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Reviewing designed plant communities' potential for optimizing the performance of urban nature-based solutions

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ABSTRACT

Urban nature-based solutions (NbS) can help to address larger societal challenges, such as climate adaptation and mitigation, by delivering multiple ecosystem services simultaneously. As multifunctional vegetation is a prerequisite for many types of NbS, finding methods for cost-effective planting design and vegetation management is vital for optimizing urban NbS performance. Designed Plant Communities (DPC) is a framework for planting design and vegetation management that endeavors to combine high aesthetic and biodiversity values with low management costs through species-rich vegetation. In this literature review, we elaborate on the design and management objectives and performance goals for vegetation in the DPC-framework and assess how scientific evidence provided by global DPC-research contributes to fulfilling four NbS criteria. This scoping review of 51 research papers shows that the DPC framework and its related evidence base align with the NbS criteria. Despite covering a large variety of vegetation types, geographical locations and NbS unit types, current DPC research gives concrete and reliable evidence on only a few research topics. The knowledge gaps on urban vegetation design and management identified in this review indicate that improving vegetated NbS performance will require further research into plant ecology and the specific ecosystem services provided by plants. Enhancing vegetated NbS performance will additionally require translating research into evidence-based planting design and vegetation management guidelines to facilitate the long-term development of reliable high-performing multifunctional urban vegetation.

1. Introduction

Nature-based solutions (NbS) is an umbrella concept for climate adaptation and mitigation measures that contribute to biodiversity and provide a wide range of additional benefits to people through ecosystem services (ESS) [1–3]. Vegetation is a key component of many urban NbS due to its potential for providing multiple ESS simultaneously. The provision of ESS by vegetation depends on various factors, including site conditions, combination of plants, spatial arrangement and structure of vegetation (such as height and density), the location of different vegetation types within the urban fabric, and subsequent vegetation management [4,5]. The performance of urban vegetation in NbS is also dependent on good vegetative development [6–9], which requires plants to be well-adapted to specific site conditions and can coexist with other urban organisms, including humans [10,11]. Despite the importance of vegetation in NbS, there is little guidance on how to enhance its performance. Consequently, the delivery of ESS from urban NbS cannot currently be accurately predicted or optimized [12–15].

Vegetation in urban landscapes is characterized by high spatial and structural diversity, as well as a higher proportion of non-native species than rural landscapes [10,16–18]. Both native and non-native vegetation can establish and develop spontaneously in urban areas or be deliberately designed and managed to provide specific ESS [19,20]. However, both spontaneous and designed urban vegetation can be associated with drawbacks and trade-offs. For example, designed plantings may not provide sufficient support for native fauna, and spontaneous vegetation is often perceived as aesthetically unpleasing, influencing perceptions of safety [21–24]. Provision of multiple ESS over time may also require regular management interventions, irrespective of the geographical origin or establishment method of the vegetation [25]. The environmental, social and economic pillars of sustainability, thus, necessitate finding methods to support cost-effective vegetated NbS in the long-term [4,26].

According to the European Commission (2021) [27], NbS should

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utilize verifiable knowledge produced through scientific methods (i.e., evidence) to solve problems, meet project goals, and to inform design decisions ("evidence-based design") [28,29]. Evidence can also guide vegetation management and green space governance [30–32]. The design and construction processes of NbS should be transparent and well-documented to support monitoring and future evaluations of projects [27,30,33]. The value of evidence-based design in the context of NbS lies in its ability to facilitate and predict solution efficiency, especially in terms of assessing broader applicability, scalability, and impact of the solution [27,34]. On the other hand, many definitions of NbS emphasize the real costs and benefits of NbS, meaning that the NbS status of any given nature-utilizing facility can only be verified through practical implementation. Thus, it is not just the design intent or use of scientific evidence that defines a NbS, but rather its realized and verifiable effects, efficiency, and ecosystem functionality [35].

To improve the reliability, multifunctionality, and efficient performance [35] of vegetation in urban NbS, it is important to further explore the available scientific evidence on planting design and vegetation management. Planting design that contributes to fulfilling NbS criteria requires rendering the implicit evidence into explicit evidence, as the effects of design decisions on the results would otherwise remain inextricable from other influencing factors [27,30,33]. For example, due to the site-specific nature of NbS, it is necessary to consider how the geographical attributes of study sites may have influenced the results of the research [36]. Furthermore, the specific characteristics of vegetation applications, e.g., the often thin substrates on green roofs, the relatively larger scale of urban forests, or the presence of road salt in stormwater swales, directly influence the vegetation types and plant taxa they can

Fig. 1. Examples of urban vegetation that qualifies as "designed plant communities," according to the criteria used in this paper Note that the term "Designed" is used to describe vegetation that has either been purposefully established through e.g., planting or sowing, vegetation that is managed with the intention to maintain and/or develop the vegetation, or both. a) Designed multi-species plant assemblages with high regard for both human interests and the ecological aspects of vegetation (e.g., Jac P. Thijssepark, Amstelveen); b) Designed multi-species plant assemblages prioritizing human interests while also considering the ecological aspects of vegetation (e.g., ornamental perennial planting in the Weihenstephan trial garden); c) Designed multi-species plant assemblages with high regard for both human interests and the ecological aspects of vegetation (e.g., urban meadow in Hirschgarten, München); d) Designed multi-species plant assemblage prioritizing ecological aspects of vegetation while also considering human interests (e.g., Urban meadow & forest in Mariehamn, Åland). Examples of urban vegetation that do not qualify as "designed plant communities," according to the criteria used in this paper: e) Non-designed, unmanaged multi-species plant assemblages (e.g., ruderal weeds on a construction site); f) Designed (planted and managed) monocultures of one plant species/ cultivar (e.g., large monocultural blocks of ornamental shrubs); g) Designed multi-species plant assemblages prioritizing human interests but with no regard for the ecological aspects of vegetation (e.g., conventional ornamental perennial planting); h) Designed multi-species plant assemblages prioritizing ecological aspects of vegetation but with little to no regard for human interests (e.g., inaccessible areas of urban nature reserves).

host, which, in turn, affect the performance of NbS [37–39].

Currently, the scientific literature on designed urban vegetation, and ornamental vegetation in particular, appears to lack well-established and defined terminology for its key concepts. This can make it challenging to evaluate the potential contributions of designed urban vegetation to NbS. Here, we suggest focusing on the concept of "Designed plant communities" (hereinafter "DPC"). DPC can be understood as a framework built on shared goals and principles, which connect practitioners in planting design and vegetation management. This framework aims to create naturalistic, multi-species plant assemblages that combine the best aspects of both spontaneous and designed vegetation [40–43]. The origins of DPC lie in garden design, and the framework is mainly associated with the ornamental herbaceous plantings of the so-called "New Perennial Movement" [44]. Besides ornamental plantings with mainly non-native species, the framework also encompasses the use of native species [40,41,45]. Moreover, it can be applied to the design and management of urban forests [46,47], wetlands [48], and semi-natural grasslands [49–51] (Fig. 1).

DPC are intended to cater to human interests by providing a broad range of ESS, especially amenity values and biodiversity support [42, 52]. Additionally, DPC are expected to maintain their capability to provide the intended services with minimal management [53–55]. Combining multifunctional vegetation performance with limited resource input is considered necessary within the DPC framework. This approach aims to secure the implementation and long-term sustenance of urban vegetation in the face of climate change, reduced management budgets, and pressure for urban densification [56]. The objectives and goals of DPC seem to align broadly with NbS criteria as described by Sowińska-Świerkosz and García, (2022) [35]. According to them, NbS should fulfill the following criteria: be inspired and powered by nature; address societal challenges; provide multiple services, including biodiversity benefits; and demonstrate high effectiveness and good economic efficiency.

Although DPC is a well-established framework among planting designers and has the potential to be a useful tool for designing vegetated NbS, it appears that there is currently no comprehensive overview of the empirical evidence supporting the claims regarding its performance or resource use. The main aim of our study is to assess how the DPC framework can enhance urban NbS performance through planting design and vegetation management. The aim is addressed by means of a scoping literature review that examines the following three questions:

1) How can the DPC framework be described in terms of objectives for planting design and vegetation management, as well as performance goals?
2) What characterizes the current scientific research on DPC in terms of: a) vegetation applications, b) vegetation types, c) geographical distribution, and d) research focus and methods?
3) How does the current scientific evidence on DPC support the fulfillment of the NbS criteria of: a) being inspired and powered by nature; b) answering to societal challenges; c) providing multiple services, including biodiversity benefits; and d) achieving high effectiveness and economic efficiency?

2. Methods

2.1. Data collection

An initial search and data collection were carried out to identify scientific and gray literature on DPC using the search terms "designed plant communities," "naturalistic planting design," and "ecological planting design." The searches led to 165 relevant documents, from which DPC synonyms, objectives, and performance goals were identified to answer research question 1. The results of the initial data collection were further used to formulate more precise search queries relevant to the concept of DPC, and to establish criteria for refining the selection of papers to answer research questions 2 and 3.

Data collection for research questions 2 and 3 was conducted through the Web of Science and Scopus between January 2023 and June 2023. The first search queries "design* plant communit*," "natural* planting design*," "ecol* planting design," "novel ornamental ecosystems," "Novel" AND "ornamental" AND "ecosystem," "dynamic vegetation design," and "dynamic planting design" sought to find key literature on "designed plant communities." The number of unique results for the first search queries was 84, despite the initial data collection having indicated a larger body of relevant material. A second search including broader queries "planting design" AND "ecolo*," "planting design" AND "urban," "planting design" AND "urban" AND "nature based solutions," and ("planting" OR "vegetation") AND "urban" AND "nature based solutions" returned 513 unique results. The initial data collection and the two searches, thus, provided 762 results in total. These were screened based on their language (English), title, abstract, keywords, and publisher for mentions of urban vegetation design and operative management, as well as plant selection and plant distribution in built environments. Only papers discussing vegetation on taxonomically or structurally distinct terms were accepted. After the first screening, the initial data collection on DPC yielded 51 papers; the first search for DPC research yielded 19 papers; and the second search for DPC research yielded 105 papers. The number of papers was further reduced by excluding duplicates, non-peer-reviewed material, and unavailable papers, resulting in 92 papers in total (Fig. 2.).

2.2. Analysis methodology

For an overview of the literature analysis process, see Fig. 3.

2.2.1. Assessment of the current evidence base within the DPC-framework

The relevance of each of the 92 papers to the concept of DPC was assessed using a four-criteria rating system. Papers that scored at least 3 points were deemed relevant to the DPC-framework. Criterion 1 was deemed the most important and awarded 2 points; fulfillment of each of the other criteria earned 1 point each.

1) Does the paper include the term "designed plant communities" or a synonymous concept? (possible synonym recorded as a direct citation)
2) Does the paper concern designed, i.e., planted or spontaneous but managed, multi-species plant assemblages [40,41,57]? (keywords for screening: "design," "multi-species/ species-rich/ multi--layer/diversity," or mentions of several plant species by name)
3) Does the paper consider ecological aspects of vegetation, e.g., interactions between plants and the abiotic site or plants and other organisms [40,53,58]? (keywords for screening: "ecological/ biodiversity/site conditions/ soil/ water/ shade/ drought/ site-adapted/ fitness/ [functional] traits," or explicit considerations of ecological aspects not covered by these keywords were also included)
4) Does the paper consider human interests regarding vegetation, e.g., positive experiences and other amenity values, human health, and technical functions [42,44,59]? (keywords for screening: "aesthetic/ attractive/ beauty/ ornamental," or explicit considerations of socio-cultural aspects not covered by these keywords)

After the assessment, additional articles were excluded due to a lack of clearly stated methodologies, incomprehensible research methodologies, or inconsistent use of terminology, which made the analysis of the studies' results infeasible.

