Designed plant communities for nature-based solutions

An investigation of urban rain gardens

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Licentiate Thesis
Swedish University of Agricultural Sciences
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Designed plant communities for nature-based solutions

An investigation of urban rain gardens

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Abstract

Healthy and diverse vegetation is the prerequisite for "nature-based solutions" (NbS), which is a concept that describes the intentional use of designed or managed vegetation to answer to societal challenges by providing multiple ecosystem services simultaneously and efficiently. Urban rain gardens (URG) are an example of a nature-based solution where vegetation is used to improve technical function, provide amenity values, and wildlife habitat.

This thesis investigates the relevance of "designed plant communities" (DPC) as a framework for designing and managing URG vegetation. The investigation consists of 1) a narrative literature review on the history, core ideas and design tools of DPC, 2) a scoping review on DPC research and its contributions to NbS criteria fulfillment, 3) semi-structured interviews on the strategic management or URG:s in Sweden and Finland, 4) designed case studies comparing four different plant selection strategies, including DPC, with regards to their short-term establishment and development, and 5) a data collection on vegetation development in URG:s in Sweden and Finland.

The narrative review highlights knowledge gaps that hinder the DPC framework's planting design tools from reliably aiding in fulfilling DPC objectives and goals. The scoping review shows that while research on DPC provides insight into urban vegetation establishment and its short-term development, it is rarely anchored in the societal challenges that NbS seek to address, and provides little evidence on how DPC provide regulating or provisioning ecosystem services. The interview results show the unpredictability of URG vegetation development, despite the innovation and effort often put into creating URG:s. The results of the case studies also indicate that while DPC-plantings can establish and perform as well as other planting design strategies in the short term, it is not an inherently successful planting design strategy.

As realized performance is more important for NbS than adherence to specific design methods, developing the DPC-framework into an evidence-based planting design practice might improve design outcomes and the framework's relevance for NbS.

Keywords: designed plant communities, nature-based solutions, planting design, rain gardens

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1. Introduction: Designed plant communities for urban nature-based solutions

1.1 Background

Climate change and continuing urbanization are causing increased pressure on urban green spaces in terms of diminishing area, increasing usage and higher demands on ecosystem service delivery (Kabisch et al. 2016; Randrup et al. 2021). As cities densify, these patterns are exacerbated by diminished shade, sealing of surfaces, urban heat island effect, and increased wear from people and pets (Grimm et al. 2008; Fu et al. 2022). To compensate for the loss of vegetation in cities, the remaining urban green spaces are expected to perform as multifunctional nature-based solutions (NbS) that are resilient, deliver multiple ecosystem services, and help mitigate climate change and urbanization-induced environmental risks and problems (Pauleit et al. 2017; Raymond et al. 2017). Yet, green space management budgets are not expected to increase to compensate for these challenges (Randrup et al. 2021). Further, there is little guidance available on planting design and vegetation management principles that would improve the establishment success, longevity, and multifunctionality of urban vegetation (Oliveira Fernandes et al. 2025).

Urban rain gardens are an example of nature-based solutions for climate adaptation (Blecken et al. 2017; Dagenais et al. 2018; Beryani et al. 2021; Vijayaraghavan et al. 2021). They are vegetated, open stormwater management facilities placed among hard surfaces, usually less than 300 sqm in size, and with distinct ornamental functions (Davis et al. 2009; Backhaus & Fryd 2013; Dagenais et al. 2018; Jones et al. 2022). Urban rain gardens are thus a combination of plants, microbiota, soils and engineered structures that are designed to capture and detain stormwater and to remove pollutants from it before the water is led further in the stormwater management system (Muerdter et al. 2018; Beryani et al. 2021; Ma et al. 2021; Yang et al. 2022). Urban rain garden vegetation can contribute to the solution by reducing the amount of stormwater, through nutrient uptake, by providing habitat not only for micro-organisms that can remediate pollutants but also for birds and invertebrates, and by adding amenity values like visual pleasantness, cultural values or microclimate regulation to the solution (Kazemi et al. 2011; Backhaus & Fryd 2013; Nocco et al. 2016; Yuan et al. 2017; Winfrey et al.

2018; Morash et al. 2019; Johnston et al. 2020; Laukli et al. 2022b; Helmreich et al. 2025). While urban rain garden vegetation has received considerable research attention in the past twenty years, many research gaps related to plant species, substrates and the suitability of solutions for different climate zones persist (Kõiv-Vainik et al. 2022; Laukli et al. 2022b; Mantilla et al. 2023; Corduan & Kühn 2024).

As plants are the key to attaining multifunctional urban green spaces, the scarcity of scientific evidence on urban planting design and vegetation management, combined with the tough growing situations plants face in urban areas, threaten vegetated NbS performance (Van Mechelen et al. 2015; Emilsson & Ode Sang 2017; Watkins et al. 2021). Additionally, the relative lack of species-specificity and reporting on site conditions in research on the services and benefits of urban vegetation can reduce the applicability of current research results, as ecosystem service delivery varies by plant species, vegetation composition, and site attributes (Filazzola et al. 2019; Fu et al. 2022; Stroud et al. 2022; e.g. Dickinson & Hobbs 2017; Hoyle et al. 2019; Kafle et al. 2022). Thus, it is vital to investigate how the professional practice and current knowledge base on urban planting design and vegetation management might help cities mitigate these threats, and how future research can improve design and management outcomes so that vegetated urban NbS can be realized. An interesting approach to planting design and vegetation management is the designed plant communities-framework, which combines ecological knowledge and landscape design skills to create multifunctional urban vegetation (Hitchmough & Dunnett 2014; Rainer & West 2015; Hansen & Stahl 2016). Designed plant communities (DPC) are multi-species plant assemblages intended to cater to human interests, while also being expected to develop and maintain their intended capabilities with minimized human intervention (Hitchmough 2014:131; Hansen & Stahl 2016:5–6). Thus, the DPC-framework has the potential to aid in solving the challenges faced by urban vegetation.

The thesis will describe some of the different aspects of planting design processes within the DPC-framework, as well as the forces influencing vegetation development and performance in urban NbS. Urban rain gardens (URG) are used in this study as model NbS, as they are at the nexus of four societal challenges: Climate resilience, water management, green space management and urban place regeneration (European Commission 2021).

The focus of the studies is on herbaceous perennial plants, although woody perennial plants are also featured in all the studies.

1.2 Designed plant communities

"Designed plant communities" ("DPC") (Dunnett 2014; Hitchmough 2014:173) is used in this thesis as a concept that describes species-rich, often ornamental plant assemblages that employ ecological understanding to intentionally utilize natural processes for the development of dynamic vegetation with naturalistic appearance (Kingsbury 2009:3; Dunnett 2014:245; Morrison 2014; Rainer & West 2015; Hansen & Stahl 2016; Köppler 2017). DPC are often associated with species-richness and large-scale plantings of herbaceous and semi-woody perennial forbs and grasses, but the framework also includes woody vegetation and short-lived herbaceous plants (Borchardt 1998:236; Hansen & Stahl 2016:48; Heinrich & Messer 2017:9). The DPC-framework can be used broadly to describe the wider field of ecological planting design (Forbes et al. 1997; Woudstra 2014), an umbrella term for naturalistic planting design approaches (Kingsbury 2014), or in a more narrow sense as a planting design framework that is explicitly connected to and drawing from the "New Perennial Movement" of the 1980's and 1990's (Kingsbury & Oudolf 2015). For the purposes of this thesis, DPC includes aspects of both naturalistic planting design (i.e. designed vegetation that seeks to embody some of the formal and visual qualities of spontaneous plant communities) and ecological planting design (i.e. designed vegetation that intentionally positions itself within the ecological processes on a site)(Forbes et al. 1997:87; Kingsbury 2014; Robinson 2016:181). The use of "designed plant communities" instead of its many synonyms (see Table 1 and Table 2) is a callback to Hansen & Stahl's "*Pflanzgemeinschaften*"; it highlights the intentional and creative anthropogenic aspects of the work by "design", and it evokes the ecological aspirations through "plant communities". Despite a lack of scientific consensus on the definition of "plant community", "plant communities" is used here to denote that the goal is to design holistic vegetation that is greater than the sum of its parts aesthetically, ecologically and functionally (Underwood 2008; deLaplante & Picasso 2011). Yet, it might be more productive to consider DPC as plant assemblages, which are non-deterministic combinations of plants that co-exist at specific places and times, and that can have positive, negative or neutral interactions with each other (Allaby 2010b; Robinson 2016). Vegetation management, including short-term maintenance and the planning of long-term development, is considered in this thesis as an instrument for design (Cobham 1990:332; Robinson 2016), and is thus generally included in the term "design" throughout.

When taken at face value, the DPC-framework could be described as follows: In the DPC-framework individual plant development, interactions between plants, interactions between vegetation and site conditions, as well as the interaction between plants and people should enable fulfilment of project-specific goals (Borchardt 1998:235; Hitchmough 2014:131; Rainer & West 2015; Köppler 2017:7). The choice of species for planting or sowing gives the starting point to the development of vegetation structure and aesthetic attributes, which are then further developed over time through spontaneous ecological processes and management (Borchardt 1998:235; Hitchmough 2014:164, 167; Hitchmough & Dunnett 2014:8; Hansen & Stahl 2016:5). The resulting vegetation should be easy to manage, diverse, stable and resilient, adapted to their sites, and provide rich sensory experiences to the people who live with the plantings (Borchardt 1998:235; Hitchmough 2014:131; Hansen & Stahl 2016:5–6; Tabassum et al. 2020). Some degree of fluctuation and changes in plant species composition and plant distribution in DPC is anticipated and accepted, although much of the design process does aim to limit change to an extent where the original design intentions can still be maintained (Dunnett 2014:245; Morrison 2014:118,127,129).

While the early DPC writers Hansen & Stahl emphasized that DPC should not be viewed as equal to natural, spontaneously formed plant communities, the DPC-framework has been used later for habitat restoration work and the creation of novel ecosystems that are intended to develop into fully self-regulating communities (Oudolf & Kingsbury 2013:18; Hitchmough & Dunnett 2014:8; Hansen & Stahl 2016:55; Robinson 2016:183; Evert [2010] Heinrich & Messer 2017:17–18). Thus, some DPC practitioners also work with the design and management of recreational woodlands, wetlands and semi-natural grasslands like prairies and meadows (Forbes et al. 1997; Gustavsson 2009, 2014; Dunnett 2014:97; Kircher 2014; Koningen 2014; Woudstra 2014). DPC can also play a role in nature conservation and provision of habitat to animals and other organisms (Oudolf & Kingsbury

2013:9,26; Hitchmough & Dunnett 2014:2, 15, 20–22; Hansen & Stahl 2016:6).

Compared with conventional ornamental planting design, the DPC-framework places more emphasis on the use of hardy herbaceous perennials and promotes more complex vegetation structure and informal planting patterns (Kingsbury 2009; Morrison 2014:118). In general, practitioners working within the DPC-framework are more concerned with the designed plant assemblage as a whole, rather than with each individual plant in a planting (Robinson 2016:13–14; Köppler 2017:7). Thus, there is a considerable focus on finding plant combinations that work well under the biophysical conditions of each project site, and that can coexist over time (Thompson 1997:12-14,55; Dunnett 2014:97–98; Robinson 2016:13–14). Conventional planting design and management is also still influenced in some places by gardening traditions, where hired gardeners left bare soil between plants and tended each plant individually, so that species with different needs and traits could be grown together (Thompson 1997:5,12-14,55). While these maintenance practices are no longer common in most public urban spaces, the emphasis of the DPC-framework on perennial, site-adapted, high-density and intermingled plantings is intended to respond to the conventional view of species-rich plantings as time-consuming and resource-hungry (Kingsbury 2009; Rainer & West 2015:43–62; Hansen & Stahl 2016:13–14).

Some DPC practitioners have been emphatic about keeping ”New Perennial Movement” and adjacent movements open to a variety of artistic, ecological and management approaches to planting design, and as such maintain the movement as an umbrella or a gradient of practices and practitioners (Gerritsen 2008:80–81; Hitchmough & Dunnett 2014:9,18; Kingsbury 2014; Kingsbury & Oudolf 2015 provide a good overview of the most important practitioners of the 1970’s -early 2000’s; Dunnett 2019:10–11). Others name more specific exclusion or inclusion criteria like a focus on emulating semi-natural grasslands (Cascorbi 2007; Kingsbury 2009:7–8; Hitchmough 2014:137; Bjørn et al. 2016; Alizadeh & Hitchmough 2019), preference for native plant species, alternately a rejection of giving native species a special status within the framework (Kingsbury 2009:7–8; Hitchmough & Dunnett 2014; Alizadeh & Hitchmough 2019), the use of plant varieties with relatively naturalistic proportions (Borchardt 1998:236; Oudolf & Kingsbury 2005:20–22, 2013:18), predominant use of fine-grain planting patterns (Oudolf & Kingsbury 2013:12, 32–33) or the application of ecological or otherwise scientific knowledge (Oudolf & Kingsbury 2005:20–22; Hunter 2011; Hitchmough & Dunnett 2014; Jorgensen 2014; Woudstra 2014; Hoyle 2015; Köppler & Hitchmough 2015; Rainer 2021; Teixeira et al. 2022).

Main principle: Inspired by nature, anthropogenic in nature *(Hansen & Stahl 2016 [1981]; p. 5-6, 55, Rainer & West 2015, p. 38, Rainer 2020, p. 118, Robinson 2016; p. 181, Hitchmough 2014; p. 131, Köppler 2017; p. 7, 10-11, Kühn 2011, p. 223, Dunnett et al. 2014; p. 244, Kingsbury 2014; p.58-60, Dunnett 2014; p. 98, Hitchmough & Woudstra 1999; p. 107)*				
Connected planting design concepts	**Designed plant communities**	**Naturalistic planting (design)**	**Ecological(ly based) planting (schemes)**	**Other**
Objectives for planting design and vegetation management				
Focus on naturalistic aesthetic in plant choices and overall design	Hansen & Stahl 2016; p. 13, 49, 53, Chang 2016; White et al. 2019 See also: Designed ecosystems (Rainer 2020); "designed communities" (Qian et al. 2021)	Oudolf & Kingsbury 2013; p. 131-132, Robinson 2016; p. 181, Alizadeh & Hitchmough 2020, p. 2, Kühn 2011, p. 224-225 See also: Stylized nature (Robinson 2016); Urban naturalistic herbaceous planting (Alizadeh & Hitchmough 2020); "naturalistic appearing woodlands" (Nielsen & Jensen 2007); "naturalistic approach to planting design" (Schmithals & Kühn 2014);	Hitchmough & Woudstra 1999; p. 107 See also: Ecological ornamental planting (Robinson 2016);	"Designed forb vegetation" (Bjørn et al. 2016); "Lebensbereich"-style, cottage garden (Oudolf & Kingsbury 2013); naturalistic plant communities (Arevalo Alvear 2020);
Utilization of ecological processes and/or patterns, allowing change	*Hansen & Stahl 2016 [1981]; p. 13, 16, 45, Kircher et al. 2012, p. 32; Chang 2016; White et al. 2019* See also: Anthropogenic plant communities *(Dunnett & Hitchmough 2014);*	*Dunnett 2019, p. 16, Hitchmough 2014; p. 130, Kühn 2011, p. 224, but see also Köppler 2017; p. 73-78)* See also: "naturalistic herbaceous communities" (Köppler et al. 2014); "Nature-Approximating Urban Forest" (Qian et al. 2021)	*Kingsbury 2008; p. 3, Dunnett 2014; p. 98, Hitchmough 2010, p. 194*	Semi-natural herbaceous vegetation (*Bjørn et al. 2016*); Dynamic Planting (*Oudolf & Kingsbury 2013*); Dynamic vegetation (*Karilas 2019*); Mixed perennial plantings (*Kircher et al. 2012, Heinrich & Messer 2016*); "mixed perennial beds - - - based on the autoregulation approach" (Kutlvašr et al. 2019);
Matching plants to the site (plant needs and tolerances, site conditions, site context)	*Hansen & Stahl 2016 [1981], Oudolf & Kingsbury 2013; p. 11, Rainer & West 2015, p. 41; Sjöman et al. 2015, White et al. 2019* See also: Anthropogenic plant communities *(Dunnett & Hitchmough 2014)*	*Hitchmough 2014; p. 131-132, 134, Kühn 2011, p. 224* See also: "semi-naturalistic plant community"(Larsen & Ørgaard 2013);	*Kingsbury 2008; p. 3*	Matrix planting (Thompson 1997); Mixed perennial plantings (Kircher et al. 2012, Heinrich & Messer 2016); "creation of ecologically novel habitats" (Lundholm & Marlin 2006); "Adaptive planting design" (Teixeira et al., 2022);
Combining plants with similar and/or complementary behavior, community before individual	*Hansen & Stahl 2016 [1981]; p. 13, 45, 47-49, 61-62, Oudolf & Kingsbury 2013; p. 11, Kircher et al. 2012, p. 321, Hitchmough et al. 2017, Rainer 2020, p. 115*	*Kühn 2011, p. 224-226*	*Kingsbury 2008; p. 3*	Mixed perennial plantings (Kircher et al. 2012, Heinrich & Messer 2016); designed urban vegetation (Hitchmough & de la Fleur 2006)

Table 1 DPC core ideas and synonyms, part 1: Objectives for planting design and vegetation management

