the interconnections in Fig. 8. Furthermore, frequently mentioned ecological concepts used in the urban ES literature (e.g. sustainable urban drainage systems, ecosystem-based approach) have first been identified and then positioned under the NBS umbrella as part of its three broad types.

From the review of urban ES literature, specific nexuses between ES classes, UC and NBS have been identified. The type of relationship between the most frequently mentioned UC, groups of ES and NBS have been discussed, depicting one group with direct plausible causal relationships (albeit qualitative). In addition, social and biophysical attributes, and processes influencing 10 ES have been made explicit, including some of their feedback relationships. These results inform which attributes (of NBS and their contexts) need to be assessed when implementing NBS for the supply of specific ES. Socio-ecological processes are shared among different ES reinforcing the importance to account for ES in bundles. As a main output, a network of relationships among UC, ES, processes, attributes and NBS has been generated and exemplified for one UC in Fig. 10. The complete network of relationships can be visualised in the files included in the Supplementary Material F. This UC-ES-NBS network can be used to provide qualitative advise on urban policies, strategies and interventions that intend to make use of NBS.

Further research is needed to move from this qualitative network towards a quantification of the impact of NBS in the supply of specific ES, and the contribution of these ES to mitigate or overcome specific UC. For example, starting from this preliminary work, NBS models (e.g. mechanistic models, system dynamic models) could be developed to quantify the supply of ES classes in bundles (some examples already exist). These models could depict quantitative cause-effect relationships between those ES and NBS, and thus advise on the effectiveness of NBS to address UC. The latter outputs would be useful to further refine urban policies supporting the mainstreaming of NBS.

CRediT authorship contribution statement

Javier Babí Almenar: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Thomas Elliot:** Writing - review & editing. **Benedetto Rugani:** Writing - review & editing, Supervision. **Bodénan Philippe:** Writing - review & editing. **Tomas Navarrete Gutierrez:** Formal analysis, Data curation. **Guido Sonnemann:** Writing - review & editing, Supervision. **Davide Geneletti:** Writing - review & editing, Supervision.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104898.

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