The assessment resulted in 51 papers with relevance for the DPC-framework (Table 3). These papers were reviewed in full to further analyze the current state of the evidence for DPC. For each paper, the studied vegetation application and research focus area were identified based on their research questions and study design. The vegetation types

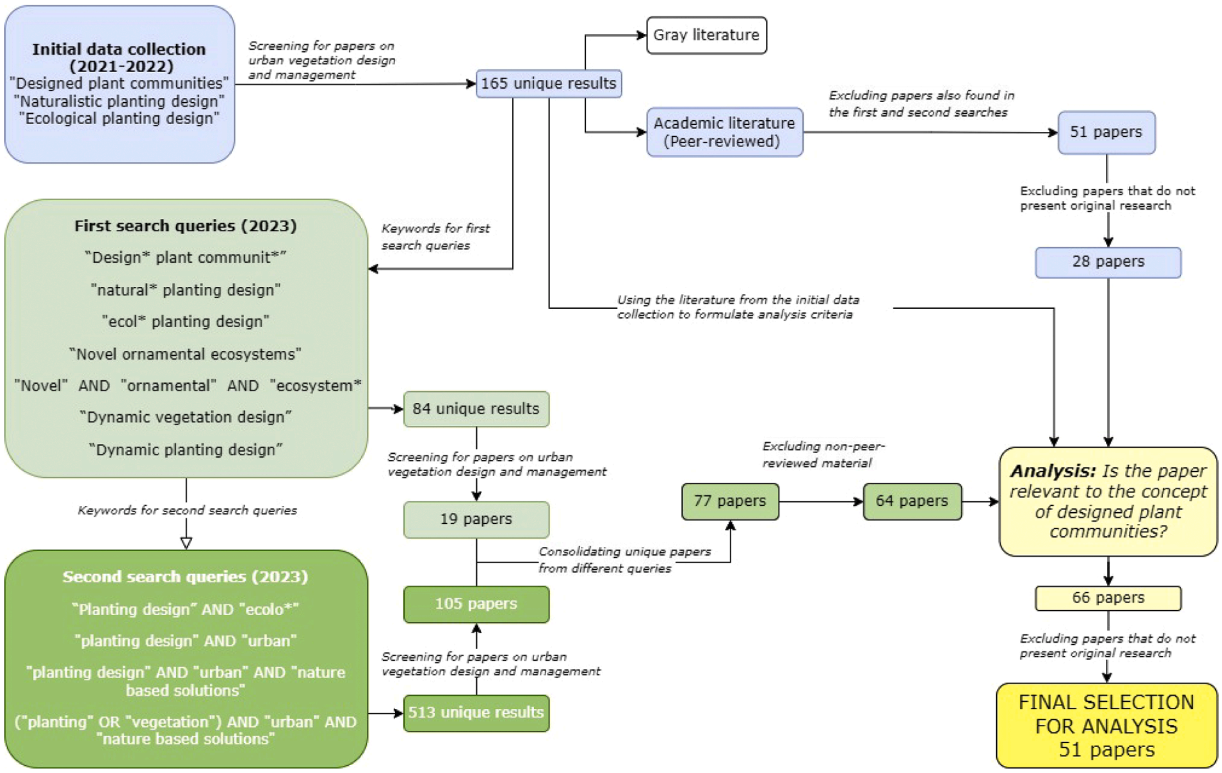

Fig. 2. Flow chart of the data collection and literature selection process for reviewing the potential of designed plant communities for urban nature-based solutions.

discussed in the articles were recorded using the exact wording and categorization of plants, as mentioned in the papers. Furthermore, the vegetation types in each study were described in terms of their life forms (e.g., forbs, grasses, shrubs) and life cycles (annual, biennial, perennial). Species-level specificity, i.e., whether or not specific plant species had been named, was noted to allow for comparisons across studies. Additionally, the studies were divided into three categories based on how many plant species were mentioned: 0= none, <7= some, >7= multiple. The geographical locations of the studies were written down. Finally, potential limitations, e.g., study duration and sample size, were recorded. The resulting datasets were used to provide a broad description and characterization of the current scientific literature on DPC.

2.2.2. Analyzing the potential contributions of DPC research to NBS criteria

The potential contributions of the DPC framework to NbS were analyzed by examining the 51 papers using the four criteria framework for NbS formulated by Sowińska-Świerkosz and García (2022) [35]. Citations were recorded from the papers for specific, predetermined "aspects" of each criterion (Table 1). Citations describing new evidence on an aspect of a criterion were classified as "results." In contrast, citations using NbS criteria and aspects to frame the paper or analyze the results were classified as "considerations." The purpose of the classification was to present the current state of evidence for NbS available through DPC-research and to describe if and how the papers contextualize DPC research in relation to NbS. Finally, citations containing results for each of the four aspects were formulated into "evidence statements" that presented the findings within their topical context. Thus, the evidence could be further grouped inductively by topic, e.g., the effect of maintenance on plant growth, or demographic differences in how people experience urban vegetation. If three or more pieces of evidence under an aspect pertained to the same topic, these were collated into a "topic cluster," which could include both corroborating and/ or contradicting evidence statements.

Results for "Inspired and powered by nature" were assumed to provide evidence on the ecological aspects that should be considered in the design and management of vegetated NbS. Results on aspects of "Answer to societal challenges" [1,27] could have exemplified possible and suitable application areas for DPC as part of vegetated NbS. Results under "Multiple services" should ideally have provided information on how planting design and management actions influence specific ESS provisions, as defined by the TEEB ecosystem service categories [3]. Ecosystem disservices were also included as an aspect of this criterion. Finally, results under "High effectiveness and economic efficiency" were expected to provide guidance on appropriate governance and management of urban vegetation and give indications of the potential of DPC for NbS in variable contexts, as well as temporal and spatial scales. The aspects of this criterion were based on the main-, and sub-dimensions of high effectiveness and economic efficiency, as provided by Sowińska-Świerkosz and García (2022) [35].

3. Results

3.1. The DPC framework: design and management objectives and performance goals

The analysis of both gray and scientific literature on the DPC framework showed that its design and management objectives, as well as performance goals, are associated with a variety of planting design and vegetation management concepts (Table 2). Based on the initial literature search, we identified four objectives for planting design and vegetation management within the DPC framework: 1) Focus on naturalistic aesthetic; 2) Utilization of ecological processes and/or patterns; 3) Matching plants to the site; and 4) Combining plants with similar and/or complementary behavior. These objectives guide practical design and management actions within the DPC framework. The framework further posits that fulfillment of the planting design and vegetation management objectives will improve vegetation performance in the long-term. From the DPC literature, five long-term performance goals for designed vegetation were identified: 1) Providing cultural ESS through seasonal visual interest; 2) Supporting low

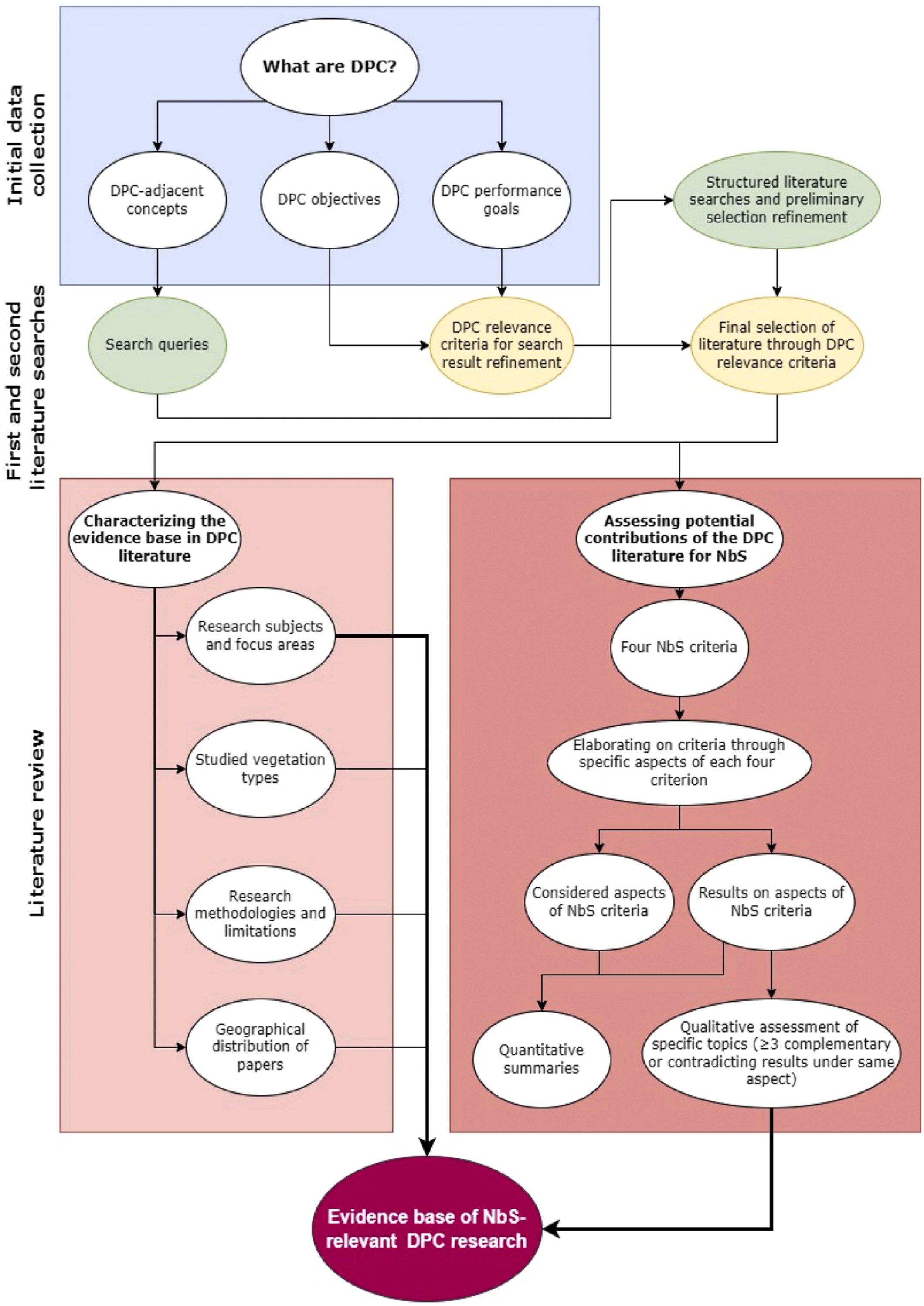

Fig. 3. The process of reviewing the potential of designed plant communities (DPC) for urban nature-based solutions (NbS).

maintenance needs; 3) Attaining resilience through self-regulation; 4) Contributing to plant biodiversity and supporting other organisms; and 5) Providing regulating ESS.

The initial data collection identified 19 different planting design and vegetation management concepts associated with the DPC framework. The most used concepts within the DPC-framework were designed plant communities, naturalistic planting design, and ecological planting/ecologically-based planting.