Connected planting design concepts	**Designed plant communities**	**Naturalistic planting (design)**	**Ecological(ly based) planting (schemes)**	**Other**
Performance goals for designed vegetation				
Enhancing cultural, social and aesthetic values: Creating spaces, enhancing amenity, focus on long seasonal interest and rich flowering, artistic expression	*Hansen & Stahl 2016; 5-6, 44, 49, 54, 58, Rainer & West 2015; 38, Kircher et al. 2012; Bjørn et al. 2016; Alizadeh & Hitchmough 2018; Hitchmough & Wagner 2013; Sjöman et al. 2015* See also: Diverse herbaceous communities for ornamental purposes *(Bretzel et al. 2012);* Horticulture community *(Droz et al. 2021);* designed herbaceous plant communities *(Hitchmough et al. 2017);* "transform[ed] - - - plant communities according to a design perspective" *(Kühn 2006);* designing - - - plant communities *(Teixeira et al., 2022);*	*Dunnett 2019;10-11, Dunnett & Hitchmough 2014; 2, 5,15, 131-132, Köppler 2017; 7, 10-11, Hoyle, 2021* See also: nature-like planting, "species rich herbaceous vegetation that mimics semi-natural vegetation" *(Hitchmough & de la Fleur 2006);* "[Designed] naturalistic, [perennial] herbaceous vegetation", *(Hitchmough et al. 2017);* naturalistic urban vegetation (*Hoyle, 2021);* semi-naturalistic plant community *(Larsen & Ørgaard 2013);* Nature-Approximating Urban Forest *(Qian et al. 2021)*	*Hitchmough 2010, p. 193-194, Hitchmough & Woudstra 1999; p. 107*	Artistically stylized habitats (*Oudolf & Kingsbury 2013)*; Colorful forb vegetation *(Bjørn et al. 2016);* Horticultural meadows *(Cascorbi 2007);* Matrix planting *(Thompson 1997);* Mixed perennial plantings *(Kircher et al. 2012, Heinrich & Messer 2016*); designed herbaceous vegetation *(Hitchmough et al. 2017)*; the ecological approach *(Richnau et al. 2012);* Adaptive planting design (Teixeira et al., 2022); novel ecosystem design *(Van Mechelen et al. 2015);*
Low maintenance needs, creativity in management	*Hansen & Stahl 2016;13, 53, Oudolf & Kingsbury 2013;11, Hitchmough 2014;132, Kircher et al. 2012; Rainer 2020* See also: "construct[ed] low-maintenance communities with diversified ecological patterns" *(Li et al. 2019);*	*Dunnett 2019;16, Dunnett &Hitchmough 2014;2, 131; Köppler 2017;7, 10-11, Kühn 2011;226-227; Nam & Dempsey 2019; Schwingesbauer & Plenk 2013* See also: naturalistic intensive green roofs *(Nagase et al. 2013);*	*Kingsbury 2008; p. 3, Hitchmough & Woudstra 1999;107, Dunnett 2014; 98, Hitchmough 2010*	Artistically stylized habitats (*Oudolf & Kingsbury 2013);* Matrix planting *(Thompson 1997);* Dynamic Planting *(Oudolf & Kingsbury 2013*); Designed urban vegetation *(Hitchmough & de la Fleur 2006);* "mixed perennial beds - - - based on the autoregulation approach" *(Kutlvašr et al. 2019);*
Self-regulation: stability, sustainability, self-regeneration capacity, robustness, longevity, self-sustainment	*Hansen & Stahl 2016; p. 16, Kircher et al. 2012; Rainer 2020*	*Dunnett 2019;16, Dunnett & Hitchmough 2014;2,130, Schwingesbauer & Plenk 2013, Hoyle 2021* See also: naturalistic herbaceous vegetation (Hitchmough et al. 2017)	*(Kingsbury 2008; p. 3, Hitchmough & Woudstra 1999)*	Matrix *planting (Thompson 1997);* Mixed perennial plantings *(Kircher et al. 2012, Heinrich & Messer 2016);* [designing] semi-natural communities, designed forb vegetation *(Bjørn et al. 2019);*
Contribution to plant biodiversity and support for other organisms (focus on local plant diversity and animal diversity on unspecified scales)	*Hansen & Stahl 2016; 5-6; Bjørn et al. 2016, Rainer & West 2015;253, Hitchmough & Wagner 2013* See also: herbaceous communities for ornamental purposes (Bretzel et al. 2012); designed herbaceous plant communities (Hitchmough et al. 2017);	*(Robinson 2016;181; Dunnett & Hitchmough 2014;2, 20-22)* See also: nature-like planting, "vegetation that mimics semi-natural vegetation" (Hitchmough & de la Fleur 2006); "[Designed, but] naturalistic, - - - herbaceous vegetation", (Hitchmough et al. 2017); "naturalistic urban vegetation" (Hoyle 2021);	*(Kingsbury 2008; p. 3, Hitchmough & Woudstra 1999; Hitchmough 2010)*	Artistically stylized habitats; *(Oudolf & Kingsbury 2013);* Dynamic vegetation *(Karilas 2019);* the ecological approach" (Richnau et al. 2012); Adaptive planting design (Teixeira et al., 2022); designed herbaceous vegetation *(Hitchmough et al. 2017)*
Provision of technical function via regulating ecosystem services	*(Rainer & West 2015, p. 253; Rainer 2020; White et al. 2019)* See also: Designed communities (Chang 2016); Horticulture community (Droz et al. 2021); self-contained artificial plant communities (Dunnett et al. 2008a);		*(Hitchmough 2010)*	"Adaptive planting design" (Teixeira et al., 2022), "novel ecosystem design" (Van Mechelen et al. 2015)

Table 2 DPC core ideas and synonyms, part 2: Performance goals for designed vegetation

Table 1 and Table 2 summarize common design objectives and vegetation performance goals for DPC practices and practitioners. It shows a range of material that is directly or indirectly connected to Richard Hansen and Friedrich Stahl's concept of "*Pflanzgemeinschaften*" (2016:55), or anthropogenic ornamental plant communities, with a special focus on ornamental herbaceous perennials (Borchardt 1998:236). The design objectives can be interpreted as rough guidelines for fulfilling the set goals for the DPC-framework:

- Naturalistic aesthetic contributes to positive human experiences (Hansen & Stahl 2016:53–54, 58) and often coincides with plant taxa that are less dependent on some maintenance interventions, like staking and deadheading (Oudolf & Kingsbury 2005:80).
- Knowledge on processes and patterns of plant ecology can be utilized to enhance the experience of a planting (Dunnett 2014; Heinrich & Messer 2017:6), to plan for less intensive types of maintenance (Schwingesbauer & Plenk 2013), and to steer plantings towards self-regulating states that combine stability with dynamism (Kingsbury 2009:3; Kircher et al. 2012), which in turn further diminishes its maintenance needs (Dunnett 2014:98; Köppler 2017:10–11)
- Matching plants to the site is a prerequisite for self-regulation and subsequently lowered need for maintenance (Hansen & Stahl 2016:42,44), but it also enables the use of a broad, locally appropriate plant palette that provides added value for people and animals (Borchardt 1998:239; Hitchmough & Dunnett 2014:2,20-22; Hansen & Stahl 2016:5–6)
- Prioritizing the planting as its own entity over individual plants is only possible when plant assemblages consist of complementary taxa (Chesson (2000) in Bjørn et al. 2016). Careful consideration of plant-plant interactions is also crucial for attaining self-regulation (Dunnett 2019:16), and the consequent economic benefits (Hitchmough & Woudstra 1999). Understanding coexistence in plant assemblages enables species-rich compositions that both benefits people and biodiversity on different scales (Thompson 1997:26; Oudolf & Kingsbury 2013:11).
- Technical function can be ensured and enhanced through the attainment of the other goals, as vegetation health, stability, longevity, diversity and resilience may be assumed to correlate with

ecosystem service delivery (Oudolf & Kingsbury 2013:215; Dunnett 2014:100; Robinson 2016:163–164; Heinrich & Messer 2017:16).

1.3 Vegetation as part of urban nature-based solutions

Nature-based solutions (NbS) can be used as an umbrella term for different kinds of interventions that utilize natural patterns, processes, and living organisms to provide multiple benefits to people and the planet (Eisenberg & Polcher 2019). NbS can be defined as

> ”interventions that: (1) are inspired and powered by nature; (2) address (societal) challenges or resolve problems; (3) provide multiple services/benefits, including biodiversity gain; (4) are of high effectiveness and economic efficiency.” (Sowińska-Świerkosz & García 2022).

In other words, NbS are about governing, designing, constructing and managing healthy ecosystems that deliver services that effectively and reliably answer to society's essential needs like clean water and food, as well as mitigate risks to human health, habitation and infrastructure (European Commission 2015; Cohen-Shacham et al. 2016; European Environment Agency 2021). Adopting climate adaptation and mitigation measures, as well as improving the quality of urban areas, are two of the four prioritized goals for NbS in the European Union. Thus, green infrastructure that help cities cope with drought, flood risks, and the adverse effects of the Urban Heat Island on people's health and well-being, is an important factor in fulfilling these goals (European Commission 2015).

Vegetation, as a representative of "nature" in urban green spaces, is a key provider of ecosystem services (ESS) such as carbon sequestration, air pollution remediation, environmental cooling, and wildlife habitat (Berghöfer et al. 2011; Beninde et al. 2015; Yu et al. 2020; Ariluoma et al. 2023; Vashist et al. 2024). Urban vegetation is shaped by human activity to varying degrees, ranging from vegetation that is entirely dependent on humans for its establishment, survival and reproduction, to vegetation that spontaneously establishes and develops on sites with relatively little human modification (Niemelä 1999; Williams et al. 2009, 2015; Aronson et al. 2016; Avolio et al. 2021). The type, quality and breadth of ESS that urban vegetation can provide depends on both the attributes of individual plants, including their size, age and health, but also the configuration of plants that form a vegetation unit, as well as the interactions between vegetation, their abiotic site conditions, and the sum of all organisms that co-inhabit a site (Sæbø et al. 2003; Williams et al. 2009, 2015; Sjöman & Busse Nielsen 2010; Aronson et al. 2016; Ferrini et al. 2020; Watkins et al. 2021; Stroud et al. 2022). It thus becomes apparent that simply employing "green" does not ensure desired outcomes (e.g. the creation of aesthetic and habitat value at low maintenance costs) for utilizing urban vegetation (Ferrini et al. 2020).

Despite a growing understanding of the value of vegetation in urban areas, numerous knowledge gaps remain on how planting design and vegetation management could improve the performance of vegetated NbS (Maco & McPherson 2003; Oldfield et al. 2015; Martin et al. 2016; Widney et al. 2016; European Commission 2020b). In addition to knowledge gaps pertaining to planting design for optimizing singular functions in NbS, research on planting design that contributes to multifaceted performance values at reasonable costs is of key relevance of urban vegetation in and as NbS (Charoenkit & Piyathamrongchai 2019; Jones et al. 2022).

Conventional approaches to planting design emphasize the provision of cultural ecosystem services through visually impressive but demanding ornamental plants, which has led to a preconception that aesthetically pleasing urban vegetation requires intensive maintenance or significant site improvement prior to vegetation establishment (Hitchmough 2010; Dunnett 2014; Robinson 2016:35; Mooney 2020:1; Tabassum et al. 2020; Symoneaux et al. 2022). Alternately, the search for low-maintenance ornamental vegetation often results in the extensive use of single-species "green concrete", where the same plant species, usually robust shrubs, are used to cover vast areas (Thompson 1997:57; Dunnett et al. 2014:246). Both approaches can fall short on the NbS criteria for resource-effectiveness and are often associated with limited capability to diversify urban nature (European Commission 2015; Sowińska-Świerkosz & García 2022). However, the concept of "ornamental vegetation" encompasses a broad range of native and exotic plants from urban trees and hardy herbaceous and woody perennials to annual or tender perennial plants, which, when used wisely, can provide multiple ESS and habitat value at relatively low costs (Kingsbury 2009:3, 2014; Hansen & Stahl 2016).

As biodiversity is the prerequisite for healthy ecosystems, even urban NbS must contribute to the diversity of habitats, organisms, and genetic variation by fulfilling the prerequisites for diverse plant, animal and microbe life (Beninde et al. 2015; European Commission 2020c). Yet, the fundamental requirements for the establishment, development and long-term viability of vegetation and other non-human organisms may not be adequately met in urban environments, as human infrastructure often comes with a high proportion of hard surfaces and limited space above- and belowground (McKinney 2006; Cettner et al. 2013; Beninde et al. 2015; Childers et al. 2019; Randrup et al. 2020).

Planning, design and management or urban areas often give limited support for vegetation in cities such as mismatches between plant variety and the site, unsatisfactory maintenance, and vandalism, which may result in poor plant health and plant mortality (Hilbert et al. 2019; Randrup et al. 2020). Weakened performance associated with maladaptation between plants and their site may also be exacerbated by the effects of climate change (Sjöman & Busse Nielsen 2010; Alizadeh & Hitchmough 2019; Burley et al. 2019), which also increases financial risks as vegetation-dependent NbS become more prone to fail. Despite this, urban habitats can also provide spaces for a high diversity of plant species (Niemelä 1999; Aronson et al. 2016; Avolio et al. 2021).

The influence of urban environment on urban organisms is often complex, as cities can be described as social-ecological-technical systems where human actions, values, societal structures and physical artefacts interact with each other and the natural environment (McPhearson et al. 2022). These interactions shape urban flora by requiring or promoting certain vegetation attributes and excluding others, by determining how vegetation is distributed and how much space it is given, and by altering the health, life histories and longevity of individual plants (Niemelä 1999; Williams et al. 2015). The resulting composition and condition of urban vegetation not only affects the biodiversity of cities, but also the effectiveness and efficiency of urban vegetation in and as NbS.

To improve the diversity of organisms that do thrive in cities and to improve the performance of urban vegetation, the management of urban areas might need to be adjusted in the future towards practices that give plants more space, better living conditions, and that allow for more purposeful placement of vegetation (Randrup et al. 2020). For example, a planting strip that is 3 meters wide and 1 meter deep can support both shrubs and trees, and when placed in a site where runoff can be led to the planting, the plants will not only get more water but also stormwater can be detained or infiltrated in the plant substrate. Thus, the shrubs protect the soil around the tree from compacting and becoming oxygen-poor, the planting gains additional habitat value, and needs to be watered less.

Additionally, maintaining the multifunctional performance of urban vegetation as a part of NbS may require occasional maintenance actions that develop or restore vegetation structures that are essential for ESS delivery and for reducing ecosystem disservices (Lyytimäki & Sipilä 2009; Threlfall et al. 2016; Aronson et al. 2017; Mathey et al. 2018; McPhearson et al. 2022). Clearing the planting bed from toxic sediment accumulated with stormwater runoff, removing unwanted weeds that suppresses the growth of target vegetation, or cutting low-hanging branches that decrease visibility or encroach on roads might be some examples of this. Building a network of these plantings that can support diverse plant life and manage stormwater creates and upholds multifunctional and effective urban blue-green infrastructure, where individual green areas work together as NbS (Adhikari et al. 2024).

1.3.1 Urban rain gardens as vegetated nature-based solutions

Open urban stormwater management solutions, such as rain gardens, bioswales, biofilters, ponds, urban wetlands and structural soils are NbS that have been developed at an increasing frequency in the past 10-20 years (Charoenkit & Piyathamrongchai 2019; Vijayaraghavan et al. 2021; Jones et al. 2022; Kõiv-Vainik et al. 2022; Lundy et al. 2022). The two main purposes of open stormwater management solutions in urban areas are improving runoff quality through the removal of pollutants, as well as decreasing damage to people, the built environment or valuable natural environment in the case of flash floods by transporting, detaining or retaining runoff (Orta-Ortiz & Geneletti 2022). Thus, they contribute to climate adaptation, decrease environmental degradation, and help protect water resources and local hydrological cycles (European Commission 2021; Lundy et al. 2022). The choice of specific solutions depends on project goals, context and available space (Cettner et al. 2013; Beryani et al. 2021; Ekka et al. 2021). Open stormwater management solutions are often applied in a decentralized manner, where the goal is to build a comprehensive stormwater management system whose parts support each other's functioning and thus increase system resilience (Ahern 2011; Adhikari et al. 2024). Many of these utilize the combination of soils, plants and hard water engineering elements like drainage pipes and inlets to improve water quality and regulate water quantity distribution across time and space (Davis et al. 2009; Dagenais et al. 2018; Kõiv-Vainik et al. 2022; Orta-Ortiz & Geneletti 2022; Sagrelius et al. 2023). Urban rain gardens (URG) tend to be employed in very densely built, sealed areas where the site conditions may be especially harsh and variable, while they simultaneously set high demands on the socio-cultural performance of vegetation (Backhaus & Fryd 2013; Helmreich et al. 2025). Thus, URG:s are an especially interesting case for studying multifunctional planting design, vegetation development, and vegetation management in NbS.

"Rain garden" is often used as a synonym for other small-scale, vegetated open stormwater management facilities like biofilters, bioswales or bioretention facilities (Blecken et al. 2017; Dagenais et al. 2018; Beryani et al. 2021; Vijayaraghavan et al. 2021). The commonality between these approaches to open stormwater management solutions is that they are used in built environments, are often relatively small in scale, do not have permanent standing water, and they are always vegetation-clad (Davis et al. 2009; Jones et al. 2022).