3.2. Characterizing the scientific evidence base on DPC

3.2.1. Studied vegetation types in DPC research

The papers covered 19 different vegetation types. Perennial graminoids (34 papers), perennial forbs (21 papers), shrubs (20 papers), and trees (19 papers) were the most commonly discussed categories. Other categories included generic forbs (16), herbaceous vegetation (generic) (10 papers), annual vegetation (10 papers), geophytes (8 papers), sub-shrubs (8 papers), woody plants (generic) (7 papers), perennial climbers

Table 1
Criteria for NbS and analyzed aspects under each criterion.

Inspired and powered by nature

Nature-based solutions must incorporate and utilize "nature", i.e., living ecosystems and the ongoing processes within them [171]. Living ecosystems consist of **interactive non-human organisms and the habitat-providing aspects of the abiotic environment** in which they reside, including possible anthropogenic environmental features and processes. This means that pure biomimicry or the utilization of natural or naturally derived materials does not fulfill this criterion [35]. The sources for each aspects are given below.

Aspect	Description
Attributes of individual organisms	
Plant biology and ecology	Plant attributes, such as traits, anatomy, morphology and life cycles; Explicit links between attributes and vegetation development [53,65]
Relationships between organisms and their environment [173]	
Plant-plant-relationships	Ecological relationships between plants, such as competition and facilitation [42,70,163,164]
Plant-site-relationships	Effects of site conditions, such as climate, microclimate, soils, hydrology, topography, nutrients, light and typical abiotic disturbances on plants; but also vice versa [40,41]
Plant-animal-relationships	Ecological relationships between plants and animals, such as mutualism and predation (Fungi and microbiota are also considered under this aspect) [174]
Plant-human-relationships	Human-mediated ecological processes, such as disturbance and plant migration, and anthropogenic plant stressors [10,11]
Animal-site relationships	Effects of site conditions on animals in vegetation
The composite attributes of assemblages of organisms	
Composite ecosystem properties	Explicit links between multiple site conditions, disturbance types or plant attributes
Vegetation distribution patterns	Spatial arrangement of plant assemblages across a site or between sites [45,175]
Plant distribution patterns	Spatial arrangement of plants in an assemblage, viewed as a 2D-surface (placement, total density, groupings, etc.) [43,55,176]
Vegetation structure	Spatial arrangement of plants in an assemblage, viewed as a 3D-space (height, layering, density of each layer etc.) [46,169]
Vegetation dynamics	Changes in plant assemblages over time, such as succession or long-term effects of competition on community structure [46,57]
Naturalistic aesthetics	Explicit references to natural inspiration or naturalistic appearance of designed vegetation [41,46,58]

High effectiveness and economic efficiency

The effectiveness of NbS has four main dimensions: **Management and governance, local adaptation, service production, and economic efficiency** [35]. Economic efficiency entails a balance between **resource inputs, benefit outputs and possible trade-offs** in projects, which means that NbS must exceed traditional "gray" engineering solutions in terms of life cycle functionality. **Individual NbS performance must also be considered within its wider landscape context** [1,27,34,172]. The aspects have been adapted from Sowińska-Świerkosz and García (2022) [35].

Aspect	Description
Adaptability in vegetation management	Acknowledgement and acceptance of inevitable change in living systems, and preparing to make changes to management accordingly to restore or reprioritize functions on a given site
Application connectivity	Planning for interconnected blue-green infrastructure and interventions for synergistic effects and large-scale benefits
Economic efficiency	Solution benefits should outweigh its costs in a life cycle perspective; use of predetermined time scales for assessment is preferred
Efficiency evaluation and monitoring	Assessment of realized interventions in a systematic manner to accumulate knowledge for improving management, governance, and future projects
Efficiency through governance	Securing a balance between the costs and benefits of interventions through strategic planning and management
Implementation efficiency	Designed and constructed solutions should establish intended function within a reasonable timespan and through appropriate use of resources compared with the realized function
Local adaptation, environmental aspects	Application of knowledge to develop solutions that are adapted to local biophysical contexts
Local adaptation, policy aspects	Application of knowledge to develop solutions that are adapted to local norms; or adjusting local norms to enable implementation
Local adaptation, social aspects	Application of knowledge to develop solutions that are adapted to local socio-cultural contexts and needs, e.g., through the use of participatory planning and/or management methods
Solution scalability	Identification of impacts at different scales; evaluating the generalizability or applicability of a solution or parts of a solution to new contexts
Tradeoffs between ESS	Identification of ESS tradeoffs; minimizing and mitigating tradeoffs; prioritization between ESS without suboptimization
Vegetation management efficiency	Appropriate, cost effective, and well-timed management aims to maintain and develop vegetation value and facilitate ESS delivery

Answer to societal challenges

Nature-based solutions must address specific issues, such as climate change adaptation, **and be scalable and adaptable to varying contexts**. Examples of these might be addressing aspects of the climate crisis, increasing resilience in the face of hazards, reversing biodiversity loss, and ensuring the just distribution of ecosystem goods and services [1,2,34]. The aspects under "Answer to societal challenges" have been adapted from European Commission (2021) [27] and IUCN (2020) [1].

Aspect	Description
Climate change resilience, mitigation and adaptation	Decreasing the effects of climate change through management of greenhouse gases and by adapting societies to climate risks and the adverse effects of climate change
Environmental degradation and biodiversity loss	Reducing harmful impacts on ecosystems and biodiversity e.g., by protecting nature, managing resource use, and controlling invasive alien species
Green space management and urban place regeneration	Strategic approaches to implementing and managing urban blue-green infrastructure for technically functional and socially valuable networks of green spaces
Human health and well-being	Securing safe and health-promoting environments
Knowledge and social capacity building for sustainable urban transformation	Knowledge assessment, creation, co-creation and communication within a society, aiming for just outcomes and shared ownership of the common environment

Provide multiple services, incl. biodiversity benefits

Nature-based solutions must contribute to upholding global biodiversity through local conservation, recreation, and enrichment of organisms and ecosystems. **Simultaneous provision of further social/cultural, economic, and ecological services and benefits is required**. The aim is to always maximize co-benefits to avoid suboptimized solutions [1,2,34]. The aspects below have been adapted from the TEEB ecosystem service categories [3]).

Aspect	Description
Aesthetic appreciation and inspiration for culture, art and design	Aesthetically pleasing sensory experiences and their connection to cultural values
Biodiversity support	Generic support for biodiversity; support of biodiversity outside of habitat provision, e.g., maintenance of genetic diversity
Carbon sequestration and storage	Storing CO2 in organic litter and living tissues
Food provision;	Provision of nutrition for humans
Erosion prevention and maintenance of soil [health] and fertility	Plant-based erosion control and regulation of water-, and nutrient cycles as well as microbial life in soils. Phytoremediation and related processes are also included.

(*continued on next page*)

Table 1 (*continued*)

Answer to societal challenges		Provide multiple services, incl. biodiversity benefits	
Natural and climate hazard risk reduction	Remedying known risks, rectifying known weaknesses, and preparing for natural hazards	Habitat provision	Provision of shelter, food, nesting sites etc. for animals, fungi, and microbiota
Water management and water security	Mitigating negative human impacts on the water cycle and securing access to potable water	Local climate and air quality regulation	Temperature and wind regulation, airborne pollutant management
		Medicinal resource provision	Provision of traditional medicine and chemicals for medicine production
		Moderation of extreme events	Climate and natural hazard risk reduction through stabilizing effects, wind speed reduction, etc.
		Pollination	Benefits provided by pollinating animals; in the current context also facilitation of pollinator life through food and habitats
		Raw material provision	Provision of organic raw materials such as wood and chemicals
		Recreation and mental and physical health	Benefits of outdoor recreation on human health and well-being
		Spiritual experience and sense of place	Nature as a source of or place for spiritual and religious experiences; the spiritual, religious, and cultural values of specific places and place recognition
		Waste [- and stormwater] treatment	Water quality control in organic and mineral materials and through organisms, water quantity control
		Ecosystem disservices	Perceived or real detrimental effects of ecosystems; negative perception of certain ecosystems and/ or their attributes

(6 papers), biennial vegetation (3 papers), moss (2 papers), ferns (2 papers), lichens (2 papers), algae (1 paper), aquatic plants (1 paper), epiphytes (1 paper), and succulents (1 paper).

The categorization of plant groups varied across the papers in terms of the levels of distinction. Most articles (46 papers) included specific species names, and a majority of these studied multiple species (41 papers). Five papers mentioned some species, and five did not mention any specific species.

3.2.2. Vegetation applications in DPC research

Nine vegetation applications could be identified from the literature, in combination with identified research focus areas (Fig. 4). The most researched vegetation application was general ornamental vegetation (24 papers), followed by studies on designed meadows (16 papers) and green roofs (13 papers). The other applications were urban forests (4 papers), spontaneous vegetation (3 papers), ornamental lawns (2 papers), green walls (1 paper), food crops (1 paper), and annual vegetation (1 paper).

3.2.3. Geographical distribution of DPC studies

Nineteen countries from four different continents were represented in the analyzed literature. The majority of the studies were conducted in Europe (28 papers), with the most originating from the UK (13 papers). The remaining papers originated from Eastern Asia (6 papers), Western Asia (4 papers), North America (4 papers), and Australia (3 papers). Additionally, six papers were based on geographically diffuse modeling or desktop studies.

3.2.4. DPC research focus areas

The eleven identified research focus areas were relatively evenly distributed across the analyzed papers (Fig. 4). The most common focus was vegetation establishment, i.e., studies lasting <3 years (14 papers). This was followed by planting design strategies and methodologies (10 papers) and vegetation development lasting >4 years (10 papers). The other identified focus areas were plant selection frameworks (8 papers), vegetation preference and perception (7 papers), vegetation typology and distribution (5 papers), vegetation management (3 papers), habitat provision by vegetation (3 papers), ecosystem service delivery by vegetation (3 papers), horticulture (1 paper), and vegetation survey (1 paper). Note that each paper could have several focus areas and that papers without an explicit focus on a specific area might still provide relevant evidence.

3.2.5. DPC research methodologies

The most prominent methodologies identified in DPC-related research papers were empirical studies involving controlled experimentation in the physical reality (20 papers). All 20 papers relating to experimental research methods were conducted as field experiments, largely in situ. Six of the papers described very short-term projects lasting less than two growing seasons, nine papers described short-term projects of 2–3 years, and the remaining five papers described mid-term projects with an evaluation period of 4–5 years. The total number of plots in these studies varied between 6 and 162, and the number of replicates per each combination of variables ranged between one and three (10 papers), or between four and five (6 papers). Three papers described 8 replicates, while one included 24 replicates. The number of treatments per study ranged from 3 to 54, and most studies (6 papers) had <10 treatments or 10–20 treatments (6 papers).

The second most common research methodology identified was site surveys (9 papers). Most surveys concerned vegetation typology and vegetation distribution in varying urban environments or vegetation types. Two surveys [60,61] were undertaken to find suitable wild plant taxa for horticultural cultivation and use in urban areas, and one of the studies concerned insects rather than vegetation [62]. The remaining papers described site surveys based on singular visits, with the exception of Köhler (2006) [63], whose observations spanned 20 years, and Mata et al. (2021) [62], whose data was sampled on three occasions per site.

The third methodology identified was design research, with an emphasis on the development of design tools or methodologies in 8 papers, most of which involved modeling or simulation. A few of these studies were geographically explicit.

Interview- and survey-based research was described in seven papers, and they focused solely on vegetation preference and perception.

Case studies on pre-established vegetated sites, experimental vegetation under uncontrolled conditions, and qualitative or non-statistical analyses of vegetation were included in five papers, which all employed <4 study plots and had limited time frames (<1 year) or an undefined observation period.

Only one paper described data collection as its primary research methodology. No review papers or theoretical papers on planting design with a clear research methodology were identified, despite the large numbers of exploratory narratives and perspective papers available [55,56,64–71].

3.3. Contributions of DPC research on NBS criteria fulfillment

With the exception of two papers [72,73], all studies included at least one piece of explicit evidence in relation to the NbS criteria. Six papers provided evidence for all four criteria, 19 papers provided evidence relevant to three criteria, 18 papers provided evidence relevant to two criteria, and four papers provided evidence on one criterion. The number of papers providing results for each criterion can be found in Fig. 5. The aspects of "Inspired and powered by nature" had 108 connected results, "high effectiveness and economic efficiency" had 82 results, "Provide multiple services, including biodiversity benefits" had 45 results, and "Answer to societal challenges" had 34 results (Table 4). The following sections will describe the results from the 49 DPC research papers in relation to specific NbS criteria.

3.3.1. Inspired and powered by nature

3.3.1.1. Attributes of individual organisms. A total of seven papers presented research on individual plant attributes. Three papers described trait-related competitive success [49,74,75]. They found that the development of plant assemblages was more strongly influenced by the presence of specific, highly competitive taxa than by vegetation density. This effect was particularly clear in species capable of establishing clear dominance, irrespective of their initial abundance, possibly due to traits that steer resource allocation toward increasing the plant's above-ground biomass and height [49,74,75].

One paper described traits specific to certain plant taxa [61]. Other studies addressed various factors such as plant longevity for some taxa [50], the effect of the timing of mowing on plant resource allocation [76], differences in dry matter production [76], and plant community development from seed [76].

3.3.1.2. Relationships between organisms and their environment. Twenty-six papers reported results on plant-site-relationships. Four different topic clusters could be identified: 1) The effects of site productiveness on plant growth and performance [49,51,77–82], 2) Vegetation survey results and their indications for plant-site-relationships [60,61,83–86], 3) The effects of site productiveness on plant assemblage development [63,65,77,87,88], and 4) The effects of mulches on vegetation development [74,89–91], where evidence from different studies was found contradictory or inconclusive. Increased light availability, water availability, rooting space, and suitable warmth conditions were found to increase biomass production and flowering [51,77–82]. The results from surveys of spontaneous vegetation composition and distribution further support the claim that site conditions significantly influence vegetation performance [22,60,61,83,84,86,92]. Improved site productiveness was, on the one hand, found to support higher species richness on green roofs [63,77,87]. However, in studies focusing on embedding exotic species into native and/ or spontaneous vegetation, site productiveness was found to have a lesser impact on species establishment and persistence than competitive pressures [88,93]. Other results described the effect of wind on vegetation development [82], the negative effects of poor fit between a plant and light conditions [94], methods for assessing plant water needs [95], and the effect of variation in plant rooting depths on soil moisture retention at different soil depths [96].

Fourteen papers focused on plant-plant-relationships, specifically the spontaneous colonization of designed plant assemblages [50,63,77,78,81,82,84,89,91,93] or plant interactions within designed assemblages [65,74,75,97]. The studies show a clear trend of plant diversity decreasing over time in designed assemblages due to changing competitive circumstances [49,74,75,78]. Besides competition among target species [49,74,75], competition from spontaneously colonizing plants is a known driver of change in plant assemblages. This competition may lead to decreased target species density and coverage already during the first three years after establishment [91]. Spontaneous colonization by unwanted species may out-compete pre-established vegetation [63], prevent the establishment of target species altogether [81], or reduce the survivability of planted ornamental taxa [93]. Conversely, higher target vegetation density was found to hinder the spontaneous establishment of seedlings, which might help to reduce

Table 2
The DPC framework: Planting design concepts with shared objectives for planting design and vegetation management, and shared performance goals for designed vegetation.

Objectives for planting design and vegetation management	Connected planting design and vegetation management concepts
Focus on naturalistic aesthetic in plant choices and overall design, creativity in management	Naturalistic planting design [43,52,54,80]; Designed plant communities [40,41]; Ecological(ly based) planting (schemes) [177]; Stylized nature [43]; Ecological ornamental planting [52]; "Designed for vegetation"[68]; Designed ecosystems [67]; Urban naturalistic herbaceous planting [80]; "Lebensbereich"-style, cottage garden [43]
Utilization of ecological processes and/or patterns, allowing change	Naturalistic planting design [54,58,174], but see also [178]; Designed plant communities [40,41,48]; Ecological(ly based) planting (schemes) [53,57,170]; Mixed perennial plantings [55,169]; Semi-natural herbaceous vegetation [68]; Anthropogenic plant communities [42]; Dynamic Planting [43]; Dynamic vegetation [179]
Matching plants to the site (plant needs and tolerances, site conditions, site context)	Designed plant communities [40,41,43]; Naturalistic planting design [54,174]; Mixed perennial plantings [55,169]; Ecological(ly based) planting (schemes) [53]; Anthropogenic plant communities [42]; Matrix planting[176]
Combining plants with similar and/or complementary behavior, community before individual	Designed plant communities [40,43,55,67]; Mixed perennial plantings [55,169]; Naturalistic planting design [54]; Ecological(ly based) planting (schemes) [53]
Performance goals for designed vegetation	**Connected planting design and vegetation management concepts**
Enhancing cultural, social, and aesthetic values: Creating spaces, focus on long seasonal interest and rich flowering, artistic expression	Designed plant communities [40,41,55,68]; Naturalistic planting design [42,58,174,178]; Ecological(ly based) planting (schemes) [170,177]; Mixed perennial plantings [55,169]; Artistically stylized habitats [43]; "Rich garden habitats[43]; Colourful forb vegetation[68]; Horticultural meadows [51]; Matrix planting [176]
Low maintenance needs	Designed plant communities [40,41,43,55,67,174]; Naturalistic planting design [42,58,125,174]; Ecological(ly based) planting (schemes) [53,57,170,177]; Artistically stylized habitats [43]; Rich garden habitats [43]; Matrix planting [176]; Dynamic Planting[43]; But see also: Urban ecosystems vs. novel ecosystems [87]; Vs.: Lebensbereich-plantings vs. semi-natural native plantings [53]
Self-regulation: stability, sustainability, regeneration capacity, robustness, longevity, self-sustainment	Naturalistic planting design [42,58,125,174]; Designed plant communities [40,55,67]; Ecological(ly based) planting (schemes) [53,177]; Mixed perennial plantings[55,169]; Matrix planting [176]
Contribution to plant biodiversity and support for other organisms (small-scale considerations)	Designed plant communities [40,41,68]; Naturalistic planting design [42,52,119]; Ecological(ly based) planting (schemes) [53,170,177]; Artistically stylized habitats [43]; "Rich garden habitats"[43]; Dynamic vegetation [179]
Provision of regulating ecosystem services	Designed plant communities [41,67]; Ecological(ly based) planting (schemes) [170]

Table 3
Overview of the final selection of analyzed articles.

Article	Place, methodology, and short description/ aim of research
Alizadeh & Hitchmough, (2020) [80]	United Kingdom; Experimental (3 years); Evaluating the effects of climatic scenarios on ornamental vegetation development
Alizadeh & Hitchmough, (2020b) [99]	Sheffield, United Kingdom; Experimental (5 years); Evaluating the effect of disturbance (herbivory) on ornamental vegetation development
Bjørn et al., (2019) [50]	Denmark; Experimental (3 years); Studying plant community composition and development in designed native ornamental meadows
Bretzel et al., (2012) [76]	Italy; Experimental (2 years); Studying the performance and assessing the feasibility of three different mixes of herbaceous flowering species
Cascorbi (2007) [51]	Germany; Experimental; Investigation of the effect of establishment circumstances and species on including ornamental vegetation in a native meadow (2 years)
Cerra & Crain, (2016) [109]	United States; Design research; Developing and testing planting design strategies for increased ecological value, focus on avian habitat enhancement
Droz et al., (2021) [79]	United States; Experimental (4 years); Comparison of ESS provision between three green roof constructions, two plant assemblages and mycorrhizal treatment
Dunnett et al., (2008) [77]	United Kingdom; Experimental (5 years); Observations on individual plant growth and flowering in ornamental planting on a green roof
Dunnett et al., (2008) [112]	United Kingdom; Experimental (3 years); Investigation of water retention by different vegetation types applied to green roofs
Fumagalli et al., (2020) [105]	Italy; Interview/ simulation; Assessing cyclists' perceptions of different simulated rural roadside vegetation types
Gamrat & Saran, (2018) [86]	Poland; Site survey; Survey on lawn species composition in urban housing areas
Ghazal, (2021) [60]	Saudi Arabia; Site survey; Survey-based plant selection scheme
Hitchmough & Fleur, (2006) [91]	United Kingdom; Experimental (3 years); Establishment and development of North American prairie vegetation under different management regimes
Hitchmough & Wagner, (2013) [78]	United Kingdom; Experimental (5 years); Investigation of establishment and development of ornamental rosette-forming forbs in native meadow vegetation
Hitchmough et al., (2017) [49]	United Kingdom; Experimental (5 years); Urban prairie vegetation establishment and development
Hong et al., (2020) [113]	South Korea; Experimental (5 months); Conceptual paper on plant classification and the impact of intercropping on growth
Hoyle, (2021) [106]	United Kingdom; Interview; The effect of views on environmental issues on perceptions of amenity and biodiversity values of three planting types
Hoyle et al., (2017) [107]	United Kingdom; Interview; Surveys and interviews on the public perception on urban plantings of varying degrees of nativeness
Hu et al., (2017) [110]	United States; Interview; Investigation of urban stormwater pond vegetation perception by different stakeholder groups
Kutková et al., (2018) [81]	Czech republic; Experimental (1 year); Investigation of annual ornamental vegetation and weed establishment on three different substrates
Kutlvašr et al., (2019) [74]	Czech Republic; Case study; Evaluating the invasive potential of ornamental plants in 6–10 year old "mixed perennial beds"
Kühn, (2006) [88]	Germany; Case study; Investigation on enriching spontaneous urban vegetation with added exotic plants for increased ornamental value
Köhler, (2006) [63]	Germany; Site survey; Following up plant community composition and development on two green roofs over a 20-year period
Köppler et al., (2014) [93]	Germany; Experimental (3 years); Studying the establishment and development of prairie-, and steppe-based ornamental taxa among spontaneous urban vegetation
Li et al., (2019) [84]	China; Site survey; Survey on spontaneous vegetation in designed urban spaces
Li et al., (2019) [104]	China; Interview; Questionnaire-based survey on the perception of spontaneous vegetation and other types of public plantings in urban parks
Lundholm & Marlin, (2006) [83]	Canada; Site survey; Plant inventory on spontaneous urban vegetation to identify their dominant habitat origins and preferences
Mata et al., (2021) [62]	Australia; Site survey; Insect distribution in different urban vegetation types
Nagase & Nomura (2014) [82]	Japan; Site survey; Observations on vegetation development and invertebrate species in different parts of a green roof garden.
Nagase et al., (2013) [89]	United Kingdom; Experimental (1 year); Observations on weed colonization and competition in ornamental planting
Nagase et al., (2017) [89]	United Kingdom; Experimental (1 year); Observations on plant growth and flowering in ornamental planting with regards to planting diversity
Nam & Dempsey, (2019) [103]	United Kingdom; Interview- and survey-based; Investigating how different stakeholders perceive the choice of different planting types in public parks
Nazemi Rafi et al., (2020) [108]	Iran; Experimental (1 year); Investigating different types of mulches and plant combinations in relation to soil moisture and temperature
Nazemi Rafi & Kazemi, (2021) [96]	Iran; Survey-based; Investigating people's perception of plantings on varying levels of drought tolerance and mulch types
Nielsen & Jensen, (2007) [180]	Denmark; Case study;Comparison of four visual aspects of three different forest types, in terms of design and management paradigms
Nouri et al., (2013) [95]	Australia; Case study; Testing different methods for assessing mixed-species urban vegetation irrigation needs
Qian et al., (2021) [92]	N/A; Design research; Survey- and site-based digital planting design method
Radhakrishnan et al., (2019) [102]	Singapore; Design research; International survey and analysis of multifunctionality and selection of plant species for GI
Richnau et al., (2012)	Sweden & Denmark; Case study; Investigation of urban forest development over 20–30 years, incl. design and management effects
Schmithals & Kühn, (2014)	Germany; Experimental (3 years); Investigation of ornamental prairie vegetation development under variable management regimes
Sjöman et al., (2015) [61]	Romania; Site survey; Identification of plant taxa paved urban spaces in Scandinavia through vegetation surveys in eastern Romanian steppes
Smith et al., (2015) [98]	United Kingdom; Experimental (1 year); Study on insect distribution in grass-free lawn replacement mixtures
Suter et al., (2010) [75]	Switzerland; Experimental (3 years); Studying plant community composition and development in designed native wetland vegetation
Teixeira et al., (2022a) [72]	N/A; Design research; Trait-, effect-, and site-based plant selection framework
Teixeira et al., (2022b) [73]	N/A; Data collection based on a desktop study; Data on plant traits for use in plant selection for urban green spaces
Thorpert et al., (2022) [101]	N/A; Design research; Effect-based plant selection framework with optimization for both aesthetics and pollinator support
Threlfall et al., (2016) [22]	Australia; Site survey; Comparative study on urban vegetation structure and composition
Van Mechelen et al., (2015) [87]	N/A; Design research; Plant selection framework to maximize functional trait diversity/ ESS delivery. Green roofs as an example application.
Watkins et al., (2021) [9]	N/A; Design research; Evaluating trait-based approaches for site-adapted tree selection in urban forestry by testing them on a single genus
Wei & Huang, (2015) [94]	China; Design research; Development of a GIS-based landscape analysis method for assessing light availability at a site
Yalcinalp et al., (2017) [85]	Turkey; Site survey; Survey of spontaneous urban vegetation on green roofs