Most often, open stormwater management solutions have been promoted by initiatives to develop and mainstream decentralized water management that combines engineered solutions with biophysical processes and structures, like plants, soils and micro-organisms to protect or reinstate "natural" hydrological cycles (Fletcher et al. 2015). The best known of these initiatives are low-impact development (LID) in the USA, Canada and New Zealand, water-sensitive urban design (WSUD) in Australia, and sustainable urban drainage systems (SUDS) in the UK (Fletcher et al. 2015). Since the vocabulary on the topic is not used consistently in the research, the term "rain garden" is chosen for this thesis due to the prevalence of the corresponding term "*regnbädd*" in Sweden (Pettersson Skog et al. 2023), but also due to the clear implication that the term "garden" means that plants are an integral and valuable part of a multifunctional stormwater management solution. Urban rain gardens (URG) are thus a part of the green and blue infrastructure of built environments (Jones et al. 2022; Adhikari et al. 2024).

Globally, research and application of URG:s as open stormwater management facilities has been gaining popularity especially in the USA, China and Australia from the late 2000's onwards, with a notable increase in the volume of studies happening in 2015-2016 (Spraakman et al. 2020; Vijayaraghavan et al. 2021). Open stormwater management facilities involving vegetation have been discussed, researched and implemented in Sweden since the 1970's-1980's, including the successful Malmö projects of the renovation of Augustenborg district in late 1990's and the building exhibition Bo01 in 2001 (Cettner et al. 2013; Haghighatafshar et al. 2014; Lundy et al. 2022). However, URG:s have been popularized in Sweden only in the past 10 years, after a supra-urban (i.e. located in areas with high building density and surrounded by impervious surfaces) application was piloted in the Stockholm region in 2012 (Cettner et al. 2013; Beryani et al. 2021; Lundy et al. 2022). As Sweden and the other Nordic countries differ from USA, Australia and China in terms of climate and policies, best practices for the design, construction and maintenance of URG:s must evaluate the applicability of international research results to national and local conditions (Sage et al. 2015; Mantilla et al. 2023; Knapik et al. 2024).

Design, construction and maintenance phases are all crucial for attaining operational multifunctional biofilters (Blecken et al. 2017; Beryani et al. 2021; Adhikari et al. 2024). Nordic recommendations for rain gardens describe them as relatively small, vegetated stormwater management facilities for 1–2-year return period rain events with coarser filter materials than recommended for temperate climates (Robinson et al. 2019; Beryani et al. 2021; Adhikari et al. 2024). One Swedish guide states that URG:s should prioritize water quality treatment over stormwater retention capabilities (Robinson et al. 2019), which contradicts Swedish regional and municipal guidelines for stormwater treatment requirements where retention volume per catchment area as the only basis for determining URG size and placement (Pettersson Skog et al. 2023).

Overall, Swedish URG practice shows highly variable solution functionality, and a low degree of adoption of scientific URG best practices (Beryani et al. 2021; Lundy et al. 2022). An example of this is the prominent use of macadam-based URG substrates in Sweden, which is not internationally prevalent or backed up by academic research (Pettersson Skog et al. 2023). Because long-term rain garden research on field scales is scarce (Boehm et al. 2020; Beryani et al. 2021; Biswal et al. 2022; Yang et al. 2022), the influence of different URG design parameters on their performance in the long term is also difficult to assess.

Some identified factors that seem to have a considerable effect on URG functionality is the size of the URG in relation to catchment size, sediment loading rates from the environment, the establishment success of vegetation, and maintenance of inlets and outlets (Le Coustumer et al. 2012; Beryani et al. 2021).

URG:s are still considered to be a "new" element in Swedish urban design projects, and no national best practice for URG:s exist despite intensive Swedish research efforts as well as guidelines provided by municipalities, administrations and commercial actors (Robinson et al. 2019; Beryani et al. 2021; Lundy et al. 2022). As a result, Swedish URG:s exhibit a high variation in URG design parameters such as substrates, inlet and outlet design, and sizing. This suggests that there are many open questions concerning URG:s in all project phases, from their siting to detailed design, from construction to maintenance and governance.

How URG:s are defined and conceptualized influences priorities for their development and management: If URG:s are seen primarily technical solutions for stormwater quality and quantity management, the focus might be on improving methods for evaluating runoff quality and flooding metrics, removing stormwater pollutants, and creating space for stormwater detention; If they are considered integral to the urban green infrastructure, their development might be rather geared towards improved vegetation health and longevity, urban habitat connectivity, and the provision of socio-cultural values. As the concept of NbS requires URG:s to efficiently provide multiple functions without suboptimization, a key question for URG development is to explore how and to which extent these interests can be combined in urban areas.

1.3.2 Role of vegetation in URG:s

Vegetation can have a positive influence on stormwater quantity management through upholding hydraulic conductivity of the filter substrate, intercepting water on leaves, shoots, and trunks, and by transporting water from cisterns and soils into the air through evapotranspiration (Le Coustumer et al. 2012; Dagenais et al. 2018; Skorobogatov et al. 2020; Baker et al. 2021a; Yang et al. 2022). Plants also participate in stormwater quality control through mechanical pollutant filtering, phytoremediation and assimilation of nitrogen and phosphorus into plant tissues (Bratieres et al. 2008; Read et al. 2008; Glaister et al. 2017; Vijayaraghavan et al. 2021). Additionally, plant root exudates and dead plant tissue provide food and habitat for microbes that participate in stormwater pollutant management (Muerdter et al. 2018; Chen et al. 2019; Ma et al. 2021). Vegetation that contributes to stormwater management and provides wildlife habitat and cultural ESS allows URG:s to deliver on all three sustainability dimensions, and thus is a prerequisite for URG:s to be classified as NbS (European Commission 2015; Winfrey et al. 2018).

While utilizing urban plantings for stormwater management has been seen as beneficial for plants due to the increased amounts of water and sometimes oxygen they might receive as opposed to traditional urban plantings, the plants in URGs still often have to contend with combinations of mechanical wear from trampling, water- and airborne pollutants such as salt and heavy metals, as well as drought, heat and shade (Mazer et al. 2001; Laukli et al. 2022b; a). In international URG literature the capacity of plants to withstand periodical inundation and the resulting lack of oxygen is also often highlighted as an important consideration for URG plant selection (Payne et al. 2018; Yuan & Dunnett 2018; Laukli et al. 2022a). Another source of stress for plants in URG:s might be nutrient scarcity, since observed leakage of nutrients from URG substrates is leading to the development of nutrient-poor substrate materials (Boehm et al. 2020; Okaikue-Woodi et al. 2020; Valenca et al. 2021; Pettersson Skog et al. 2023).

In stormwater management literature the planting substrate is often called "filter medium", as from stormwater quality treatment perspective the mechanical pollution filtering capacity as well as the hydraulic conductivity of substrates is central (Larm & Blecken 2019; Boehm et al. 2020; Okaikue-Woodi et al. 2020; Beryani et al. 2021; Valenca et al. 2021; Biswal et al. 2022). Ideally, filter media also retains water long enough for plant uptake, and for biological and chemical processes to be able to bind and/ or transform pollutants into harmless or inert compounds (Larm & Blecken 2019; Boehm et al. 2020; Beryani et al. 2021; Valenca et al. 2021; Vijayaraghavan et al. 2021; Biswal et al. 2022).

There is much uncertainty about how vegetation for open stormwater facilities should be designed for optimal performance with regards to both singular and multiple goals, smaller and larger scales (Figure 1) (Dagenais et al. 2018; Baker et al. 2021a; Corduan & Kühn 2024). Overall, different plant species have different strengths and weaknesses in terms of specific ESS delivery, including services like pollutant remediation or aesthetic appeal that are especially relevant for URG:s (Brisson & Chazarenc 2009; Funai & Kupec 2017; Baker et al. 2021a). The performance of vegetation in URG:s seems to depend on plant fitness and functional traits that are beneficial for pollutant uptake, interception capacity, evapotranspiration rate, upholding hydraulic conductivity, and so on (Gonzalez-Merchan et al. 2014; Funai & Kupec 2017; Dagenais et al. 2018; Winfrey et al. 2018; Fowdar et al. 2022). Yet, the trend in URG research is the same as for urban ESS and GI research in general: Plants and site conditions are not addressed at specific enough levels (species, traits, measurable site variables like size, pH or light conditions) to contribute to optimal plant choices for improved URG functionality or, indeed, multifunctionality (Filazzola et al. 2019; Spraakman et al. 2020; Stroud et al. 2022; Corduan & Kühn 2024). The lack of species-specific information is exacerbated by the fact that across urban URG research, only a few plant species have been tested for their performance more than once (Corduan & Kühn 2024).

URG:s are expected to require regular maintenance, which can also involve vegetation maintenance measures like watering, weeding, and removal of both living and dead plant tissues (Blecken et al. 2017; Beryani et al. 2021; Knapik et al. 2024). For URG:s to fulfil NbS criteria of cost-effectiveness and efficiency it is thus crucial that the realized need and extent of URG maintenance actions does not exceed the value of benefits they provide (Sowińska-Świerkosz & García 2022; Knapik et al. 2024). There is also a need to further develop analysis methods that on one hand allow measuring the stormwater management contribution of plants separate from the effects of URG substrate and other engineered components (Pettersson Skog et al. 2023; but see Ow et al. 2018), but on the other the interactions and interdependencies between vegetation attributes and the abiotic elements of the URG also need to be studied to be able to evaluate and later design these solutions optimally. A good example of this is the effect of vegetation on URG substrate clogging, which in some cases is hastened by vegetation, whereas in other cases plants help maintain the hydrological performance of URG substrates (Le Coustumer et al. 2012; Yang et al. 2022).

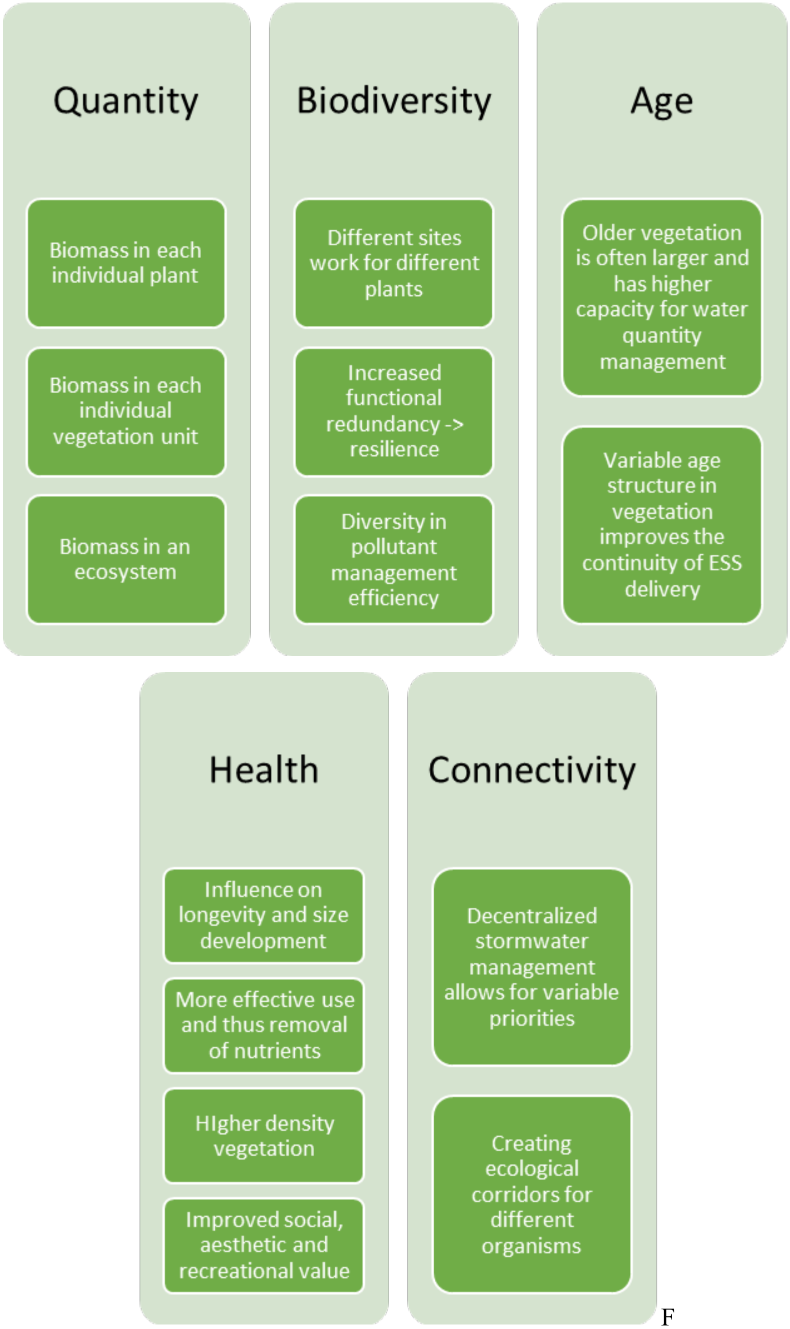

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Figure 1 Vegetation attributes that can improve the performance of multifunctional stormwater management solutions

2. Aims and objectives of the thesis

The aim of this licentiate thesis is to investigate the relevance of "designed plant communities" as a planting design framework for urban nature-based solutions, with a focus on applying the framework to urban rain gardens. The main research questions of the study are: 1) *How does the "designed plant communities"-framework relate to urban nature-based solutions? 2) to which extent is "designed plant communities" (DPC) a relevant planting design framework for urban rain gardens (URG) conceptualized as nature-based solutions (NbS)?*

The aim and main research questions are pursued through a combination of qualitative and quantitative methods within a "research through design"-strategy to explore the potential of DPC to contribute to urban NbS in following ways:

1) on a theoretical level by analyzing the evidence base, core ideas, and design tools of the planting design and vegetation management framework called "designed plant communities" ("DPC"), and assessing how relates to urban NbS.

2a) on an empirical level by assessing DPC as a planting design framework for urban rain gardens in Sweden and Finland, and relating it to the strategic management and governance of urban green spaces. Some complementary research questions are:

- What are the challenges for DPC implementation, establishment and performance in urban rain gardens?
- Which factors besides planting design variables can be identified as potential drivers of causes for URG vegetation development outcomes in the case studies and the example projects used in the interviews?

2b) on an empirical level by studying the establishment, development and maintenance of real-world DPC in designed case studies on urban rain gardens, and relating observations on DPC to observations on urban rain garden vegetation composed outside of the DPC-framework. The most important research questions are:

- How do plantings based on the DPC-framework develop in URG:s during the establishment period?

- How does the establishment, early development and maintenance of DPC:s in URG:s compare with URG plantings based on other design strategies?
- How do realized site conditions, including abiotic URG-components, influence URG vegetation establishment and development in built environments?

To this end, the objectives of the thesis are 1) identification of the core ideas (goals, claims, principles, methods and design tools) on and evidence base for planting design and vegetation management in the DPC-framework, and evaluating their applicability for creating vegetated urban nature-based solutions; 2) assessing contemporary planting design and vegetation management practices of urban rain gardens as representatives of vegetated NbS in Sweden and Finland, as well as the opportunities and challenges related to these; 3) investigating how the DPC-framework can be applied to urban rain garden planting design; and 4) comparing the establishment, early-stage development and maintenance of DPC in urban rain gardens with three alternative planting design strategies in real world contexts.

The thesis thus consists of four studies: 1a) The narrative literature review presented in chapter 5 of the thesis describes DPC history, core ideas and design tools (pre-study); 1b) A scoping literature review of research on "designed plant communities", and the body of evidence it provides for planting design that aims to improve the performance of urban nature-based solutions (paper 1); 2) An interview study on the urban rain garden vegetation strategic management in Sweden and Finland, with a focus on 6 Swedish and 4 Finnish example projects (study 2); and 3.) A 2-year case study of vegetation establishment and development in 27 urban rain gardens, each of which represents one of four planting design strategies (shrub monoculture, non-site-specific polyculture of exotic perennial herbs, non-site-specific polyculture of native perennial herbs, or designed plant communities) (study 3).

The relationship between the aims, paper, studies and conceptual framework of the thesis is illustrated in Figure 2.

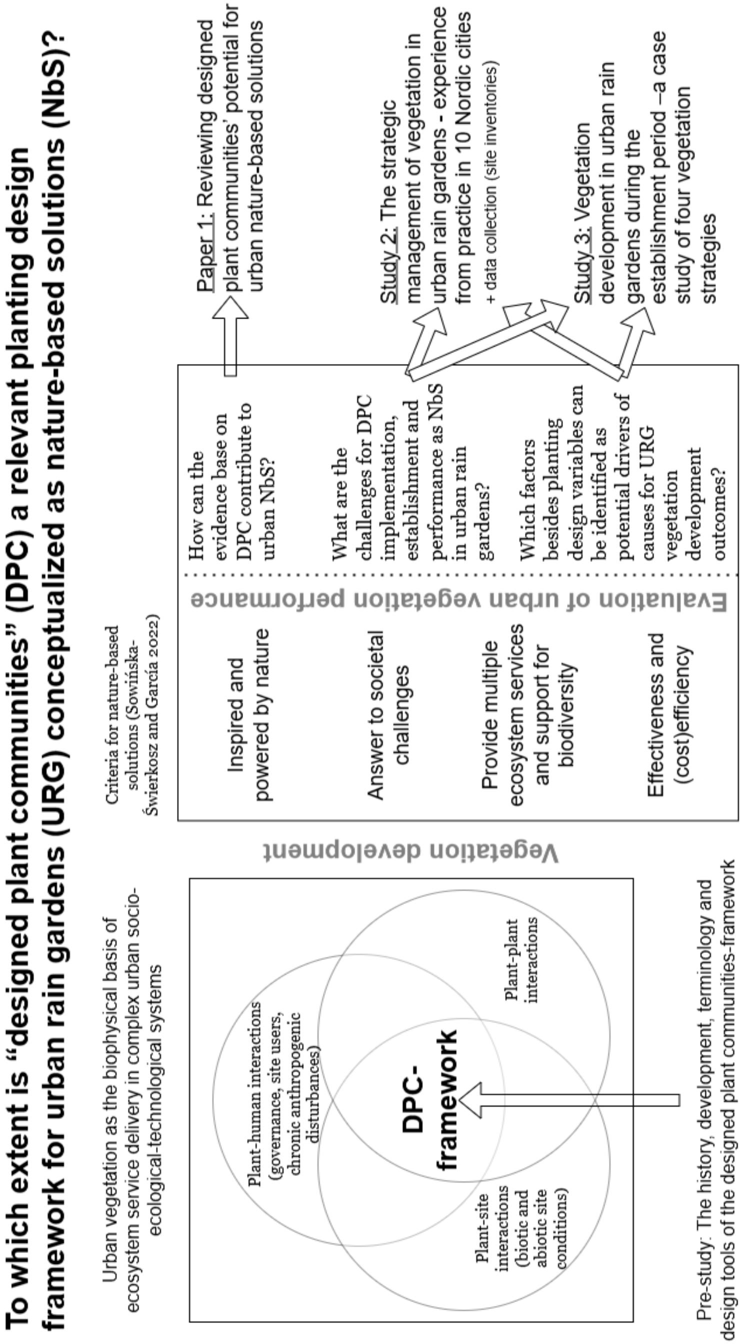

Figure 2 Summary of the aims, paper, studies and conceptual framework of the thesis.

2.1 Delimitations

The questions are primarily explored within a Nordic context and through Nordic urban sites. Urban rain gardens are the only specific nature-based solution studied.

The thesis focuses on ornamental herbaceous perennials (grasses & forbs) due to emphasis on these within the DPC-framework. Other plant life forms (e.g. woody plants, bulbs) are included in a limited fashion in all of the studies, but the discussion and conclusions of the thesis focus on forbs and grasses. Multi-species urban vegetation types that are not ornamental herbaceous plantings, such as woodlands, ruderal vegetation, aquatic vegetation or hay meadows, have been considered to an extent in the pre-study and paper 1 as they are relevant to the history of the DPC-framework and the field of ecological planting design and vegetation management.

Written material in English, Swedish, Finnish and German are used for this thesis.

The study period for the case studies was limited to two growing seasons. This means that they only provide data on the short-term establishment and development of URG vegetation. However, data collection is ongoing even after the completion of the first study period.

Additionally, the research design for the case studies (study 3) and the site inventories are not suitable for making causal inferences between site, design, and design outcomes due to the complex interactive social, ecological and technological variables of urban sites.

3. Theoretical and conceptual frameworks

This thesis concerns the conceptual frameworks of designed plant communities (Oudolf & Kingsbury 2013; Hitchmough & Dunnett 2014; Kingsbury 2014; Rainer & West 2015; Hansen & Stahl 2016) and nature-based solutions (European Commission 2015; IUCN 2020a; Sowińska-Świerkosz & García 2022). The primary theoretical frameworks in this thesis are urban socio-ecological-technological systems (SETS) (McPhearson et al. 2022), the ecosystem service cascade model (Potschin & Haines-Young 2011; Potschin-Young et al. 2018), and the strategic management of urban green spaces (Randrup & Persson 2009; Randrup & Jansson 2020) (Figure 3). As conceptual frameworks, the study of and discussions on DPC and NbS in this thesis are informed by the researcher's own experiences with the concepts and their practical applications, the different interpretations of and discourses surrounding these concepts, as well as the theoretical assumptions behind the concepts (Rallis 2018). The theoretical frameworks are then used to interpret and analyze specific aspects or processes of these concepts (Varpio et al. 2020).

The thesis is rooted in the context of practical urban landscape design as a professional activity (sensu Stompff et al. 2022). In this context, the role of theory can be viewed as instrumental: theories in landscape architecture are instruments for achieving intended outcomes in the physical world through application in design work, chosen to fit the needs of each project, to improve the performance of designed environments (Murphy 2005 via Thompson 2016; Araabi 2017; Weller 2006 via Herrington 2017:237). The function of theory is to provide foundational knowledge that can be utilized to make informed design choices, and so landscape architecture researchers are primarily tasked with generating and updating professional knowledge (Mulkay 1977 in Swaffield & Deming 2011). Similarly to landscape architecture, the urban ecological view on what constitutes "theory" within the discipline is not generally agreed upon (Lehvävirta & Kotze 2009; Araabi 2017; Herrington 2017). Lehvävirta & Kotze (2009) quote Ford (2000)and define theory in urban ecology as "a body of knowledge that can be used to construct potentially falsifiable predictions (i.e. hypotheses)", or more pragmatically as an applicable driver of physical change (Lehvävirta & Kotze 2009). These views on theoretical background in landscape architectural and urban ecology research also mean that theories can be considered as constructs that do not necessarily need to be true, as long as they represent the "*best explanation thus far*" (Underwood 1991 via Lehvävirta & Kotze 2009). In social sciences, on the other hand, theories are used to interpret phenomena, and thus they help scholars to contextualize the study and find meaningful connections between the research data and wider societal or cultural constructs (Herrington 2017:1). As this thesis uses a mixed-methods approach that combines qualitative and quantitative methods, the instrumental and pragmatic view of theory are applied in study 3 to work with hypotheses pertaining to expected DPC and NbS performance, whereas paper 1 and study 2 use theories for analyzing and describing the data from the perspectives of DPC, NbS and strategic management of urban green spaces. The view of built areas as urban socio-ecological-technological systems (SETS) (McPhearson et al. 2022) informs both studies 2 and 3, even if it is not explicitly mentioned.

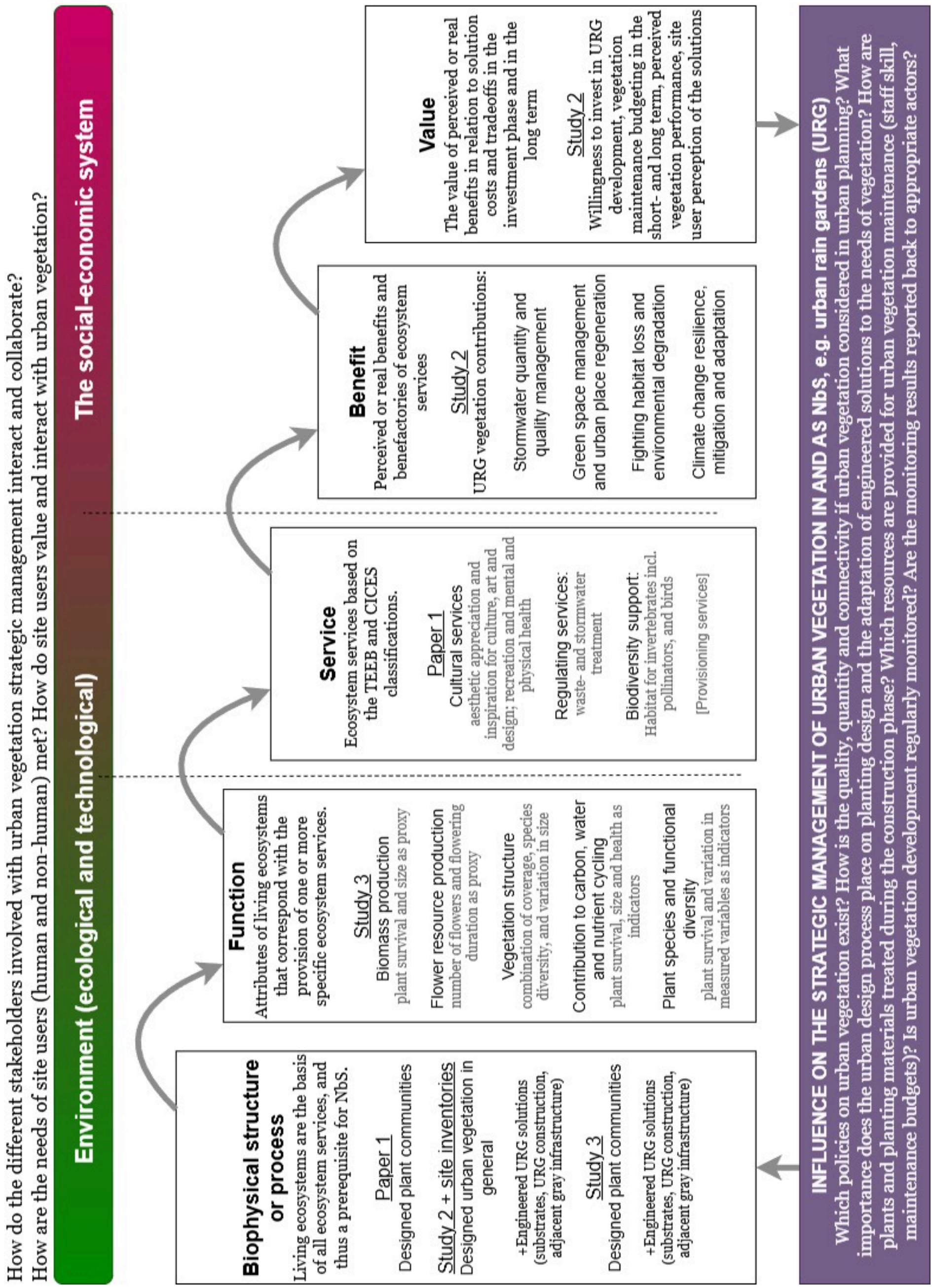

Figure 3 How the paper and studies in this thesis relate to the theoretical frameworks of SETS, the ecosystem service cascade model, and strategic management of urban green spaces.

3.1 Nature-based solutions

Nature-based solutions (NbS) is a concept for sustainable environmental governance aimed at solving global societal challenges like climate change adaptation and mitigation, environmental degradation and biodiversity loss, or economic and social development (European Commission 2015; Eisenberg & Polcher 2019; IUCN 2020b). The NbS concept emphasizes that nature, i.e. diverse living ecosystems consisting of organisms and their abiotic living environment, is the key to providing ecosystem services (ESS) that are critical for human life and well-being as well as for local and global economies (European Commission 2015; IUCN 2020a): Providing food, clean water, oxygen and raw materials like wood, fibres and medicinal components; Regulating air quality, sequestering carbon, remediating pollutants, upholding soil health for agriculture and mitigating risks from natural disasters; and forming a basis for human culture, physical and mental health (Berghöfer et al. 2011). In other words, protecting, upholding and developing the biophysical structures and processes that deliver ecosystem services and goods is necessary not only for nature-based solutions for specific societal challenges, but also generally for life on Earth as we know it (IUCN 2020a).

NbS encompasses nature-based approaches for strategic environmental governance (ecosystem-based adaptation and risk reduction), spatial planning (blue and green infrastructure), as well as environmental design and engineering (ecological engineering, sustainable urban drainage systems, water-sensitive urban design and other similar approaches to urban water management) (Eisenberg & Polcher 2019; European Commission 2021). The performance of these approaches can then be measured in terms of the quality, quantity and diversity of ecosystem services they provide (Eisenberg & Polcher 2019; Dumitru et al. 2020; European Commission 2021; Sowińska-Świerkosz & García 2021), and how effectively they contribute to solving societal challenges (IUCN 2020a; European Commission 2021). Additionally, NbS performance should be compared to the effectiveness, efficiency and costs of non-nature-based approaches for managing the same issues (European Commission 2015; Cohen-Shacham et al. 2016)., for example when determining whether a stormwater pipe or an open ditch will be a better choice for transporting water on a specific site. Unlike conventional engineered solutions, NbS must be multifunctional and provide additional ecological, cultural and economic value beyond the technical services they provide, which should also be considered when evaluating NbS performance (IUCN 2020b; European Commission 2021; Sowińska-Świerkosz & García 2021).

Although the aforementioned attributes are widely used to characterize NbS, the exact definition varies between sources (Eisenberg & Polcher 2019; Sowińska-Świerkosz & García 2022). Two widely quoted definitions are by the European Commission (European Commission n.d.) and the International Union for Conservation of Nature (IUCN 2020a):

> "[Nature-based Solutions are] Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions." (European Commission n.d.)

> "[Nature-based Solutions are] Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." (Cohen-Shacham et al. 2016)

The IUCN definition centers complete ecosystems and nature conservation and are applied at a wider landscape scale (Cohen-Shacham et al. 2016; Eisenberg & Polcher 2019). The European commission's definition also allows for the inclusion of small-scale, urban NbS applications, and even individual but interconnected facilities can be accepted as NbS when the definition is fulfilled (Maes & Jacobs 2017). The same differences between prioritization of large and small scales or urban and natural contexts is also true for the definition and formulation of societal challenges EU that NbS are meant to answer identified by IUCN vs. the EC (IUCN 2020b; European Commission 2021). For the purposes of this licentiate thesis, the EU definition of NbS complemented with the NbS criteria formulated by Sowińska-Świerkosz & García (2022) are used throughout due to the chosen project scale and urban context of the studies, although at larger scales the IUCN definition would be a valuable complement to the EC definition.

Sowińska-Świerkosz & García (2022) define NbS through four inclusion criteria and 11 exclusion criteria to further concretize and detail the concept. The inclusion criteria are:

> "(1) inspired and powered by nature; (2) address (societal) challenges or resolve problems; (3) provide multiple services/benefits, including biodiversity gain; (4) high effectiveness and economic efficiency" (Sowińska-Świerkosz & García 2022)

and the exclusion criteria are

> "(1) lack of functioning ecosystems; (2) random actions; (3) post-implementation goal(s); (4) negative/no impact on biodiversity; (5) same benefits as grey infrastructure alone; (6) unfair distribution of benefits; (7) 'copy-paste' implementation approach; (8) top-down model of governance; (9) static management approach; (10) financial expenses disproportionate to benefits; and (11) 'point scale' approach." (Sowińska-Świerkosz & García 2022).

Each of the inclusion criteria, together with complementary exclusion criteria, is explained in more detail from an urban vegetation perspective in the following chapter.

3.1.1 Plants as the basis for ESS delivery

Nature-based solutions rely on the interplay between living organisms and their environments, including engineered systems like constructed ponds, plant substrates or man-made bird nests that are inhabitable by plants, animals, fungi and micro-organisms (IUCN 2020a; Sowińska-Świerkosz & García 2022). As many NbS definitions of "nature" place emphasis on "living ecosystems" with interacting species of organisms, biomimicry or the use of natural materials do not count as NbS themselves (Schleuning et al. 2015; Cohen-Shacham et al. 2016; Sowińska-Świerkosz & García 2022). Thus, in simplest terms, for vegetation to function in and as NbS, the plants must be alive and preferably consist of several different species. Whether these combinations of plant species are defined as plant communities, i.e. distinct holistic units of vegetation characterized by plants' interactions in time and space, or as more generic plant assemblages consisting of individual plants that may or may not interact with each other, is partly a matter of context and partially a matter of different schools of thought in plant ecology (Underwood 2008; Allaby 2010a; deLaplante & Picasso 2011). For the purposes of designed, intentionally established vegetation, which is an important consideration for urban NbS and is also the focus of this thesis, the broader term of “plant assemblage” is preferred and used in a way that meets NbS criteria for what constitutes as “nature” (Robinson 2016:14).

Since the corresponding exclusion criterion for “*inspired and powered by nature*” is “*lack of functioning ecosystems*” (Sowińska-Świerkosz & García 2022), the important question is: What counts as functioning ecosystems? Similar to the concept of “ecological community”(DeLaplante & Picasso 2011:190–191; Götzenberger et al. 2012; Denslow 2014), “ecosystem functioning” is a somewhat contested concept with multiple meanings: a) ecological processes or interactions between organisms or between organisms and their site; b) the networks of ecological processes and interactions across an ecosystem, as well as the roles each organism or abiotic feature plays in the system (e.g. trophic levels, Raunkiær life-form types, the “plant strategy types” by Grime (2001), “functional types” or ”functional groups”); c) an ecosystem’s capacity to stay resilient and perpetuate itself over time d) “function” from an anthropocentric point of view, i.e., how well ecosystems support human life and endeavours (Jax 2005; Inostroza et al. 2020).

In the first, second and third senses of the term, ecosystem functioning is a combination of flows of energy, water and mineral cycles, as well as species composition and diversity (Inostroza et al. 2020). In the fourth sense, functioning ecosystems can be measured against their capacity to regulate environmental processes (including the biogeochemical cycles of water and minerals), to provide habitat, to produce essential substances and materials, and to provide humankind with information about the natural world (De Groot et al. 2002). Based on these definitions, a functioning ecosystem should be able to sustain itself in terms of approximate biodiversity, structure, organization and the regulating processes that maintain these, but also keep up a certain level of biological production and retain features that deliver cultural ecosystem services (Inostroza et al. 2020).