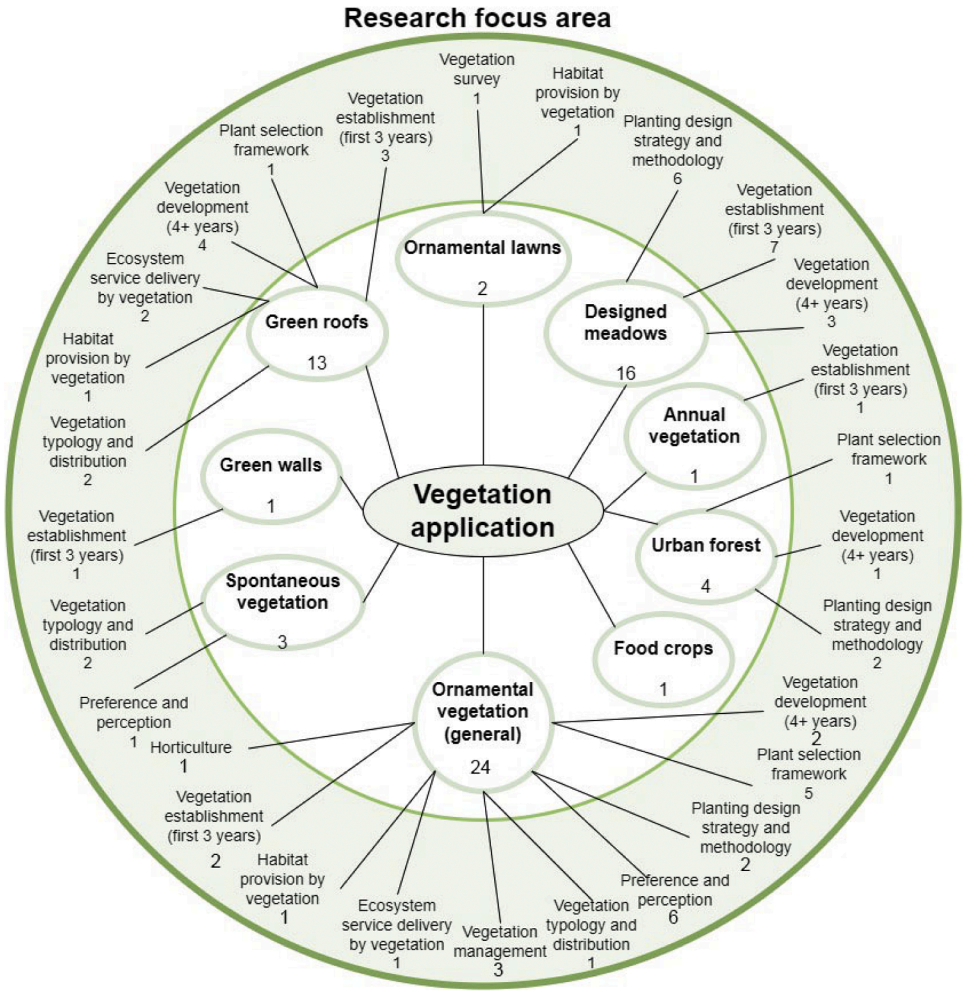

Fig. 4. Vegetation applications and research focus areas in the analyzed papers on designed plant communities.

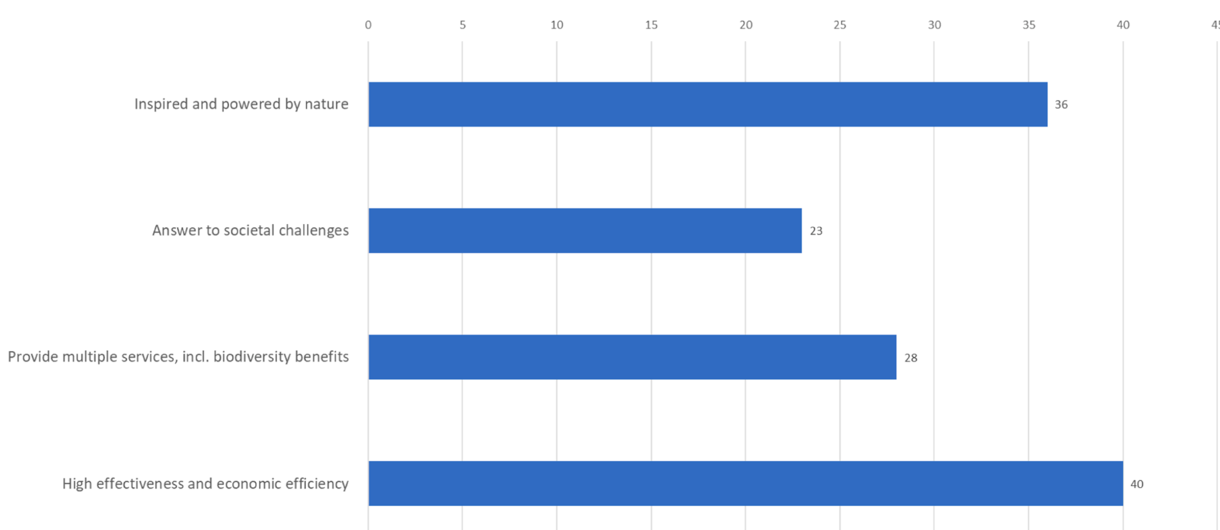

Fig. 5. Number of analyzed papers on designed plant communities (DPC) with results pertaining to the four criteria for nature-based solutions (NbS) (Sowińska-Świerkosz & García, 2022).

colonization by unwanted taxa [50,77,78,82,89,91].

Ten papers provided results on plant-animal-relationships. Most of the evidence on this aspect pertained either to the effects of herbivory on vegetation development [49,61,78–80] or invertebrate diversity in urban vegetation [62,82,98]. The selectiveness of herbivory was found to be an important driver of plant assemblage composition, as grazing decreases vegetation density, increases plant mortality, and influences flowering [49,61,78,79,91,99]. Lawns were found to be the least

Table 4
Distribution of results on NbS criteria and aspects in the analyzed literature.

Inspired and powered by nature	Hits	Answer to societal challenges	Hits
Results on plant-site-relationships	26	Results on environmental degradation and biodiversity loss	10
Results on plant-plant-relationships	14	Results on knowledge and social capacity building for sustainable urban transformation	9
Results on plant-animal-relationships	10	Results on green space management and urban place regeneration	9
Results on vegetation dynamics	10	Results on water management and water security	3
Results on plant-human-relationships	9	Results on climate change resilience, mitigation and adaptation	1
Results on vegetation structure	8	Results on human health and well-being	1
Results on plant distribution patterns	7	Results on natural and climate hazard risk reduction	1
Results on vegetation distribution patterns	7	*Results:*	*34*
Results on plant biology and ecology	6		
Results on combined ecosystem effects	5	**Provide multiple services, incl. biodiversity benefits**	**Hits**
Results on naturalistic aesthetics	3	Results on aesthetic appreciation and inspiration for culture, art and design	17
Results on animal-site relationships	2	Results on habitat provision	13
Results:	*108*	Results on pollination	5
		Results on recreation and mental and physical health	4
High effectiveness and economic efficiency	Hits	Results on waste- and stormwater treatment	3
Results on vegetation management efficiency	22	Results on ecosystem disservices	2
Results on implementation efficiency	18	Results on food provision;	1
Results on local adaptation, social aspects	8	Results on biodiversity support	0
Results on efficiency evaluation and monitoring	8	Results on carbon sequestration and storage	0
Results on local adaptation, environmental aspects	8	Results on cultural ecosystem services	0
Results on local adaptation, policy aspects	5	Results on erosion prevention and maintenance of soil health and fertility	0
Results on tradeoffs between ecosystem services	4	Results on generic ecosystem services	0
Results on economic efficiency	3	Results on local climate and air quality regulation	0
Results on solution scalability	3	Results on medicinal resource provision	0
Results on adaptability in vegetation management	2	Results on moderation of extreme events	0
Results on efficiency through governance	1	Results on provisioning ecosystem services	0
Results on application connectivity	0	Results on raw material provision	0
Results:	*82*	Results on regulating ecosystem services	0
		Results on spiritual experience and sense of place	0
		Results:	*45*

Note that the total number of papers within each descriptive category may exceed the total number of papers overall.

insect-diverse urban vegetation type, while other types of native and non-native urban vegetation were found to host more diverse invertebrate communities [62,82,98]. There were also two studies highlighting that some plants are more attractive to pollinators than others [78,82], and one study assessed the effect of mycorrhiza on vegetation development [79].

Nine papers provided evidence related to plant-human-relationships. Several studies described the positive effects of weeding, thinning, and irrigation on target vegetation development [63,81,82,100], as well as how humans influence site conditions. These activities can either add or alleviate stresses and cause disturbances, which, in turn, influence the distribution of spontaneous vegetation, both positively and negatively [82–84]. Other studies have observed varying effects of management practices on grassland vegetation development [50,61,91].