The latter definition of ecosystem function categories corresponds roughly with ecosystem service categories used by Common International Classification of Ecosystem Services (CICES 2018) and The Economics of

Ecosystems and Biodiversity (TEEB 2011), although in TEEB habitat provision is considered a supporting service, and information functions are expanded into cultural ecosystem services in TEEB and later versions of CICES (Berghöfer et al. 2011; Haines-Young & Potschin 2018; Haines-Young 2023).

Within the concept of NbS, one way to define sufficient levels of vegetation self-sustenance as an aspect of ecosystem functioning is to contextualize the included ecosystems within the rough NbS typology provided by Eggermont et al. (2015): Utilization or protection of unmanaged or lightly managed ecosystems as NbS (type 1); Actions to enhance the long-term biodiversity and NbS-performance of managed ecosystems (type 2); and creating completely new NbS through design and management of green-blue and hybrid infrastructure (Eggermont et al. 2015; Babí Almenar et al. 2021; European Commission 2021). Type 1 NbS within this scheme are thus expected and allowed to have a higher degree of self-organization and a lower degree of human input compared with types 2 and 3, as they are not manipulated to optimize their performance as NbS (Figure 4). Type 3 NbS, which are the primary concern of this thesis, are conversely created to answer to specific societal needs, and thus deliberate design choices and maintenance actions are employed to optimize the delivery of multiple ecosystem services (Eggermont et al. 2015; European Commission 2021; McPhearson et al. 2022). Thus, plants in type 3 NbS should be expected to have enough self-organization and self-sufficiency to survive and persist on their own after establishment, and to be resilient against the typical frequency and intensity of disturbance on their specific site. Still, engineering solutions or maintenance actions to regulate changes to plant assemblage and vegetation structure or to encourage biomass production and growth resource allocation might occasionally be required to optimize type-3 NbS performance (Skorobogatov et al. 2020; Knapik et al. 2024).

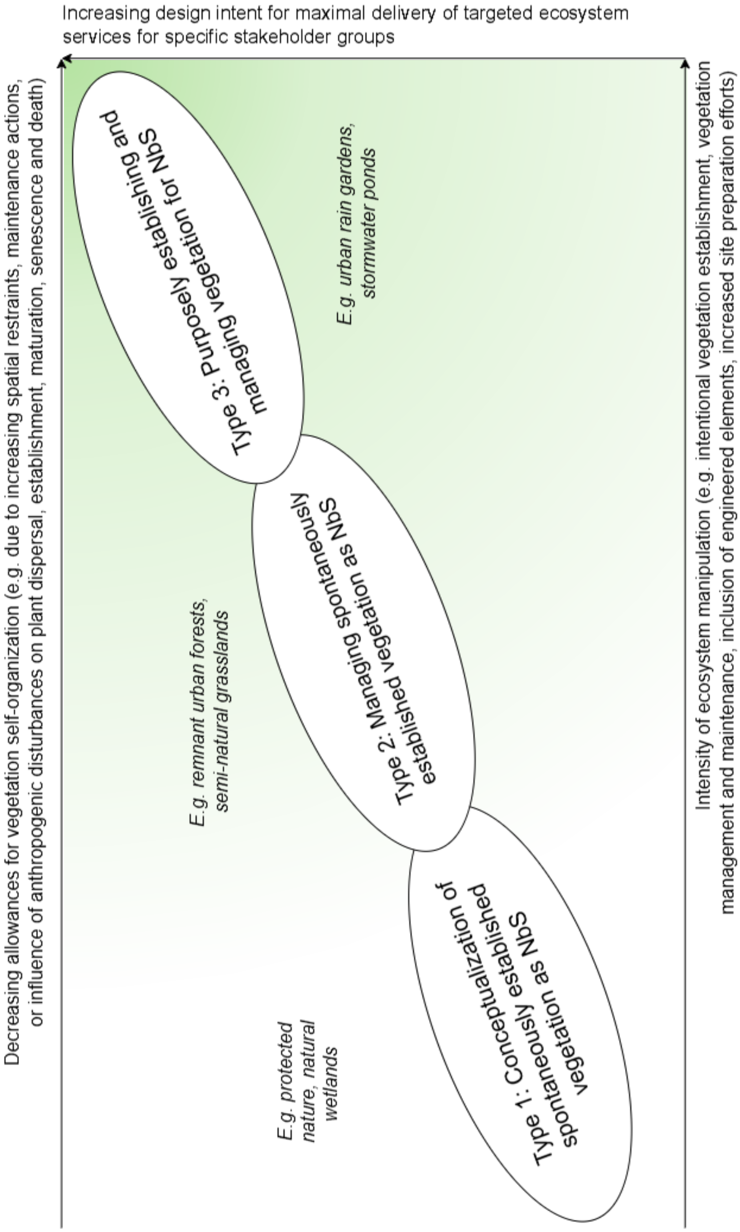

Figure 4 Three main NbS types and corresponding vegetation attributes, modified from the schematic representation of different NbS approaches by Eggermont et al. (2015). Note that this version does not assume that number of services and stakeholder groups increase with intensity of ecosystem manipulation or attempted ecosystem service maximization.

Vegetation in urban ecosystems consists of spontaneously and purposefully established native and exotic plant species, both of which have been found to provide ESS (Pyšek 1998; Williams et al. 2009; Lososová et al. 2012; Potgieter et al. 2017; Avolio et al. 2021). Neither the EC, IUCN nor Sowińska-Świerkosz & García's definitions of NbS place demands on the degree of domestication or the geographical origin of organisms, i.e. whether for example the plants living in NbS are exotic or native, although genetically modified organisms are prohibited from NbS (European Commission 2015; IUCN 2020a; Sowińska-Świerkosz & García 2022).

Aggressively spreading exotic organisms that cause damage to environments and ecosystems where they have been introduced, however, form a group called "invasive alien species", and are a real problem for biodiversity outside their native geographical range (Secretariat of the Convention on Biological Diversity 2005; IUCN 2020b). While only 6% of alien plant species globally have been determined as invasive and harmful in their introduced geographical range, following up the spreading patterns of exotic plant species in urban areas is important for recognizing potentially problematic organisms before they can cause trouble for their new ecosystems (Boltovskoy et al. 2018; IUCN 2020b; Roy et al. 2024:XVI; European Alien Species Information Network 2025). Thus, exotic plants and native plants can both be appropriate for NbS, as long as they fulfil their intended roles according to NbS definition, and as long as included exotics don't threaten the biodiversity and functions of ecosystems in their introduced geographical range.

It is critical that future research on vegetated NbS vegetated NbS approaches plants on their own terms, and thus paves way for more plant-friendly urban areas and more purposeful use of vegetation in and as urban NbS. Much research into vegetation performance in and as NbS has thus far been focused either on a very general level (vegetation or no vegetation, forest vs grass, trees vs. herbaceous plants etc. (Stroud et al. 2022), e.g. (Threlfall et al. 2016; Winfrey et al. 2018) or a very detailed level (comparisons between plant species, centering different functional traits or functional types, e.g. Hitchmough & Wagner (2013), Cascorbi (2007), Bjørn et al. (2019), van Mechelen et al. (2015). While plant functional traits are an underutilized design consideration especially in the context of NbS, the fact is that information on plant functional traits at species level is currently limited (Cameron & Blanuša 2016; Payne et al. 2018; Winfrey et al. 2018;

Watkins et al. 2021), as is the correspondence between functional traits and specific ESS delivery or site fitness (Sjöman & Busse Nielsen 2010; Watkins et al. 2021; Corduan & Kühn 2024). Another contributor to slow accumulation of knowledge on urban vegetation performance is that the vegetation typologies and plant taxon pools researched thus far have been very limited in scope (Stroud et al. 2022; Corduan & Kühn 2024). For example, studies on optimizing urban vegetation for singular functions like the removal of specific heavy metals often promote the use of very narrow selections of plants when trying to optimize simple functional or design objectives (Brisson & Chazarenc 2009). Studies that aim at providing general recommendations for implementing NbS into city planning, on the other hand, rarely give actionable guidance for planting design (Stroud et al. 2022). Both approaches risk losing sight of the multifunctional character of NbS, as well as obscuring the fact that vegetation is usually composed of several distinct plant taxa, appearing in variable species combinations, distribution patterns, and spatial structures over relatively small levels of observation.

3.1.2 Answering to societal challenges

NbS must, by definition, provide solutions to specific societal challenges, and be governed accordingly (European Commission 2015; IUCN 2020a; Babí Almenar et al. 2021; Sowińska-Świerkosz & García 2022). IUCN (2020a), the EC (2021) and the EEA (2021) provide their own lists of prioritized challenges to be addressed by NbS, which are compiled in Table 3.

List of NbS-relevant societal challenges (Linkages between SDG:s and EEA societal challenges by European Environment Agency 2021; United Nations 2024)				
Summary	**IUCN** (2020a)	**European Commission** (2021)	**European Environment Agency** (2021)	**SDG** (United Nations 2024)
Environmental risk management	Disaster risk reduction	Natural and climate hazards	Weather- and climate resilience	Climate action (SDG 13)
Climate change mitigation and adaptation	Climate change mitigation and adaptation	Climate resilience	Climate change mitigation	Climate action (SDG 13)
Food and material security for people	Food security		Sustainable agriculture for food security, sustainable forestry	Zero hunger (SDG 2), Life on land (SDG 15)
Management of urban blue-green infrastructure		Green space management	Combating loss of biodiversity through habitat preservation and increased green and blue spaces	Life below water (SDG 14), Life on land (SDG 15)
Environmental stewardship for securing biodiversity	Environmental degradation and biodiversity loss	Biodiversity enhancement		Life below water (SDG 14), Life on land (SDG 15)
Pollution management		Air quality	Managing environmental quality, air and waste	Responsible consumption and production (SDG 12)
Water quality management	Water security	Water management	Water management	Clean water and sanitation (SDG 6)
Socio-economically sustainable, inclusive and just human communities and societies	Economic and social development	Social Justice and Social Cohesion	Social justice, cohesion and equity (prio: climate change risks)	Reduced inequalities (SDG 10)
		New Economic Opportunities and Green Jobs	Sustainable economic development and decent employment	Decent work and economic growth (SDG 8)
		Place regeneration	Inclusive, safe, resilient and sustainable inhabited areas for humans	Sustainable cities and communities (SDG 11)
		Participatory Planning and Governance		Sustainable cities and communities (SDG 11)
		Knowledge and Social Capacity Building for Sustainable Urban Transformation		Sustainable cities and communities (SDG 11)
Human health and well-being	Human health	Health and Well-being	Public health and well-being (prio: climate change impacts)	Good health and well-being (SDG 3)

Table 3 List of NbS-relevant societal challenges, grouped by theme.

The exclusion criterion that corresponds with "*address (societal) challenges or resolve problems*" is "*random actions*" (Sowińska-Świerkosz & García 2022). Thus, every step of installing an NbS must clearly define the societal challenges addressed and deliberately consider the factors that influence the relevance of the proposed solution to prioritized challenges on each site (Cohen-Shacham et al. 2016, 2019; IUCN 2020a).

For a type 1 NbS (Eggermont et al. 2015) this might simply mean the decision to protect a specific natural area that is important for ecological network continuity (combating biodiversity loss), produce goods for foragers (food security), participate in groundwater recharging processes (water security) and welcome a significant number of recreational visitors (human health and well-being) (European Commission 2021), using a form of "benign neglect" as a management strategy (Haila and Levins 1992 in Niemelä 1999).

NbS type 2 might rather be manipulated to some extent to improve its intended functions, without creating entirely new features in the environment (Eggermont et al. 2015). Removal of invasive plant species (combating biodiversity loss) or thinning forested areas closest to roads or paths to improve visibility (Inclusive, safe, resilient and sustainable inhabited areas for humans) could be small-scale examples of maintenance objectives for type-2 NbS. On a larger scale, an example of this could be projects where existing agricultural ditches on private property are given more space to create meandering shapes for the ditches and to complement them with buffer zones to reduce nutrient loading in the receiving water body (Environmental degradation), to reduce flood risks to food production in the surrounding fields (food security, Natural and climate hazards), and to improve habitat complexity and connectivity in the rural landscape (Biodiversity enhancement) (European Commission 2021; European Environment Agency 2021).

For NbS type 3, including stakeholders in the planning, construction and long-term management or even financial support of the solution might be necessary to address several societal challenges that are not directly related to the technical solution itself, like Participatory Planning and Governance, Knowledge and Social Capacity Building for Sustainable Urban Transformation, and Economic and social development (European Commission 2021). Knowing the stakeholders and their social, economic and ecological interests is thus essential to prioritizing the challenges that are most relevant for a specific context, to finding appropriate solutions, and to monitoring the effects of NbS actions (IUCN 2020a; European Commission 2021; Sowińska-Świerkosz & García 2022).

For vegetation to be a part of these solutions, it is important to consider the scale at which an intervention does contribute significantly to solving a societal challenge (IUCN 2020a; Sowińska-Świerkosz & García 2021, 2022). Size, quantity, quality, distribution, diversity, accessibility and synergies with the surrounding ecological, economic and social structures are some of the metrics that impact the scale at which green spaces can work as NbS (IUCN 2020a; European Commission 2021). For example, the combined vegetation of an entire mosaic landscape can help solving societal challenges on a regional or national level, whereas the vegetation of a riparian buffer zone has greatest effect on a watershed scale and an allotment garden might contribute most to the food security of a single household or a small neighbourhood. Another example could be that while a single street tree, the trees of a whole street, and the comprehensive tree population of a city district can all be reasonably defined as service-providing units with roughly the same services, the benefits they provide come at distinct scales: A single tree can provide shade and cooling for one or two adjacent houses; the combined canopies of all the trees on a street might provide additional cooling by deflecting light and heat that otherwise would have warmed up the asphalt; and the urban forest of the district might also have high enough evapotranspiration to regulate air temperature even in those areas of the district where there are no trees (Costanza 2008; McPhearson et al. 2022).

Verifying and comparing the effectiveness and efficiency of large-scale vs. interconnected small-scale NbS has not yet been comprehensively studied, but there are some indications that different scales are relevant for different challenges, for example in the case of urban stormwater management (European Commission 2020a; Hutchins et al. 2021; Boening-Ulman et al. 2022; Adhikari et al. 2024). In any case, it is important to design and manage NbS vegetation in a way that makes them technically functional, resource-effective and robust at multiple scales in their local contexts (IUCN 2020b).

3.1.3 ESS as the basis for human life and well-being

Nature-based solutions need to contribute to all three pillars of sustainability, and thus deliver ecological, economic and sociocultural benefits simultaneously (European Commission 2015; Sowińska-Świerkosz & García 2022). Thus, actions that have "*negative or no impact on biodiversity*" or that have "*the same benefits as grey infrastructure alone*" cannot be defined as NbS (Sowińska-Świerkosz & García 2022). The benefits are borne out of ecosystem services, i.e. organism- and ecosystem-based regulation of environmental processes like carbon and water cycling but also local climate and soil quality, provisioning of materials, substances and energy, and support for human culture and well-being through cultural ecosystem services (ESS) (Berghöfer et al. 2011; Costanza et al. 2017; Haines-Young 2023).

"Ecosystem services" as a concept correlates with the anthropocentric view in that nature can provide services for the common good of societies, and centers quantifiable benefits to humans, e.g., by framing the problems of biodiversity loss primarily in terms of the costs it would entail in terms of lost ESS and thus lost benefits and value (Potschin & Haines-Young 2011; Costanza et al. 2017). Because of this, biodiversity on biosphere-, habitat-, organism-, and genetic levels is counted as a supporting service in the TEEB classification of ecosystem services (Berghöfer et al. 2011), although some argue that it should rather be understood as the prerequisite for all ESS (Kremen 2005; Haines-Young & Potschin 2010).

The services, benefits and value vegetation or vegetative processes (considered as "natural capital" within the social-economic domain) can provide is influenced by their specific attributes at predefined spatial and temporal scales (Kremen 2005; Costanza 2008; Haines-Young & Potschin 2010; Potschin & Haines-Young 2011; Harrison et al. 2014). For example, ecosystem-mediated climate regulation, carbon sequestration and -storage are services that are provided through the global sum of organisms, including plants, whereas habitat provision and stormwater quality and quantity control require appropriate service capacity from local and/ or regional ecosystems (Kremen 2005; Costanza 2008; McPhearson et al. 2022). The role and performance of vegetation in and as NbS can be described through the ecosystem service cascade model, which is most often conceptualized as a transdisciplinary theoretical or conceptual framework for systemic analyses of natural capital and the values it provides through ESS at specific scales (Figure 6)(Potschin & Haines-Young 2011; Potschin-Young et al. 2018; but see also Costanza et al. 2017).

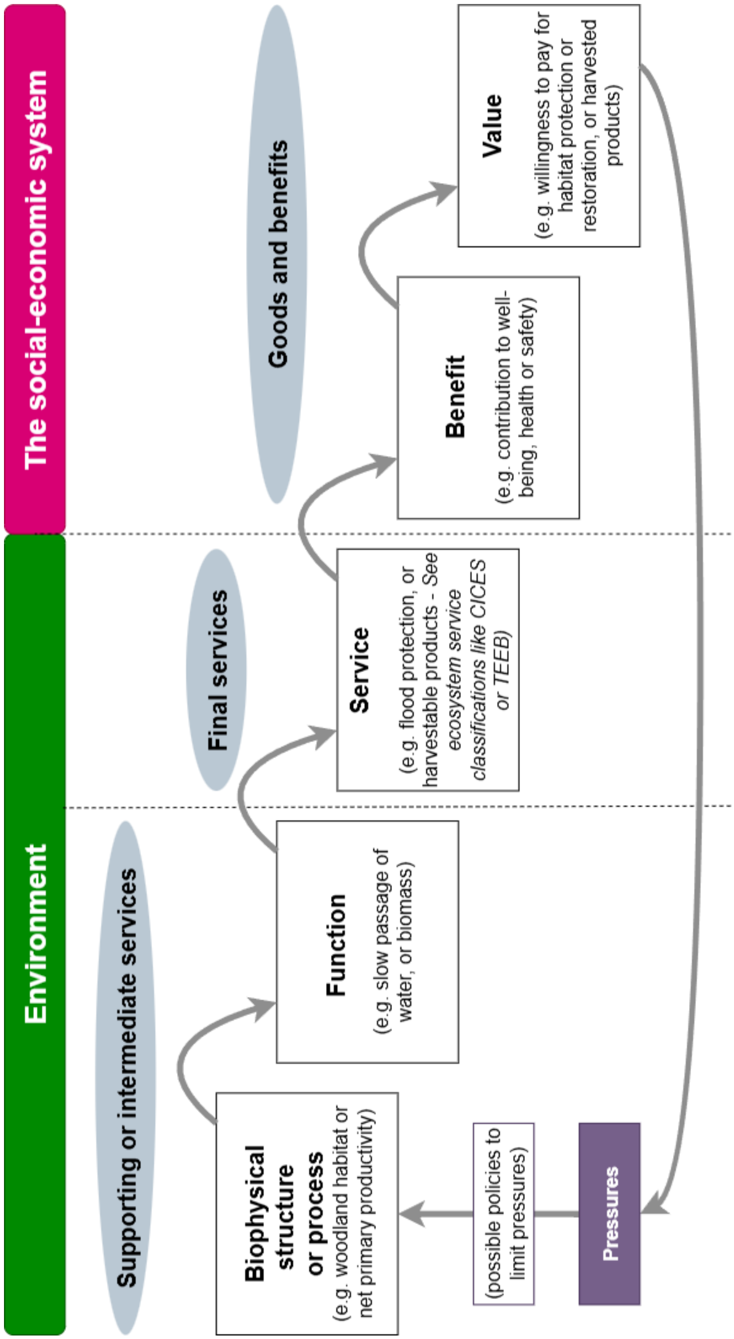

Figure 5 The ecosystem service cascade model, adapted from the version presented in Potschin-Young et al. 2018.

In the context of NbS, the biophysical basis of the cascade corresponds with the criterion "*inspired and powered by nature*" (Sowińska-Świerkosz & García 2022). How the scale and dimensions of vegetation as a "service-providing unit" is defined is a matter of social or cultural judgements, although the quality and quantity of services provided by each unit is dependent on its biophysical properties and functioning (Potschin & Haines-Young 2011).

Harrison et al. (2014) provide a review of linkages between various ecosystem attributes like area, age, and biomass, and their influence on specific ESS provision. Additionally, the size, quality and connectivity of vegetated areas not only influences habitat provision for birds, mammals and invertebrates (Niemelä 1999; Beninde et al. 2015; Aronson et al. 2017; Biella et al. 2025), but also recreational value for people and thus their health and well-being (Nguyen et al. 2021; but see also Kabisch et al. 2017).

The amount, diversity, structure, age and health of vegetation have been shown to have an effect on the delivery of some ESS (Sæbø et al. 2003; Sjöman & Busse Nielsen 2010; Williams et al. 2015; Keeler et al. 2019; Ferrini et al. 2020; Watkins et al. 2021; McPhearson et al. 2022; Stroud et al. 2022). For example, the amount and quality of biomass allocated into trunks of trees used for timber or into the fruits of crop species correlates quite directly to their provisioning ESS, but the magnitude of biomass production can also have an influence on carbon sequestration and storage (Velasco et al. 2016; Vargas et al. 2019; Skrzypczak et al. 2025). A further possible separation is to divide vegetation-mediated ESS into services provided by the physical structure of plants and vegetation, or services provided by specific functions provided by vegetation (Childers et al. 2019). To continue from the previous example, increased biomass production can thus also have a positive effect on stormwater quantity management through increased interception area (structural ESS) or evapotranspiration (functional ESS) (Berland et al. 2017; Szota et al. 2018, 2024; Carlyle-Moses et al. 2020). Even the placement of individual plants or plantings can influence their efficiency as NbS (Amorim et al. 2021).

The influence of biodiversity on vegetation performance as NbS has not been exhaustively studied, and in many cases the relationship between diversity and different ecosystem functioning metrics is somewhat contested (DeLaplante & Picasso 2011; Potschin-Young et al. 2018; Weiskopf et al. 2024). Yet, it can be inferred from other contexts that plant biodiversity might have a positive influence on vegetation resilience against disturbances and changing climate and weather patterns (Niemelä 1999; Hunter 2011; Oliver et al. 2015b; a). Diverse vegetation might also be able to retain a broader palette and better continuity of ESS in space, time and quality in the face of changes to vegetation assemblage, although the result might depend on more on functional trait diversity than plant species diversity per se (Flynn et al. 2011; Schleuning et al. 2015). The habitat value of urban vegetation can be enhanced or diminished through manipulation of the composition of urban plant assemblages, including diversity metrics, but also vegetation structure, vegetation coverage, and soil attributes (Byrne 2007; Beninde et al. 2015; Threlfall et al. 2016; Aronson et al. 2017).

The dimensions of time influence all aspects of vegetation development and performance: Individual plant growth is largely a function of linear time, whose length depends on plant identity and life history; The habitat and food value of plants or even vulnerability to pests is dependent on how well the timelines of plants match those of dependent organisms or pests; Plant development and reproduction might be adapted to specific seasonal weather or disturbance patterns; plant assemblage in vegetation develops as a result of individual plants' development cycles; vegetation with different developmental histories might diverge for a time, only to converge at a later point in time; Urban plant assemblages are always shaped by prior influences, like annual mowing or trends in plant popularity (Ramalho & Hobbs 2012; Albuquerque et al. 2018; Ossola et al. 2021). Some of these temporal influences on vegetation development are regular or even deterministic, whereas others are unpredictable (Ossola et al. 2021). Thus, urban vegetation and its ESS delivery and habitat value are not just functions of space, but also of time, both of which need to be assessed when evaluating reasons for vegetation development and performance in and as NbS.

Cultural and amenity values of urban vegetation, which include aesthetic richness, and recreation, safety, public relations and education (Echols & Pennypacker 2008), are more difficult to measure than their environmental benefits, and are sometimes considered more of a bonus than a worthy goal in themselves (Ong 2003). However, cultural ecosystem services are acknowledged by many ESS classification systems, including CICES and TEEB (Berghöfer et al. 2011; Haines-Young 2023). Cultural ecosystem services attached to vegetation are dependent on the overall sensory experiences of the observer and the meanings they attach to the object of observation, and thus highly contextual (Dickinson & Hobbs 2017). Unlike regulating ESS, cultural ESS only exist when they are perceived by an observer, and demand some degree of active engagement with the environment so that the observer has time to interpret and experience them (Porteous 1996:11–12, 22; Berleant & Carlson 2007:16; Shelley 2013 in Herrington 2017:9). Thus, it might not be enough to create urban vegetation that might provide a site user with aesthetic appreciation, for example, if they just stopped to look; Rather, sometimes urban vegetation does need to employ strong sensory stimulus to create "wow-effects" that encourage busy and unfocused urban dwellers to engage with their environment (Hitchmough 2017b; Dunnett 2019). These sensory stimuli can be visual, but also auditory, olfactory or tactile (Berleant & Carlson 2007). However, positive experiences with nature and natural elements are not exclusive to striking features, but more mundane yet pleasant everyday landscapes may also help people connect to their living environment and thus contribute to their appreciation of NbS and other urban nature (Li et al. 2022). Certain cultural ESS, like sense of place or spiritual experiences, might also be tied to specific plants of local significance: for example, the blooming of *Prunus padus* and *Syringa vulgaris* denote specific phases of spring- or summertime in the Nordic countries, whereas in China *Prunus mume* plays the role of the spring herald (Wistrand 2015; Zong 2020).

3.1.4 Cost-effective and efficient solutions

The final criterion for NbS is that they should be of "*high effectiveness and economic efficiency*" (Sowińska-Świerkosz & García 2022). This criterion also has the most exclusion criteria attached to it, which can be divided into a few categories:

- Adaptation of NbS to realized local conditions
    - *"'copy-paste' implementation approach"*
    - *"Static management approach"*
- NbS governance
    - *"Unfair distribution of benefits"*
    - *"Top-down model of governance"*
    - *"'Point scale' approach"*
- Evaluation methods for and -results of NbS service production
    - *"Post-implementation goal(s)"*
    - "*Financial expenses disproportionate to benefits"*

- (Adapted from Sowińska-Świerkosz & García, 2022)

NbS function is dependent on the biophysical conditions, policies, and social context of the site where they are applied (European Commission 2015; Sowińska-Świerkosz & García 2022). Thus, NbS cannot be copied between sites, but must rather be scaled and adapted to be appropriate for each application (European Commission 2015, 2021; Sowińska-Świerkosz & García 2021). One way to understand the factors that form together the prerequisites for local adaptation of urban NbS is to address cities as complex social-ecological-technological systems (SETS), where multiple interests and drivers of urban development meet, intertwine and collide (McPhearson et al. 2016, 2022; Markolf et al. 2018). The social, ecological and technical dimensions of ESS provision (McPhearson et al. 2022) can thus be formulated as prerequisites for or limiters of biophysical structures or processes (e.g., climate, management, ecosystem structure), complements, hindrances or replacements to biophysical structures or processes (e.g., pipes, adjacent constructions and engineered materials), drivers of service and benefit distribution (e.g., policy, urban planning, financial resource allocation in space and time) and influences on benefit valuation (e.g., cultural norms and values, people's perceptions) (Potschin-Young et al. 2018; Keeler et al. 2019). NbS' adaptability is also important for solution resilience, as the multiple spatial and temporal scales, complexity and dynamics of SETS make them unpredictable and can make even robust solutions redundant in changed situations (Potschin & Haines-Young 2011; Markolf et al. 2018; Ossola et al. 2021; McPhearson et al. 2022). Thus, an understanding of cities as dynamic SETS forms an integral part of the context in which NbS effectiveness and efficiency is evaluated.

The fact that cities are primarily human habitats means that they need to serve people's basic needs, but also provide possibilities for higher functions like culture, social life, innovation and economic activity (Childers et al. 2019). Additionally, a high density of humans comes with large amounts of materials required for human life (e.g., food, energy) and waste as a result of human activity (e.g., sewage, pollution, garbage) (McDonnell et al. 2008). NbS governance also needs to give space for changing priorities, needs, and conditions that influence NbS deployment and performance over time and space (Markolf et al. 2018; Sowińska-Świerkosz & García 2022). To do this, NbS governance must be sensitive to its stakeholders, and allow them to be involved in different stages of NbS lifecycles (Jansson & Lindgren 2012;

Sowińska-Świerkosz & García 2021). Thus, the need for multifunctional solutions that satisfies both physical and cultural needs of humans is apparent, as is the need to maintain the ecological functions that underlie provisioning of these needs (Childers et al. 2019). Different maintenance actions or other interventions may influence the services provided by multifunctional biophysical elements or processes may in different ways, and can even lead to trade-offs between the effectiveness or efficiency of different services (Potschin & Haines-Young 2011; Gaston et al. 2013). Thus, NbS management should be adaptable so that the changing situations can be met without decreased NbS functionality or adverse effects on biodiversity (Niemelä 1999; Aronson et al. 2017; Sowińska-Świerkosz & García 2021).

Urban nature has both considerable biophysical similarities and dissimilarities with less urban environments (Pyšek 1998; Niemelä 1999; McDonnell et al. 2008; Williams et al. 2009, 2015; Kowarik 2011; Lososová et al. 2012). Urban areas distinguish themselves from less built or unbuilt areas through a high degree of human influence, which has been called "*chronic anthropogenic disturbances*" by some ecologists (McDonnell et al. 2008; Albuquerque et al. 2018). They exhibit patterns of abiotic site condition and disturbance that are different from natural habitats, especially in terms of higher temperatures and decreased water availability, but also increased nutrient and pollutant loads as well as generally higher pH levels, which influence plant species composition and diversity (Niemelä 1999; McDonnell et al. 2008; Kowarik 2011; Avolio et al. 2021). For vegetation in NbS to be able to survive and perform as intended, the plants used must have suitable fitness to site, both in terms of stress tolerance, adaptation to urban disturbance patterns, and suitable competitive strategies (Williams et al. 2009; Kowarik 2011; Aronson et al. 2016). As a result, vegetated NbS must in urban areas also be adapted to local urban environmental conditions.

Finally, to be able to evaluate NbS effectiveness and efficiency, clear performance goals and benchmarks must be set from the beginning (Dumitru et al. 2020; European Commission 2021; Sowińska-Świerkosz & García 2021). One aspect of NbS evaluation might be the monetary value of the ESS they provide (Potschin & Haines-Young 2011). However, for the total evaluation of NbS it is important not to overemphasize "ESS production" over the long-term availability and development of biophysical elements at the top of the cascade, as biodiversity benefits and continued ecosystem functioning might otherwise be at risk (Potschin & Haines-Young 2011; IUCN 2020a). Besides instruments for evaluating tangible and intangible ESS services and values, NbS evaluation should thus also include environmental quality metrics like biodiversity, canopy cover or plant health, as well as maintenance costs for the NbS (Sowińska-Świerkosz & García 2021).

In the context of designed urban vegetation, NbS evaluation frameworks must also account for design intentions, including target species composition, vegetation development goals, and the rationale behind plant selection for a project. Understanding design intentions is critical for evaluating project goal fulfilment and the saliency of design solutions with regards to initially identified societal challenges and design restrictions. If NbS effectiveness is evaluated without knowledge about design intentions, the evaluation results risk regarding solution performance "in a vacuum", i.e. in comparison to an "ideal NbS" rather than in comparison with the project assumptions and realized conditions. This makes evaluation results less useful for evaluating design outcomes, and thus hinders troubleshooting efforts in the case of vegetation failure: Did the NbS fail because the plants died, did the planting fail because the plant selection was not adapted to the expected and/ or realized site conditions? Did the planting fail because the realized site conditions did not provide decent living conditions for plants? Or did the vegetation fail to establish in the first place because the initial vegetation maintenance was insufficient? Evaluation that can give accurate answers on why project outcomes did or did not meet project goals is thus also invaluable for developing a solid evidence base for urban vegetation design and management.

Developing the evidence base for urban vegetation design and management requires not only data collection and result evaluation on a project-by-project-basis, but also an analysis of design outcomes across projects so that trends and causal effects can be teased out (Sutherland et al. 2004; Brown & Corry 2011; Prominski 2016; e.g. The Landscape Performance Series n.d.; the Urban Nature Atlas n.d.). In addition to gathering evidence by assessing project outcomes, evidence for the effective design and management of vegetated urban NbS should also be gathered through scientific research projects that seek to find answers to specific research questions (Kadykalo et al. 2021; e.g. the Nature-based solutions evidence platform n.d.). Together, project evaluations, as well as scientific evidence from applied and basic research can provide the kinds of generalizable and specific knowledge that are required for evidence-based design, i.e. design decisions based on best available scholarly knowledge (Brown & Corry 2011; Jensen et al. 2025). However, for observations or even research results to be validated as "evidence" that can be used for evidence-based design, they need to be reliable (Yin 2018:46–47), traceable to a concrete source, and be presented in relation to other observations or results on the same topic (e.g. explicitly supporting, complementing or refuting previous evidence).

3.2 Urban socio-ecological-technological systems and the ecosystem service cascade model

Around 55% of the global population lived in urbanized areas by at the end of 2020 (UN-Habitat 2024:294). Each of these urban inhabitants are stakeholders that interact with each other and their environment in space and time (Preiser et al. 2018; Krueger et al. 2022). When multiplied with the interactions that plants, microbiota and non-human organisms have with each other, humans, and their interactions with environmental objects and processes in the same place, complex urban systems emerge (Preiser et al. 2018; Menconi et al. 2021). To meet humans' basic needs and control the social and ecological complexities of environments, people also build infrastructure like housing, roads and sewer lines. People are also often well aware of other organisms and the natural elements of sites and might also manipulate conditions for them by building planting beds or channelling rivers. Thus, the social and ecological systems are complemented with technological systems (McPhearson et al. 2016). The governance of these intertwined systems includes policies, laws and regulations on how urban environments may be used or manipulated, when, and by whom, further influencing the dynamics between human and non-human urban dwellers as well as their dynamics (McPhearson et al. 2016; Krueger et al. 2022). As a result, the technological, social and ecological aspects of urban environments are best understood as holistic, complex and dynamic socio-ecological-technical systems (SETS) (McPhearson et al. 2016, 2022). Even smaller units of urban environments, like URG:s, can be understood as amalgamations of socio-cultural drivers, biophysical elements and ecological processes, and technological structures (McPhearson et al. 2022).