3.3.1.3. Composite attributes of assemblages of organisms. Ten papers examined vegetation dynamics, and provided evidence on identified drivers of the observed dynamics [50,74–76,78,88], as well as observations of vegetation dynamics over time [50,63,77,86,97]. The presence of large, quickly reproducing taxa with a high potential to become dominant in an assemblage was identified as the most notable driver of vegetation dynamics [50,74,75]. Additionally, three studies noted a gradual decrease in species diversity over time [63,77,97].

Eight papers presented some evidence on plant distribution patterns, focusing on the effects of planting density [51,75,82,89,97] or sowing density [49,78,91] on vegetation development. Higher planting and sowing densities of target species were found to improve their establishment success and resistance to invasion [82,89,91], but had no influence on which taxa became dominant in the assemblages over time [49,75].

Eight papers reported results on vegetation structure [22,50,62,78,84,96,98,100]. Five of these papers elaborated on the topic of vegetation stratification or layering in designed plant assemblages. They highlighted the role of coexistence-promoting plant traits [49,100], a diversity of complementary traits [84,100], and vegetation management [22,100] as crucial drivers in developing and maintaining multi-layered vegetation.

Seven papers described survey and inventory-based observations of vegetation distribution patterns, and found that they were affected by a multitude of co-occurring natural and/ or anthropogenic site conditions and disturbances [22,60,61,83–85,92].

Two results [62,98] described vegetation structure in terms of plant-animal-relationships. Additionally, one paper found that layered vegetation may help maintain soil moisture levels [96].

3.3.2. Answer to societal challenges

Environmental degradation and biodiversity loss were explored in ten papers. Most of the results focused on exploring the use of non-native plant species and the risks associated with their invasiveness [51,74,76,78,82,84], or investigated the role of non-native vegetation as a habitat for invertebrates [22,62,82,101]. One study also sought to catalog local native biodiversity for use in nature restoration and urban sites [60]. According to the evidence in the analyzed literature, non-native plants are not automatically invasive nor necessarily ecologically detrimental [22,76]. While the use of native species is important as it caters to native specialist invertebrates, native generalist invertebrates have also been shown to benefit from non-native plant species, especially when structural complexity is secured [22,62,82,101]. On the other hand, the invasive potential of alien plant species should not be discounted [74,78].

Nine papers described results on “knowledge and social capacity building for sustainable urban transformation,” which can be divided into two broad clusters: 1) findings on data deficiencies, research gaps, and implementation problems relating to plant traits and site tolerances, ESS delivery by vegetation, as well as long-term vegetation development and its dependence on management actions [9,74,87,100,102], and 2) evidence of variation in different groups’ understanding of their environment [103–106]. People’s perceptions of and preferences for urban vegetation, both spontaneous and designed, were found to be influenced by factors such as socio-economic status, educational and professional background, gender, age, location, and previous experiences with different types of vegetation [103,104,106–108].

Nine papers provided insight into "green space management and urban place regeneration," focusing on optimizing irrigation and soil moisture for improved plant growth and resource effectiveness [82,95,96], and the use of spontaneous and semi-natural vegetation in urban green spaces [76,84,88]. Two papers provided results on trends in green space management [100,103], and one study investigated combining aesthetic value with biodiversity support in urban living walls [101].

3.3.3. Provide multiple services, including biodiversity benefits

3.3.3.4. Evidence on aesthetic appreciation and inspiration for culture, art, and design. Seventeen papers presented evidence related to aesthetic appreciation and inspiration for culture, art, and design. Two prominent topics emerged: 1) flowering as a proxy for aesthetic value [49,61,76–80,91,97,108] and 2) variation in people's perceptions of the visual aspects of urban vegetation, often depending on demographic variables [105–107]. The use of flowering as a measurement of aesthetic value was supported by the evidence that flowers are broadly appreciated by the public [78,91,108]. However, if flowering is a prioritized, it is important to look into possible correlations between sustained species diversity and flowering performance. Some studies found that decreasing target species diversity and density coincided with a decline in floriferousness [49,78,97].

Two papers studied methods for balancing insect diversity and visual attractiveness in urban vegetation [98,101], and two others mentioned increasing aesthetic value through structural and foliage interest [49,77]. Further results were provided on the following topics: mismanagement leading to unfulfilled design goals [90], differences in preferences and perceptions of spontaneous versus traditional ornamental vegetation [104], the use and identification of characteristic species from a reference habitat [61], the effect of foliage distribution on vegetation's visual vulnerability [61], and the minimization of colonizing plant species as a proxy for vegetation's visual attractiveness [78].

3.3.3.5. Evidence on habitat provision and pollination. Thirteen papers focused on "Habitat provision," with most papers examining plant diversity as a proxy for habitat value [22,50,63,76,77,79,82,87,98,109]. Other findings in this area explored insect diversity in vegetation, with both non-native and native species [80], the effects of mowing frequency on insect richness [98], the effects of mulching on invertebrate diversity [82], the value of indigenous graminoids for urban insect diversity [62], and the link between homeowners' appreciation for wildlife and the creation of habitat value in their stormwater ponds [110]. Five papers presented research on "pollination," with a similar focus to those on "habitat provision" [49,78,79,82,101].

The main findings from studies on habitat provision and pollination indicate that urban vegetation provides habitat for invertebrates [62,80,98], and that the attractiveness of ornamental plant taxa to pollinators varies [78,82]. Other results noted the positive effect of increased floral resource availability on pollinators [49,79]. This finding is consistent with the results of a systematic review by Wenzel et al. (2020) [111], which found that increasing floral resource availability, through either native or non-native plants in urban areas, improves the habitat conditions for generalist pollinators. One paper also studied via modeling how color theory could be combined with provision of floral resources for pollinators [101], yielding positive results.

3.3.3.6. Evidence on waste- and stormwater treatment. Two papers addressed "waste and stormwater treatment," finding that the success of stormwater quality and quantity treatment on green roofs was more dependent on the construction of the green roof than on the vegetation type. However, vegetation cover density and horticultural versus native origin of plants were also found to play smaller roles in the end result [79,112]. Additionally, one study investigated homeowners' attitudes toward residential stormwater ponds [110].

3.3.4. High effectiveness and economic efficiency

3.3.4.7. Evidence on vegetation management efficiency. Twenty-two papers provided evidence on "vegetation management efficiency" through three identified topic clusters: 1) the effect of mowing on vegetation development [49,50,76,78,90,91], 2) the effect of irrigation on vegetation development [78,79,82,93,95], and 3) experiences or perceptions of naturalistic vegetation management, which varied among park managers, green industry professionals, and homeowners [100,103,110]. The effects of mowing on vegetation development varied across studies, partly depending on whether the research focused on North American prairie vegetation or Eurasian meadow and steppe vegetation [50,76,78]. The positive effects of irrigation, on the other hand, seemed to persist across study sites [82,95,96], although any evidence-based watering recommendations will need to be geographically adapted [79,82,95].

Individual papers presented findings on various topics, including long-term plant taxon persistence and richness with low management [63,74], the benefits and drawbacks of herbicide use [91], the effect of management flexibility in biodiversity support [22], the effect of lawn height on aesthetic and biodiversity goals [98], the use of creeping plants as weed deterrents in intercropping systems [113], weeding needs and procedures in sown annual vegetation [81], the effect of management actions on spontaneous taxa assemblages and their distribution [84], and the impact of management on the distribution and abundance of plants from different geographical origins in urban areas [62].

3.3.4.8. Evidence on implementation efficiency, evaluation, and monitoring. Three topic clusters were identified from eighteen papers studying "implementation efficiency": 1) semi-natural herbaceous vegetation establishment methods [49,50,78,81,91,93], 2) variable recommendations for green roof vegetation system choice [77,79,89,112], and 3) the benefits of digital plant selection schemes in planting design, despite their external validity and real-life benefits being unverified thus far [87,92,101]. Pre-treating meadow sites through soil removal, herbicides, or tilling, as well as using mineral mulches, were found to benefit the establishment and mid-term development of semi-natural herbaceous vegetation, especially in the absence of selective weeding [49,50,78,81,91,93]. Individual papers also provided insights into taxon persistence in the long-term [74], differences in soil temperature and moisture retention due to mulch type [96], the effect of planting density on wind and drought resistance [82], the influence of initial design parameters on vegetation development goal fulfillment [49] even without management [100], the use of GPS in mechanized plant bed construction [92], and the effect of intercropping on agricultural productivity and management needs [113].

Research papers reporting on efficiency evaluation and monitoring emphasized the differences between long-, and short-term vegetation development, and the resulting need for long-term monitoring to gather evidence on design impacts [74,75,77,90,97]. One paper emphasized the importance of monitoring and evaluation, especially for planting projects that are a part of developing digital modeling methods [92]. Other results pertained to the usage of monitoring as a tool for evaluating and validating modeled plant water needs [95], and the influence of sampling methods on invertebrate observations [82].

3.3.4.9. Evidence on local adaptation. Eight papers examined "local adaptation, social aspects," revealing that local trends in DPC perception were influenced by several variables. These included educational and professional background, gender, age, location, previous experiences with vegetation, views on environmental issues such as climate change, and aesthetic preferences [104,106–108]. Other results related to the effect of socio-economic variables on participation in park vegetation management [103], design professionals' attitudes toward different dimensions of urban green infrastructure [102], differences in how homeowners and different professional groups view residential stormwater ponds [110], and combining homeowners' interests with bird habitat provision in gardens [109].

Seven papers explored "local adaptation, environmental aspects," most of which related to the influence of local, regional, and temporal climate variables on vegetation development and management [80,82,93,95]. For example, Alizadeh and Hitchmough (2020)[80] found in their study that, in climate change scenarios where temperature may increase and precipitation may increase or decrease, water availability had a greater impact on plant growth than temperature. Plants from drier climates performed worse in wetter conditions, whereas plants from more humid climates benefited from additional water. Other papers highlighted the promotion of local spontaneous vegetation use in urban areas as a link to connect plant life with their surrounding environments and site conditions [60,88], and the use of site inventories of local vegetation as a basis for developing digital plant selection schemes [92,94].

4. Discussion

Although vegetation is a key aspect of urban NbS, few studies have explored how planting design and urban vegetation management can be used to enhance the performance of NbS [4,5]. To assess how designed urban vegetation might improve NbS performance, we first assembled planting design and vegetation management approaches that integrate cultural, ecological, and economical goals under a framework called "designed plant communities" (DPC). The framework has its origins in practical planting design practices and has also been studied in academic settings. To define the DPC framework, we identified a number of common denominators in the DPC literature, which we formulated as five objectives for planting design and vegetation management and four performance goals for designed vegetation. Interestingly, the identified DPC objectives and goals align with the four NbS criteria outlined by Sowińska-Świerkosz and García (2022) [35]. Based on our review of 51 papers, we found that while DPC research provides evidence on each of the four NbS criteria, it has a particular focus on aspects pertaining to the criterion "inspired and powered by nature," and little focus on "answering to societal challenges."

Based on the variety of research methodologies and focus areas in the analyzed papers, research on DPC can be characterized as a multifaceted field of study. The reviewed DPC research further covered a broad range of vegetation types and vegetation applications, although not all types of NbS units [114] were represented. DPC research has been conducted on four different continents, but a bias toward research from Europe, especially Great Britain, limits the generalizability and applicability of results across diverse climates and cultures.