Vegetation and microbiome form the living biophysical basis of URG:s (Figure 7) (Skorobogatov et al. 2020; Orta-Ortiz & Geneletti 2022). These biotic components are dependent on and in constant interaction with the URG substrate, which is the key abiotic part of the URG biophysical basis (Funai & Kupec 2017; Pettersson Skog et al. 2023). The living conditions of vegetation and microbiome of URG:s are also influenced by the total socio-ecological technical system (McPhearson et al. 2022) where they are located, as this not only affects the attributes of the substrate, but also the placement, design, construction and maintenance of the facilities they inhabit, as well as the disturbance they face (Backhaus & Fryd 2013; McPhearson et al. 2022). The ecological dimensions of the system also include key site factors like overall climate and vegetation zone with its temperature and precipitation patterns, and surrounding ecosystems from which plants, animals and micro-organisms can migrate to the URG and thus potentially cause adverse effects like aggressive competition for space or plant illnesses, but also positive and neutral interactions like pollination, seed dispersal, and an increase of co-existing plant species in an assemblage (Gonzalez-Merchan et al. 2014; Potgieter et al. 2017). Because URG:s have specific stormwater management functions, their water dynamics might become more extreme than in other plantings in the same area, which is another effect of the complex SETS they are a part of (Backhaus & Fryd 2013; McPhearson et al. 2022).

The identity and traits of URG vegetation, microbiome and substrate on each site, influenced by the conditions of the SETS, give the biophysical basis of the URG a specific functionality. Some examples of functions in this context are contributions to water, nutrient and carbon cycling and biomass production (Nocco et al. 2016; Szota et al. 2018; Corduan & Kühn 2024). Whether vegetation structure and plant and microbiome species diversity count as functions or are simply the attributes of these biophysical structure that provides functions, they are the two aspects that influence all URG ecosystem service provision (Lehmann et al. 2014; Pascual et al. 2015; Smith et al. 2015). Other functions are behind one or more ecosystem services. For example, mechanical filtering and biochemical control of pollutants only affect stormwater quality management, whereas contributions to water-, and nutrient cycling additionally influence stormwater quantity management, as well as local climate regulation and physical health through cooling (Bratieres et al. 2008; Dagenais et al. 2018; Meili et al. 2021; Szota et al. 2024).

The interpretation of benefits from ESS and the valuation of benefits comes back to the realm of SETS (Potschin & Haines-Young 2011; McPhearson et al. 2022). The value of benefits and goods consists of use and non-use values and can be applied for monetary or non-monetary valuation. This can also be assessed or perceived differently depending on place, time, and socioeconomical variables (Potschin & Haines-Young 2011; Schägner et al. 2013; Brander et al. 2024). Knowledge on how and which groups of people value which services and benefits more is thus important not only for distribution of services, but also for assessing the acceptability of possible ESS trade-offs (Potschin & Haines-Young 2011). However, it is important not to overemphasize market value of ESS and NbS at the cost of the total functioning of SETS, as this could be detrimental to responding to societal challenges that pertain to environmental and societal issues (Potschin & Haines-Young 2011; IUCN 2020b; European Commission 2021; European Environment Agency 2021).

How the service cascade production of each URG works in practice is a matter of how the realized conditions, including technical solutions for the infrastructure in and surrounding URG:s, influence for the biophysical structures and processes and thus the type, breadth, intensity and quality of functions and consequent services, as well as how the benefits and goods from the services are distributed and valuated (Figure 7) (De Groot et al. 2002; Potschin & Haines-Young 2011; Gómez-Baggethun et al. 2013). The realized conditions might include temperature and precipitation patterns that may or may not align with the usual patterns for the location, and that thus might aid or hinder vegetation growth, and cause premature URG substrate clogging or allow it to function past its expected life cycle (Le Coustumer et al. 2012; Beryani et al. 2021; Yang et al. 2022). The stormwater quality and quantity management performance of vegetation in URG:s also varies across the year (Muthanna et al. 2008; Barron et al. 2020; Skorobogatov et al. 2020; Yang et al. 2022), not to mention how seasonal growth cycles influence the provision of other vegetation-mediated ESS (Peters et al. 2011; Meili et al. 2021; Zhou et al. 2024; Kwak & Chen 2025). Hence, any assessments of URG vegetation performance should be performed multiple times a year, for the duration of several years, to get an understanding of their performance in time.

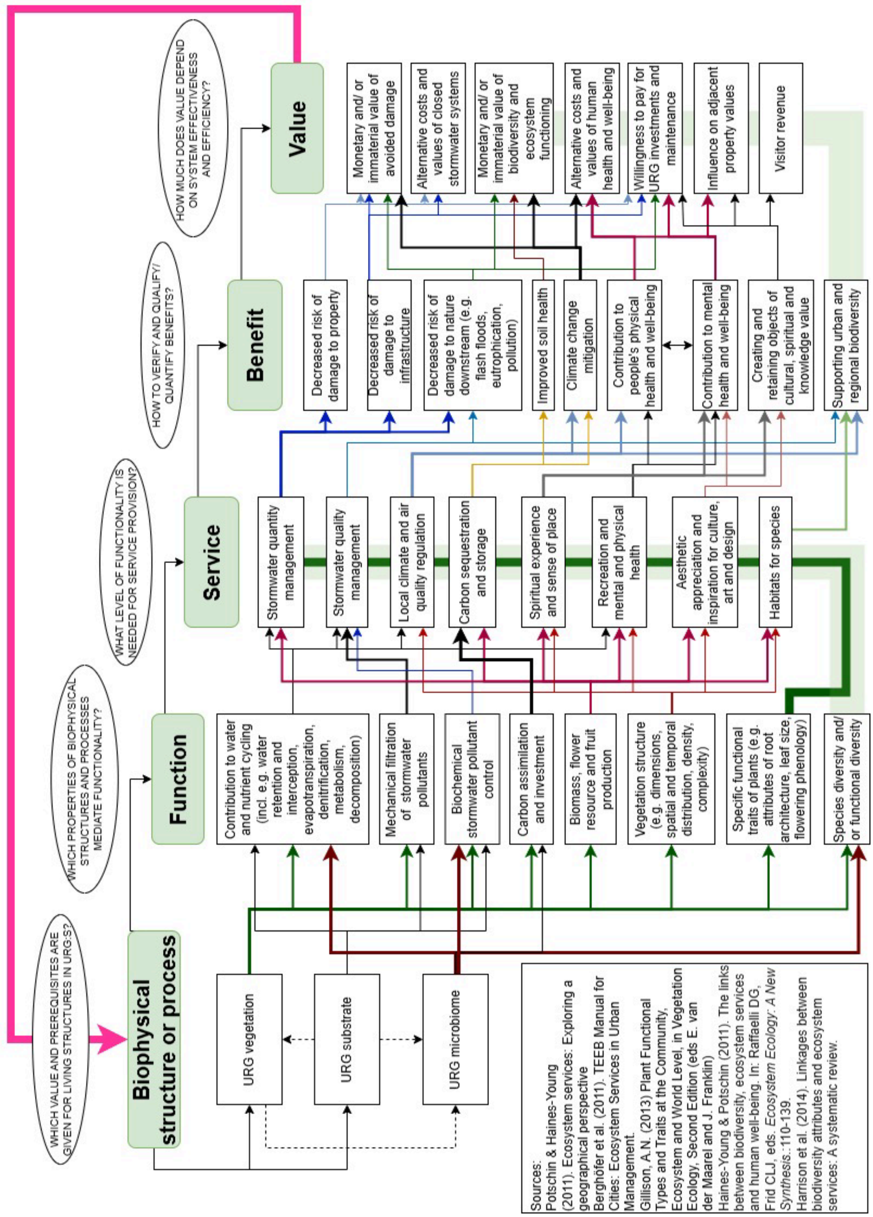

Figure 6 Urban rain gardens described in the ecosystem service cascade model. Note the feedback-loop from values to biophysical structures and processes. Thick green line from "specific functional traits of plants" to "service" emphasizes the influence of plant functional traits on the cascade. Light-green thick lines from "species diversity and/ or functional diversity" to services and from "Supporting urban and regional biodiversity" (benefit) to values denotes the importance of diversity metrics for the cascade.

3.3 Strategic management of urban green spaces

In Nordic countries, public urban green space management can cover the biotic and abiotic components of urban squares, parks, schoolyards, sports facilities and playgrounds, streetside vegetation, and recreational green and blue spaces like urban woodlands or beaches (Randrup & Persson 2009; Randrup & Jansson 2020). It involves multiple actors ranging from national and local politicians to municipal and administrative staff to private property owners and private users or inhabitants of public green spaces (Randrup & Persson 2009). Green space management works to develop and uphold users' economical, socio-cultural and environmental interests for public urban open spaces at varying scales, often with a focus on existing places and structures (Randrup & Persson 2009; Jansson & Lindgren 2012; Aronson et al. 2017). In the recent years upholding the technical functionality and interconnectivity of urban green spaces at multiple scales has been included, as the concepts of NbS and blue-green infrastructure have highlighted the role of urban vegetation and aquatic environment in providing ecosystem services and thus maintaining urban dwellers' quality of life (Gaston et al. 2013; Randrup & Jansson 2020; Randrup et al. 2021).

Which interests are prioritized at which levels of strategic management are also influenced by the interpersonal interactions and organizational structures of different stakeholders and stakeholder groups (Jansson & Lindgren 2012; Randrup & Jansson 2020). Possible tensions between stakeholder groups are especially prominent in cases where their interests such as biodiversity goals, amenity goals and technical goals are *de facto* or seemingly contradictory (Gaston et al. 2013; Lindholst et al. 2015; Aronson et al. 2017). Green space management is both the result and a driver of urban SETS, and thus inextricable from the ESS cascade of any given site from the biophysical objects and their functions to the value and valuation of ESS.

"Strategic management" is a theoretical model that describes the cyclical relationship between the three levels of urban green space management: Operational, tactical, and policy (Randrup & Persson 2009). Policy level includes long-term and large-scale decision-making for the management of urban spaces and produces cross-sectoral guidelines like municipal stormwater management or biodiversity strategies (Randrup & Persson 2009). City planning and green space design projects can be found on the tactical level (Randrup & Persson 2009). Green space construction and maintenance are at the operational level together with monitoring of realized projects, which feeds back information to policy and tactical levels (Randrup & Persson 2009). This feedback loop is essential for evaluating how actions in the tactical and policy levels influence operative work and thus the long-term development of urban green spaces (Jansson & Lindgren 2012). Cyclical approach to the management of urban green spaces is also necessary for adapting them to changes in the social, ecological and technical systems they are a part of (McPhearson et al. 2022).

Strategic management involves both the long-term decision making and short-term actions that determine vegetation development in urban green spaces, and accounts ideally for seasonal and interseasonal variation in weather, climate, and plant pests by cultivating organizational adaptiveness (Randrup & Jansson 2020). In short, the management of urban green spaces is about determining whether NbS are built, which NbS are built, where they are built, how they are designed, built and maintained, and how their effectiveness is measured and developed. Anchoring these strategic choices into the management organization and the wider groups of stakeholders also requires a clear communication of the rationale behind each choice, as a focus on the "why" of it all allows keeping the choice of exact actions and methods flexible (Randrup & Jansson 2020).

4. Materials and methods

The overarching strategy of inquiry in this thesis is research through design, viewed through a pragmatist research philosophy that uses a mixed methods approach that aims to provide integrated results through a combination of qualitative and quantitative methods (Creswell & Plano Clark 2011; Lenzholzer et al. 2013; Maxwell et al. 2015:224).

Urban planting design and vegetation management for species-rich and multifunctional plant assemblages within or without the DPC-framework have been found to have previously been studied through a multitude of research methods: Experimental methods, site surveys, design research, interview- and survey-based research, and case studies (see paper 1). The combination of methods used in the thesis has thus allowed the study of evidence-based planting design from multiple perspectives (Swaffield 2016):

1) Theoretical analysis of the DPC-framework and its relation to the concept of NbS

- Understanding the professional practice of DPC through gray literature, and by reviewing scientific research on DPC (pre-study and paper 1);
- Relating urban planting design and vegetation management in general, and DPC in particular, to NbS and URG:s through research and policy documents (paper 1);

2a) Empirical assessment of DPC as a planting design framework for urban rain gardens

- Systematically applying the DPC-framework to case study design and thus assessing how evidence-based planting design might be conducted within the framework (study 3);
- Inventorying URG:s to explore the combined effects of planting design and site history on the development of vegetation in urban NbS (study 2 and site inventories);

2b) Empirical studies of the establishment, development and maintenance of real-world DPC and/ or URG

- Investigating through interview studies how URG strategic management, including planting design and vegetation maintenance, is conducted in Sweden and Finland (study 2 and site inventories);

- Observing and measuring vegetation establishment, development and flowering performance in the designed case studies to compare DPC with other planting design strategies in URG:s (study 3).

A mixed methods approach is pertinent since the thesis is concerned with urban planting design within the urban space as a social-ecological-technological system (SETS) with its complex, interdisciplinary contexts (Findeli 2010 via Prominski 2019; McPhearson et al. 2022). Mixed-methods research allows the researcher to approach the questions from multiple angles, and to pose complementary questions that cannot be answered with the same research methods as the main question (Yin 2015). The mixed methods approach is thus a way to keep one foot in the natural and the other in social sciences, which allows accounting for both the biophysical and socio-cultural aspects of urban environments and their management (Jansson & Lindgren 2012). In mixed methods studies qualitative and quantitative methods can be used in hierarchical or non-hierarchical manner, sequentially or parallel, or even nested within each other (Yin 2015:659, 2018:6–8).

For example, the interview study (study 2) begins with qualitative and quantitative site surveys, which provide a background for qualitative semi-structured interview methods, which are then complemented with some archive studies (Galletta 2013). In the case studies (study 3) qualitative observations and quantitative measurements are collected in parallel to provide complementary and integrated information about the individual indicators of vegetation establishment, development and performance (Maxwell et al. 2015:229–230; Yin 2015; Tight 2017). The thesis also has some transdisciplinary features, as it aims to bridge scientific research and practical design work by incorporating theoretical frameworks and research methods (Szostak 2015:129) from urban ecology, urban stormwater management, and urban sustainability research through NbS, ESS, and blue-green infrastructure into the field of landscape architecture research.

4.1 Research through, for, and about design

"Research through design/ing" or "research by design" in landscape architecture can be framed as a process consisting of different moments, where design is combined with other forms of inquiry to satisfy the criteria for scientific research and thus reach generalizable findings (Deming &

Swaffield 2011; Lenzholzer et al. 2013; Prominski 2016, 2019). This research strategy is used to search for knowledge and generate evidence that can be used in landscape architectural theory development and for practical applications (Deming & Swaffield 2011; Lenzholzer et al. 2013; Prominski 2016). Due to its process-oriented nature, "research through design" is sometimes also used nearly synonymously with "design research", which is a term that covers not only the use of design methods and design objects in research, but also research on existing design objects or methods, as well as investigations that are carried out to support design work (Frayling (1993) via Jansson et al. 2019:12). All three types of design research are employed in this thesis.

By itself, "research through design" concerns the projective moments of a study, i.e. the phases and aspects where new things are created to serve as objects, tools or sites for the research project (Prominski 2019). This projective design is particularly used in this thesis to compose the plantings for the designed case studies (study 3) (Felson & Pickett 2005; Felson 2015) through subjective and objective criteria, with the aim of testing these designs against each other and the site. The positioning of the designed case studies in real-world contexts instead of controlled settings also allows for constructivist exploration of planting design (Lenzholzer et al. 2013).

"Research for design" is both about collecting and creating new evidence for the specific purpose of informing design work (Lenzholzer et al. 2013; Prominski 2016). The scoping literature review (paper 1) can be classified as "research for design", as it critically appraises and summarizes the available evidence base on DPC that could contribute to the fulfillment of NbS goals. Within this thesis "research for design" was also carried out for systematic information retrieval and organization to create plant selection and site analysis criteria for composing the DPC for the case study sites (study 3).

"Research about design" or "research on design" comes to play in the phase where existing design theory, research and other literature as well as existing cases or ideas are assessed and reflected on to formulate the research question and set the background for the study (Lenzholzer et al. 2013; Prominski 2019). The interview study (study 2) and concurrent site inventories can be seen as "research on design", as they investigate both the design process of vegetation in urban rain gardens, as well as how the design intentions are met by the realized and aging facilities. The designed case studies on urban rain gardens (study 3) specifically will also be evaluated and compared both against each other as well as defined "ideal states" (establishment and development during the warranty period) as well as identified trends (maintenance of comparable situations on average). Both the designed case studies (study 3) and the cases around which the interviews are built (study 2) concern "real life sites", i.e. places where multiple, partially unidentifiable environmental factors interact in an uncontrollable manner and affect the outcomes. Evaluating the anthropogenic effects on the studied plantings is vital for making sense of the case study findings (study 3) and for creating further design and management guidelines based on the knowledge generated in the project (Lehvävirta & Kotze 2009; Avolio et al. 2021).

4.2 Desk studies: narrative review, scoping review, and information gathering for designed case studies

Literature review methods have been used for two different studies in this thesis: The pre-study has the form of a narrative literature review and paper 1 is a scoping literature review. Additionally study 3 has involved systematic information gathering from planting design and garden literature as a basis for designing the case studies.