The analyzed DPC articles combined provide scientific evidence supporting the fulfillment of each of the four NbS criteria. This suggests that research within the DPC-framework recognizes the importance of multifunctional, efficient vegetation applications that address societal challenges. On the other hand, only a few papers offered evidence pertaining to all four NbS criteria. The reviewed papers on DPC also provided relatively little evidence for the criteria "answer to societal challenges" and "provide multiple services, including biodiversity benefits." Beyond amenity values and biodiversity support, other ESS provided by urban vegetation have received little attention in DPC research thus far. This limited focus on the performance dimensions of urban vegetation indicates the unassessed potential of DPC as a contributor to NbS. The analyzed body of DPC research thus shows that the DPC framework does not yet provide sufficient evidence to reliably enhance the performance of vegetation in NbS.

4.1. DPC objectives and goals vs. evidence on DPC performance

DPC are often argued to be based on scientific knowledge [42,72,115], such as ecological principles [65,70,116] and human perceptions of urban vegetation [59,117,118]. These claims suggest that designers should have access to reliable site analysis methods and a comprehensive body of evidence on plant attributes. However, several of the analyzed papers highlight the absence of such resources [9,87,92,102]. Thus, the scientific evidence base needed to realize many of the design and management objectives, and, in turn, the performance goals, remain narrower than the DPC framework portrays. Building the scientific evidence base for DPC is further hindered by the lack of a clear definition or a broadly agreed, unifying name for the framework. This made a systematic literature review impossible and created a need for a scoping review process, involving multiple steps for literature search and screening (Fig. 2; see also Table 2).

It should also be noted that as most DPC have not been created as NbS, they cannot be considered NbS nor be judged as NbS according to the NbS exclusion criterion of "random actions" [35]. However, evaluating and judging DPC using the framework's own objectives and goals can still provide useful information for creating and managing future vegetated NbS. If the DPC framework can attain its own objectives and goals, it can also contribute to the corresponding aspects of each NbS criterion.

4.1.1. Low maintenance needs through self-regulation

The DPC framework suggests that vegetation management needs can be reduced through design decisions that promote plant fitness to the site, coexistence among plants, improve resilience, and resist invasion [41,119]. Within gray DPC literature, these design decisions are often facilitated by using systematic plant selection frameworks, such as the Garden habitat-system, or by referring to the C-S-R-theory as a guide for plant selection [55,66–68]. In scientific literature, approaches based on plant functional traits have been recommended as tools to determine plant fitness to the site [9,120], explain and predict competition [75,78], indicate initial establishment and development success [121,122], and assess the invasiveness of plant taxa [123,124]. Thus, detailed knowledge of plants, the site, and planting patterns is a prerequisite for achieving low maintenance requirements [40].

Another key aspect of the DPC framework relating to management needs is the consideration of the planting as a structurally complex, multi-species vegetation unit, rather than a collection of individual plants [40–42]. Finding ways to facilitate plant coexistence and slow down changes in plant diversity and assemblage composition over time [49,74,75,78] can be conducive to retaining the ecological, aesthetic, and technical performance of designed vegetation in NbS. As decreased competitive stress and increased site productivity help to retain plant diversity while also promoting growth and blooming [51,63,77–82,125], it would be useful to identify the optimum balance between the positive effects of productivity-increasing interventions, the costs of these interventions, and the potential negative effects of increased interspecies competition.

Scientific literature highlights significant knowledge gaps in matching plants to sites [87,92], despite site adaptation being the most frequently investigated subject in DPC studies. For example, few empirical in-situ-experiments or case studies present a clear rationale for their plant selection (or substrate choice), making it difficult to evaluate the site adaptation of the studied plants [55,65,66,68]. On the other hand, anecdotal evidence on plant tolerances and the effects of site adaptation on vegetation performance is widely available [7], as are results from surveys of spontaneous vegetation composition and distribution [22,60,61,83,84,86,92] that show the influence of site conditions on plant assemblages. Detailed trait data is also available for a wide range of plants [126,127], although data on plants of horticultural origin, including cultivars and horticultural proveniences, is currently lacking. For DPC creation, this means that the available evidence base is insufficient for making certain claims of fitness between any given plant and/ or sites [7]. This lack of evidence also makes extrapolation of claims on the positive effects of site adaptation on vegetation ecosystem service delivery and management efficiency unsound [9], especially since none of the analyzed papers explicitly studied site adaptation or its effects on ecosystem service delivery or management needs (although see [80]).

4.1.2. Provision of cultural ecosystem services

Cultural and aesthetic values in the context of DPC are usually approached through the visual attributes of vegetation. Factors such as a spatial configuration in relation to the observer, plant habit, texture, leaf color, and overall composition are often considered equally, or even more, important for the experience of vegetation than flowering (e.g., [128–130]). Vegetated NbS that aim to be adapted to local social contexts, thus, need to look beyond just flowering and explicitly consider how multi-sensory stimuli, local culture, demographic attributes, history, and values influence the experience of urban vegetation [103,104,106–108,131]. Besides community involvement, familiarization, and education [103–106], neutral and positive attitudes toward wilder-looking vegetation may be attainable through appropriate framing and enhancement actions [88,103,132,133]. Further research on adapting vegetated NbS to different socio-cultural contexts should focus on finding participatory methods to triangulate project-appropriate prioritizations between the social, technical and ecological functions of NbS. Moreover, efforts should be directed toward finding ways to improve the local cultural relevance of vegetated NbS while retaining the intended technical and ecological performance.

4.1.3. Provision of regulating ecosystem services

Both gray DPC literature and the analyzed papers approached regulating ESS mostly through green roofs [63,77,79,82,87,89,97,112,134,135] or stormwater management applications [41,110,136–138]. Among these, stormwater management was the only regulating ESS for which the analyzed literature provided evidence. However, the relative scarcity of evidence on the performance of DPC in stormwater management applications is in contrast to the substantial body of research on the role of urban vegetation in stormwater management in general (e.g., [136,137,139–142]). For example, Charoenkit and Piyathamrongchai (2019) [143] found in their review that flood mitigation was the second-most studied ecosystem service in research on multifunctional urban green spaces, after recreational value. Other regulating ESS, such as local climate and air quality regulation or erosion control, have not gained much attention in DPC literature thus far. The potential of DPC to provide regulating ESS is thus largely unexplored. Furthermore, there is little scientific guidance on how to design DPC that contributes to the delivery of specific technical functions, even in applications studied as stormwater management.

4.1.4. Supporting biodiversity

The general tendency in DPC literature is to focus on plant biodiversity and the support of invertebrates, especially through the lens of comparing the pros and cons of native versus non-native plants in urban areas [42,144,145]. The analyzed studies reflect these foci by providing general evidence on the fact that urban vegetation can be diverse and does provide a habitat for invertebrates [62,80,98]. However, the analyzed DPC literature does not offer evidence for organism groups other than invertebrates, nor does it establish a link between urban plant diversity and habitat provision, despite DPC literature often implying such a correlation [43,57]. Factors that influence pollinator abundance and richness in urban areas beyond floral resource availability [111] are not considered either. Furthermore, to promote the multifunctionality of vegetated NbS, further research is needed to understand how to balance vegetation complexity for habitat value with perceived safety and amenity values, as well as management methods and costs [22]. Thus, the current evidence base gives a few clues for NbS planting design that would optimize habitat value.

4.2. Characterizing the current scientific research on DPC

The breadth of studied vegetation applications, research focus areas, vegetation types, and geographical distribution suggests that the DPC framework has broad relevance for a variety of purposes, habitats, and bioregions. The variation in research methods also highlights how the different dimensions of DPC performance require different research designs to take into consideration experiential qualities as well as to cover a wider range of variation in site ages, locations, and development histories.

The range of studied vegetation applications covers several urban NbS unit types [114]. Most studies concern large-scale applications suitable for parks or green roofs, whereas studies on street-scale vegetation are completely absent. This is notable, as multi-layered urban street greening has considerable potential to deliver multiple benefits in a decentralized manner [146,147], not least through the implementation of stormwater management facilities such as rain gardens. A cross-referencing of vegetation applications and research focus areas shows fairly little overlap between studies: notably, 43 % of the papers present a novel approach to combining vegetation applications and focus areas, either in isolation or in conjunction with one additional study. DPC preference and perception, as well as ornamental meadow design and meadow vegetation establishment, are among the most studied topics, and can be considered to be emerging research areas in their own right.

The papers show notable variation in the level of detail and categorization systems used for vegetation types. This makes comparisons across papers difficult, except at the species-specific level. Notably, 91 % of the studied papers included species-specific information as a part of their research study. This is contrary to the findings from a prior review of the ESS provision by urban vegetation, which reported that only 32 % of all the reviewed papers described specific species [5]. Besides improving comparability, including species-specific information also aids the development of evidence-based planting designs for NbS. Such data provide valuable information on how plant species' behaviors, responses to treatments, and ESS delivery can vary between studies and geographic locations (e.g., [49,50,74,79]).

The current use and focus of DPC research is largely based in Europe and Great Britain, which can be related to the origin of the New Perennial Movement [40,44,66,148] and Sheffield University's strong representation in the analyzed literature [49,77,78,80,89,91,97,99,103,149]. On the other hand, the bias of the literature toward studies from the Global North and the focus on humid temperate climates limits the generalizability of the results [5]. Another artefact of this geographical distribution is the effect of locality on the categorization of plants into exotic and native, invasive or non-invasive. Any application of taxon-specific evidence from the analyzed studies must, thus, consider the differences between policies and climatic factors in the studies and the current project site to assess the appropriateness of the use of each taxon. Research on the connections between vegetation development, site conditions, and plant traits in urban NbS should also promote the study of plant taxa that are already widely used locally to improve the applicability of the results [7].

In the analyzed literature, experimental methods were the most common. As most of the studies that used field experiments were influenced by non-controlled variables, characterizing them as quasi-experiments might be more accurate. Experimental DPC research also tended to include at least three and up to 12 research questions, which resulted in numerous treatment combinations and a relatively low sample size in terms of replicates. Consequently, many papers acknowledged difficulties in interpreting results, as interactions between controlled variables and uncontrolled variables are difficult to disentangle. On the other hand, DPC research is often intended to cater to landscape and planting design practitioners. Including and acknowledging the complexities of real life designed vegetation may thus make the results of quasi-experiments, case studies, site surveys, designed experiments [150–152], and even applied research published in non-peer-reviewed publications (e.g., [125,153–155]) more practically applicable than strictly controlled experiment results. Nevertheless, more focused studies with fewer research questions and variables are still needed to study causal relationships that can be used in formulating best practices.

4.3. Support for NBS criteria fulfilment in the DPC evidence base

The criteria for NbS, as defined by the IUCN [1] and the EU [27,34], as well as the synthetized criteria by Sowińska- Świerkosz and García (2022)[35], are strictly defined, forming a multilayered framework that few projects can fully satisfy, especially given the often very short timeframes for project responsibility assigned to a landscape designer or contractor. Above all, the requirements of evaluating NbS efficiency and effectiveness in a life-cycle perspective mandate long follow-up periods to decide whether a project result can be called a NbS at all [35]. While this can be seen as a weakness, the strict criteria also serve to protect the concept of NbS from greenwashing [156], as the inclusion of verified functionality excludes failed exemplars from the concept altogether. This duality can also be seen as both a challenge and an opportunity for developing evidence-based planting design and management practices that facilitate the creation of NbS. The challenge becomes that the use of scientific evidence in the design process does not inherently create or improve vegetated NbS; the opportunity is that vegetated, nature-based applications, even those created through insufficient evidence, may prove to be functional as NbS in practice.

4.3.1. Inspired and powered by nature

Humans influence urban vegetation through the modification of site conditions and disturbance patterns, both inadvertently and through design and management actions [22,61,83,84,157]. Due to the lack of *in-situ* supra-urban DPC research, there is little evidence that could aid in creating site-adapted vegetation for urban NbS that can withstand challenges such as deicing salt, air-, and waterborne pollutants, domestic animals, and soil compaction. The role of planting patterns and vegetation structure in DPC performance has not been sufficiently addressed in the analyzed literature to infer how these might be designed or managed to enhance vegetated NbS. Particularly, the drivers of vegetation layering and the impact of more structurally complex vegetation on NbS performance should be further studied. The structural complexity and diversification within DPC, as results of both design decisions [49,50,100] and management actions [22,100], should be investigated. This also means that site-survey-based research on designed vegetation needs to be complemented with design documents and information on realized management, similar to the study by Richnau et al. (2012) [100], to more accurately determine the effects of initial site conditions and management actions on the observed outcomes.

The development of NbS could also benefit from further studies on the effects of site productivity, stress factors, disturbance, and plant fitness to site on ESS delivery. Currently, there seem to be three obstacles to fully realizing the potential of improving plant selection efficiency: a) Insufficient coverage and quality of plant data, both in terms of biological attributes and performance metrics [7,87,116,158]; b) Lack of tools for analyzing site conditions in a manner that directly correlates with data on plant site tolerances and resource needs; and c) a lack of designerly and ecological parameters for creating DPC, which are necessary for predicting plant-plant-relationships and thus optimizing the long-term vegetation dynamics and structure [159].

4.3.2. Answer to societal challenges

The characterization of the DPC framework and the analysis of its potential contributions to NbS criteria fulfillment point in a similar direction: addressing explicit societal challenges is not high on the DPC agenda. In the light of the analysis results, this does not seem to be due to ignorance or disinterest in societal issues. Rather, the body of analyzed literature shows tendencies towards more exploratory studies than on research aimed at solving specific problems. Thus, few of the analyzed papers [95,112] set out to define performance metrics for designed vegetation, and none have compared the results against established indicator values to verify the magnitude of contributions. This makes assessing the potential of DPC to address societal challenges impossible [27]. Future research that aspires to investigate DPC performance in and as NbS, particularly via ESS measurements, would do well to reflect on the results from the perspective of relevant societal challenges. By doing so, such studies can better connect them to the larger discussion on how to tackle local and global environmental, economic, and social problems.

There is an awareness of significant knowledge gaps surrounding DPC creation, such as insufficient data availability on plant traits and site adaptation, and a poor understanding of how biodiversity/ functional diversity influence ecosystems [87,160]. Uncertainties in basic plant ecological definitions, such as plant communities [161–164], ecosystem functionality [165], and functional traits [166], are in itself hindrances to defining and designing DPC with predictable performance. Gaps in understanding plant fitness also prevent the reliable selection of “right plant to right place,” which, in turn, makes it impossible to guarantee that DPC would help to make NbS more adapted to local site conditions. Radhakrishnan et al. (2019) [102] also note that more research is needed to ascertain the functionality and sustainability of vegetation as green infrastructure in a life cycle perspective. This may also be related to the lack of data on vegetation management that could be used to develop theories on the effects of management actions on vegetation development [160] and ESS provision [102]. Additionally, Richnau et al. (2012) [100] found that improved knowledge availability alone is not enough to change vegetation management praxis toward improved performance, as the knowledge needs to be implemented from early on for it to have the intended impact on vegetation development. These knowledge gaps are in no way unique to the DPC framework, nor are they limited to non-native vegetation and novel ecosystems in urban areas [167,168]. The primary challenge for planting design and vegetation management is to fill these knowledge gaps as soon as possible, while also finding viable ways to address societal challenges despite the existing knowledge gaps.

4.3.3. Provide multiple services, including biodiversity benefits

The focus of the analyzed literature on aesthetic appreciation and its inspiration for culture, art, and design is logical, as the DPC framework is firmly rooted in ornamental planting design [119]. However, the DPC framework also aims to combine aesthetic value with habitat provision for animals and promote human health and well-being [40–42,56,169]. Additionally, there is increasing interest in contributing to regulating ecosystem services [170], especially urban stormwater management [41,136,138]. Despite this, only a portion of the analyzed literature explicitly states ambitions to achieve multifunctional urban vegetation [72,87,102], with Droz et al. (2021) [79] alone focused on verifying multifunctionality. The lack of explicit reflections on how the results affect vegetation multifunctionality, and the dearth of contextualizing study results in terms of contributions to solving societal challenges, might stem from the same main issue: few papers set out to solve specific societal problems or assess specific ESS delivery. To overcome this, embedding NbS-relevant performance goals and measurements [27] into DPC research could help formulate more goal-oriented inquiries on synergies and trade-offs between biophysical variables, the delivery of multiple ESS, and the overall effectiveness and efficiency of urban vegetation within the DPC framework.

4.3.4. High effectiveness and economic efficiency

The analyzed literature provides relatively little quantitative data on the efficiency of vegetation management across management measures [90,91]. Management interventions are key to plant survival in urban spaces [82], but there are maintenance habits and conventions in place that overestimate and oversimplify management needs [95]. Among other things, this can limit the role of spontaneous vegetation as an alternative or complement to designed vegetation [84,88]. On the other hand, at some point, management costs may eventually override the benefits it has on vegetation development, e.g., through decreasing drought stress or limiting competition within plantings.

None of the analyzed studies provide comparative data on the management costs of DPC versus vegetation composed outside the framework. The analyzed literature also fails to provide a baseline for how much urban vegetation management can be expected to cost, either in terms of time, natural resource use, staff skill, or money. This makes the efficiency of vegetated NbS difficult to evaluate, both in theory and in practice. Evidence on DPC management costs would also be needed to guide decision-making when designing vegetated NbS. As long as clearly defined, measurable metrics for vegetation management needs in relation to their expected performance are not specified in the studies, their results are difficult to contextualize and compare. In particular, the impact of management staff skills on management costs, vegetation development, and NbS performance stand out as a topic that warrants further investigation [100,103,125]. Thus, the claim that DPC would have especially low management needs is neither supported nor refuted by the results.

The results from the studies on suitable establishment methods for semi-natural herbaceous vegetation provided in the papers are practically actionable, and could be used to inform best practices for choosing soil and mulches [49,81,91], pre-treating sites for ornamental meadow establishment [50,78,93], deciding between sowing and planting [49,78], and determining sowing densities and timing [78,81,91], at least in Northern and Central Europe where the studies were conducted. However, it should be noted that evidence regarding the effects of mowing on vegetation development is partially contradictory, with varying results depending on the geographical location of the study and the origin of the target vegetation [49,50,76,78,90,91]. The effects and effectiveness of mulching warrant more research to better understand the balance between mulch improving target vegetation establishment from seed [91], and mulch deterring the establishment of unwanted spontaneous vegetation [89].

NbS projects are increasingly expected to include evaluations of their development and performance over time [27]. Effective evaluation and monitoring are contingent upon reliable methods, funding, and clearly defined design and follow-up parameters [27,33]. In this light, it is strange that most of the papers that present experimental studies fail to provide clear rationales or methods for their plant selection. Similarly, only a few of the analyzed papers that describe plant selection methods or frameworks test these approaches, either on a theoretical or practical level. More refined digital plant selection tools could make the design process faster, but there seems to be no evidence yet that it would make the design results more effective in achieving the intended goals compared with traditional methods of manually gathering and applying plant and site data [87,92,101]. In both cases, the planting design method and its impact on outcomes remain impossible to evaluate. To improve DPC research on these topics, greater transparency in experimental planting design should become standard protocol, and proposals for plant selection schemes should be tested at least by modelling or expert testing, if not directly applied in practice.

As long-term studies lasting for >3 years were relatively few, it is also difficult to evaluate how DPC and their performance develop over extended periods. Evidence of gradual declines in plant diversity and the role of management in mitigating or slowing down this effect indicates that maintaining diversity-dependent ESS delivery in herbaceous vegetation will require some level of ongoing management. Furthermore, research evaluating the long-term efficiency of DPC as NbS should consider multiple parameters that could influence ESS delivery, such as possible correlations with biomass production or dependencies on specific plant taxa of special local cultural or ecological value.

5. Conclusion

The significant knowledge and research gaps identified within the DPC framework in this study clearly show the immaturity of the concept as a research field, a theoretical design framework, and as a design and management practice. More work is needed to develop the concept of DPC toward a set of tested and corroborated tools that can help researchers, designers, and green space managers in optimizing vegetated NbS for multiple ecosystem services. Some of the knowledge gaps within DPC could be addressed through synthesis and application of evidence from contemporary research in plant community ecology, environmental psychology, and urban green area governance. Research on applications that incorporate DPC into urban stormwater management, green roofs, or other established NbS types would, in turn, benefit from a deeper understanding of these specific research fields. Additional work is also needed to strengthen the evidence base specific to the practical implementation of the DPC framework, helping to further develop multifunctional urban vegetation design and management.

The strengths of the DPC framework that might aid in creating better vegetated NbS are that it covers a wide variety of vegetation types, its awareness of the possible contributions of vegetation to addressing multiple societal challenges, its dual focus on plant ecology and cultural ecosystem services, as well as its understanding of the multiple interactions influencing vegetation development and performance. However, the weaknesses of the DPC framework stem partially from its lack of commonly accepted terminology, which makes it difficult to assess the full scope of DPC research. The low number of researchers engaging with the subject also contributes to an uneven geographical distribution of studies and a tendency to incorporate numerous research questions and experimental variables in individual studies. Assessing the potential of DPC in and as NbS is also made difficult by the framework's relatively limited interest in verifying its effectiveness and efficiency, at least in the light of the results of this review. Refocusing future DPC research to explicitly incorporate performance metrics in terms of ESS delivery, as well as implementation and management costs, should be prioritized if it is to contribute to NbS development. Intentionally building research communities and programs for studying urban vegetation would allow more efficient knowledge generation and thus hasten the optimization of vegetated NbS.

Impacts and implications

The review uses the four NbS criteria as described by Sowińska-Świerkosz & García (2022) as the main analytic framework for the review, thus covering environmental, economic and social concerns throughout the manuscript. Based on the review, we highlight following results:

Social impacts and implications

Designed plant communities seem to be capable of combining the delivery of both biodiversity and amenity values through structural complexity and flowering performance, but their potential to provide regulating ESS delivery simultaneously has gained little attention in research thus far.

Environmental impacts and implications

There is a clear trend of plant diversity decreasing in designed vegetation over time. The decrease has been found to slow down or even reverse with the help of management interventions such as watering or weeding, indicating that upholding diversity-dependent NbS functioning may require regular management.

Economic impacts and implications

We found no papers explicitly describing the dependence of ESS delivery on vegetation management actions, which indicates a notable knowledge gap on the economical resources needed to uphold optimal NbS functioning over time.

CRediT authorship contribution statement

Ella Uppala: Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Johanna Deak Sjöman:** Writing – review & editing, Methodology. **Tobias Emilsson:** Writing – review & editing. **Marcus Hedblom:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Supplementary materials

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Data availability

Data will be made available on request.

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