"Literature review" is an umbrella term for studies that summarize, analyze and critique literature on a specific field or topic (Baumeister & Leary 1997; Wee & Banister 2016; Rewhorn 2018; Snyder 2019; Fan et al. 2022). Literature reviews can also be used to define concepts, develop single- or transdisciplinary theories, identify research gaps, assess the quality and methodologies of previous research, test hypotheses, and generate practical design guidelines (Baumeister & Leary 1997; Wee & Banister 2016; Rewhorn 2018; Fan et al. 2022). Literature reviews can be conducted in multiple ways, resulting in different types of reviews with their own strengths and weaknesses (Grant & Booth 2009; Snyder 2019; Fan et al. 2022). For example, Grant and Booth (2009) identify 14 different types of literature reviews, which use varying combinations of search, appraisal, synthesis and analysis methods.

The pre-study (chapter 5) was undertaken as a preparation for the scoping review (paper 1), which in turn was conceptualized as the main study for attaining research objectives 1 and 3. The purpose of the pre-study was to get familiarized with DPC-literature and to analyze and summarize its core concepts and key figures in order to create research questions and hypotheses, formulate relevant search queries and selection criteria for literature collection, and to begin theorizing about the topic of study (Swedberg 2014:24–27). The results of the pre-study are presented as a narrative review, i.e. an informally conducted review that synthesizes chosen literature (Grant & Booth 2009; Snyder 2019; Fan et al. 2022). Narrative reviews are useful for theory development and explorative studies, as they allow for flexible and iterative search methods like snowballing and thus can accommodate gray literature (i.e. non-peer reviewed publications) and research from multiple disciplines (Baumeister & Leary 1997; Snyder 2019; Fan et al. 2022; Sukhera 2022). The most common critique for narrative reviews is that they are heavily influenced by the reviewer's personal attributes, and thus exhibit bias in literature selection, analysis and presentation (Fan et al. 2022; Sukhera 2022). Similarly to many other narrative reviews on DPC (Hitchmough 2010; Köppler & Hitchmough 2015; Cai 2020; Rainer 2021), the pre-study on DPC in this thesis was undertaken without a clearly formulated question or search and analysis methodologies and thus reinforces this negative view on narrative reviews.

The initial data collection and literature selection process for the narrative review (pre-study, chapter 5) was conducted via SLU Library's Primo-engine and Google Scholar, and favored contemporary landscape architecture and garden design authors whose publications have been influential among professional and amateur planting design practitioners in English-, and German-speaking countries and in the Nordics. "Snowballing" was used as a method to find further sources based on previously collected literature (Wohlin 2014). While gray literature and non-English language literature were essential for identifying the core ideas of the DPC-framework, it was not suitable for assessing the evidence base for planting design within the DPC-framework (Levac et al. 2010; Fan et al. 2022). The subjective selection of gray and scientific literature was thus complemented with following searches for scientific literature in the databases Scopus and Web of Science: "Design* plant communities" (24 unique results), "Natural* planting design" (3 unique results), "Ecol* planting design" (3 unique results), "Novel ornamental ecosystems" (0 results), "Dynamic vegetation design" (0 results), "Dynamic planting design" (0 results), "Staudenverwendung" (0 results), "Pflanzgemeinschaften" (0 results) and "Planting design" + ecolo*" (136 unique results). While the query "Planting design" + ecolo*" provided many unique search results, less than a third (43 results) were relevant for urban vegetation design and management, and even fewer for the DPC-framework in specific. The data collection performed for the pre-study thus highlighted the need to formulate broader search queries and to devise detailed literature selection criteria for the scoping review.

The scoping review (paper 1) was conducted to systematically assess the extent and characteristics of scientific literature on DPC, and to describe and analyze the evidence base for planting design and vegetation management for NbS found in DPC-literature (Arksey & O'Malley 2005; Grant & Booth 2009; Levac et al. 2010; Jesson 2012). The scoping review (paper 1) methodology attempts to diminish the biases often present in narrative reviews and to improve the rigor of the review by being explicit about literature selection and analysis methodologies, as well as by having clear aims and scope for the study (Sukhera 2022). Details about the literature selection and analysis methods for paper 1 are described in the paper itself.

4.3 Semi-structured group interviews

Semi-structured group interviews were used as the main method for study 2 to learn about current practices of planting design, vegetation management and vegetation performance in urban rain gardens. Interview studies enable the researcher to learn from and about other people's experiences and how they interpret the world by engaging in a discussion with them (Weiss 1995:1; Brinkmann 2014). Unlike quantitative surveys, qualitative interviews make it possible for the informants to develop their answer as the interview goes on and thus provide a richer dataset that covers multiple and sometimes even contradictory perspectives (Weiss 1995:3,9; Brinkmann 2014). Kvale & Brinkmann (2014) divide qualitative research interviews into seven phases: 1) Thematic description of the interview project; 2) Planning the interview project; 3) The interviews in themselves; 4) Transcription; 5) Analysis; 6) Verification; and 7) Reporting. Although the phases are represented in linear fashion, especially more explorative interview studies tend to involve revisions and complementary work, and thus individual phases may be repeated or conducted in parallel (Weiss 1995:14; Kvale & Brinkmann 2014).

In the first phase, the interviewer should inform themselves about the theme of the interview as preparation for the interview study (Galletta

2013:47; Kvale & Brinkmann 2014:149–151; Kanazawa 2017:313–314). Preparations are necessary for framing and formulating relevant research and interview questions, for identifying topics the interviewees should elaborate on during the interview, and for interpretation of the answers (Kvale & Brinkmann 2014:149–151; Kanazawa 2017:313). In this thesis the preparations were conducted by reading scientific and professional literature on urban rain gardens, site visits to and inventories of URG:s, and through work as a landscape designer in projects including URG:s. The basic premise of the study became thus about interviewing green area designers, construction contractors and maintenance staff about their experiences with URG vegetation. The order and formulation of the interview questions was also influenced by the chosen analytical framework (strategic management of urban green spaces), a wish to encourage openness in the interview situation, and an awareness of the often complex social relationships between the interviewer and the interviewee and between interviewees (Alvesson 2003; Brinkmann 2014). To encourage more detailed and concrete answers, the interviews and interview questions focus on specific URG projects that the interviewees have participated in.

The second phase is about planning the methodological and practical conduct of the interview, including the format of the interview, the interview questions, and selecting the interviewees (Kvale & Brinkmann 2014; Kanazawa 2017:315–316). The degree of structuredness in interview studies may vary from strict "*fixed-question-open-response*" to relatively unstructured (Weiss 1995:12; Brinkmann 2014). Semi-structured interviews were chosen for study 2, as they are suited for in-depth but free-form explorations of specific topics in a dialogue between the interviewer and the interviewee, or between the interviewer and the members of a (focus) group interview (Galletta 2013:24, 45; Brinkmann 2014; Kvale & Brinkmann 2014:191; Taylor et al. 2016:127–128). The choice of group interviews over individual interviews was made to encourage discussions between people working in different professional roles, and thus to gain a deeper understanding of dynamics between different phases of URG projects. Group sizes in the conducted interviews varied between 2 and 5 people, which is less than the typical 6-10 people focus groups used in marketing research (Kvale & Brinkmann 2014:191; Taylor et al. 2016:127–128). 32 interviewees representing 10 example projects participated in total, which is often considered sufficient for providing relevant answers to qualitative research questions (Weiss 1995:3; Kvale & Brinkmann 2014:156). Each of the 10 example projects are located in different Finnish or Swedish municipalities.

The third phase is about the actual interview situation. Besides interviews face-to-face, interviews via telephone calls or computer programs like e-mails or chat are possible (Kvale & Brinkmann 2014:190). In study 2, video calls through Microsoft Teams were used for ease and practicality, and for the software's in-built simultaneous transcription capacity. Controlling the transcription, coding and analysis of the answers (phases 4 and 5) were partially conducted in parallel (Braun & Clarke 2006). First round of coding the answers was based on inductive categories that highlighted common themes and key questions for specific projects or project phases (Kvale & Brinkmann 2014:249). The second coding and analysis phase was based on predetermined categories directly related to the research questions and theoretical framework and served to further condensate the most pertinent information (Braun & Clarke 2006; Kvale & Brinkmann 2014:247–248). The key findings were then illustrated by one or more key citations that summarized the interpreted results (Kvale & Brinkmann 2014:249; Kanazawa 2017).

The methodology for planning, interviewing, transcribing and analysis all aim to produce reliable and valid results (Kvale & Brinkmann 2014:310). Verification of interviews (phase 6) thus often requires that the researcher is specific, precise, honest and conscientious about their process, and uses accepted methods for quality control of their own work (Kvale & Brinkmann 2014:298,302; Kanazawa 2017). To an extent, the quality control aspect is implicit in scientific work and academic publication (Kvale & Brinkmann 2014:298-299,302). However, transparency and clarity in reporting the interview results (phase 7) is necessary if the research is to be received well and accepted by its audience (Kvale & Brinkmann 2014:317–319). Interviewing people in different professional roles, using practical example projects and giving direct citations from the interviews further serve to verify and validate the interview study and its results.

4.4 Case studies on urban rain gardens

Case studies are employed in landscape architectural research to study the complexities of real-world outdoor environments (Swaffield 2016; Yin

2018:15). This was also the motivation behind using case study methodologies for both study 2 and study 3.The purpose of studying specific cases of certain types of places, situations or phenomena in depth and in context is to understand how they can help to explain similar cases (Gerring 2004; Swaffield 2016; Yin 2018:15). In this thesis, the cases are used to understand the design, management and performance of vegetation in urban and supra-urban rain gardens in Swedish and Finnish socio-ecological-technological systems. Case studies are especially useful for explorative studies on poorly understood topics, but they can also be used to test hypotheses, to serve as pilot studies, and to deepen knowledge on established research topics (Gerring 2004; Yin 2018:6–7).

Case studies can also be constructed for the purpose of specific research projects as contextually sensitive "designed experiments", which are integrated sustainably into their environment (Felson & Pickett 2005; Nassauer & Opdam 2008; Felson 2015; Moosavi 2022). Designed experiments can help to develop evidence-based design practices that are both site-specific, while also generating generalizable information (Evans 2011; Felson 2015). While designed experiments are conducted in real-world contexts and not laboratories, they should aim for some degree of control to improve comparability between experimental units and be designed to help quantitative data collection (Felson & Pickett 2005). As the main experimental units for study 2 are relatively few, their comparability uncertain, and the controllability of the study environment is low, they are better suited for case study methodologies and thus are called "designed case studies" in this thesis (Felson & Pickett 2005; Flyvbjerg 2006). Designed case studies may be a useful research design for studying unpredictable and essentially uncontrollable urban SETS in a manner that, especially combined with provision of monitoring services to site owners and managers, might provide research results that are immediately applicable for the maintenance and development of urban green spaces (Felson & Pickett 2005; Nassauer & Opdam 2008; Evans 2011; Moosavi 2022). Designed case studies thus have the potential to generate practical design knowledge on how to develop and improve urban NbS (Moosavi 2022).

Case studies can be conducted via qualitative or quantitative methods, or both (mixed-methods research), and the methodologies can be adapted over time to changing understanding or attributes of the site (Gerring 2004; Swaffield 2016; Yin 2018:15–18). Typical sources of evidence that can be used in case studies are documents, interviews, and direct observations (Yin 2018). In study 2, 10 URG example projects from different Finnish and Swedish municipalities are studied in relative depth through both one-time site inventories (qualitative and quantitative data) and through project members' thoughts and experiences of the projects (qualitative data). In study 3, qualitative and quantitative longitudinal observations of different planting mixes at 2 supra-urban sites with URG:s are contrasted with each other, as well as with observations of the same planting mixes at a suburban, non-URG context to learn about the specific and general phenomenon that take place in these plantings. While only consisting of one-time observations of each site (see Table 4), the site inventories on URG vegetation can be used to contextualize the results of both study 2 and 3. In other words, the designed case studies can be considered as "main case study units", whose observations may be interpreted with help from complementary cases, i.e. example projects from study 2 and the additional URG inventories (Gerring 2004; Flyvbjerg 2006). By representing main units and complementary cases in their specific contexts it is thus possible to learn more about similarities and differences between the cases, to define criteria for case comparability, and to understand the generalizability or specificity of case study findings (Flyvbjerg 2006; Swaffield 2016).

Basic information	Planting unit (Name of municipality, site and subsite)
	Dimensions and area
	Construction date
Plant composition and other vegetation attributes	Observed ornamental taxa/ Intended taxa according to design documents
	Vegetation coverage-% (approximation)
	Observed group sizes for observed ornamental taxa (approximation expressed according to the plant sociability-system (Hansen & Stahl 1981; Sieber 1990)
	Observed distribution pattern for ornamental taxa/ intended planting pattern based on design documents
	Layering of ornamental taxa
	Most prevalent weeds (unintended taxa)
	Weediness of planting, % (approximation)
	Estimated condition of vegetation (based on size, blooming/fruiting, leaf color, pests and diseases, other possible deficiencies)
Urban rain garden design parameters	Planting area design (topography, borders, sub-bottom shape)
	Inlets and flow routes for stormwater
	Description of estimated catchment area
	Erosion control measures and possible observed erosion damage:
	Outlets and drainage in planting areas
Observed site conditions	Apparent amount of trash in planting area
	Growing substrate construction
	Assumed light availability
	Assumed soil water availability

Table 4 Site inventory parameters for example projects of study 2 and complementary inventories on urban rain garden vegetation.

The case selection for this thesis was based on a combination of representative and opportunistic reasons throughout (Flyvbjerg 2006; Swaffield 2016): While the interviewees and municipal research partners had the final say on which example projects or case study sites would be used, the licentiate student was able to provide initial criteria for the representativeness of cases (study 2) and comparability of cases (study 3). Although "opportunistically" selected cases can generate useful knowledge, they tend to lack in comparability and thus only add incrementally to the evidence base of a discipline (Swaffield 2016). Despite a partially opportunistic selection process, the designed case study sites (study 3) of Torgny Segerstedts Allé and Hägerstensvägen proved to be representative of street-scale URG solutions in newly developed areas and as retrofit in existing street environments respectively, as comparable exemplars of both types of cases resurfaced in the example projects of the interview studies (study 2) and the complementary URG site inventories.

While the total number of cases studied for this thesis is relatively high, it should be noted that the validity of case study results is not dependent on the quantity of cases; indeed, carefully selected singular case studies may sometimes be sufficient to corroborate or disprove previous hypotheses (Dion 1998 in Gerring 2004; Flyvbjerg 2006). Thus, it is important that the hypotheses are formulated in a manner that is testable within the self-contained study design.

5. Pre-study: Overview of the development of three design tools for designing plant communities

This chapter summarizes the findings of the initial data collection for paper 1 and constitutes a “pre-study” as opposed to the “main study” presented in paper 1 (Swedberg 2014:24–27). The pre-study explores the history of some of the ideas and movements of planting design that preceded the “New Perennial Movement”, the movement itself, and its inheritance. Much of chapter focuses on prominent planting design issues that contextualize the design tools (sensu Dalsgaard 2017) for ornamental herbaceous perennial vegetation, which characterize the DPC-framework. The historical overview is largely based on secondary or tertiary sources, which limits the scope of detail and original analysis of developments before the 21st century. The focus is on Germany, the Netherlands and the UK, but some relevant developments in the USA and the Nordic countries are also included.

5.1 Setting the stage: a brief summary of the development of the DPC-framework

William Robinson’s book *“The Wild Garden”* from 1870 is often considered to be one of the earliest written representations of naturalistic planting design, and thus a direct forefather to the DPC-framework (Robinson & Darke 2009). During the late 1800’s and early 1900’s naturalistic and ecological design experienced an active developmental period in Europe and USA thanks to the development of ecological science and an interest in native ecosystems, which ended in a bit of a lull during and after the second World War, until gaining steam again with the rise of environmental movements in the late 1960’s through to 1980’s (Woudstra 2014). Some of the most quoted ideas behind contemporary DPC were published during this time: Richard Hansen and his colleagues’ work on the Garden Habitat system and the publication of “*Die Stauden und Ihre Lebensbereiche*”, Beth Chatto’s books on British habitat gardening, and the first edition of John Philip Grime’s “*Plant strategies and vegetation processes*” (Kühn 2006; Woudstra 2014; Körner et al. 2016).

Dutch and German naturalistic planting design movements ("Dutch Wave" and "New German Style") are both rooted in love for nature: its appearance, inhabitants and well-being (Kingsbury & Oudolf 2015:17,56; Duthweiler 2016:XVI–XVII). From this background “The New Perennial Movement” was formed between 1980 and early 2000’s, which brought together planting designers interested in naturalistic and ecological vegetation through symposia, publications and professional contacts (Leopold & Perennial Perspectives Foundation 1997; Kingsbury & Oudolf 2015; Kühn 2024:36). An example is the Perennial Perspectives conference held in SLU Alnarp in 1992, which brought the Dutch Wave into Swedish consciousness and was the start of Piet Oudolf and Stefan Mattsson’s collaboration that resulted in two parks by Oudolf in Sweden, as well as a translation of his and Henk Gerritsen’s book *“Drömplantor”* (Oudolf & Gerritsen 1995; Kingsbury & Oudolf 2015:156–157; Andersson 2021:197). While there has been repeated exchange between European countries and the USA about trends in in planting design and plant ecology, it is first during this time that the exchange becomes formalized (Kingsbury & Oudolf 2015:151–155; Duthweiler 2016:XVI–XVII).

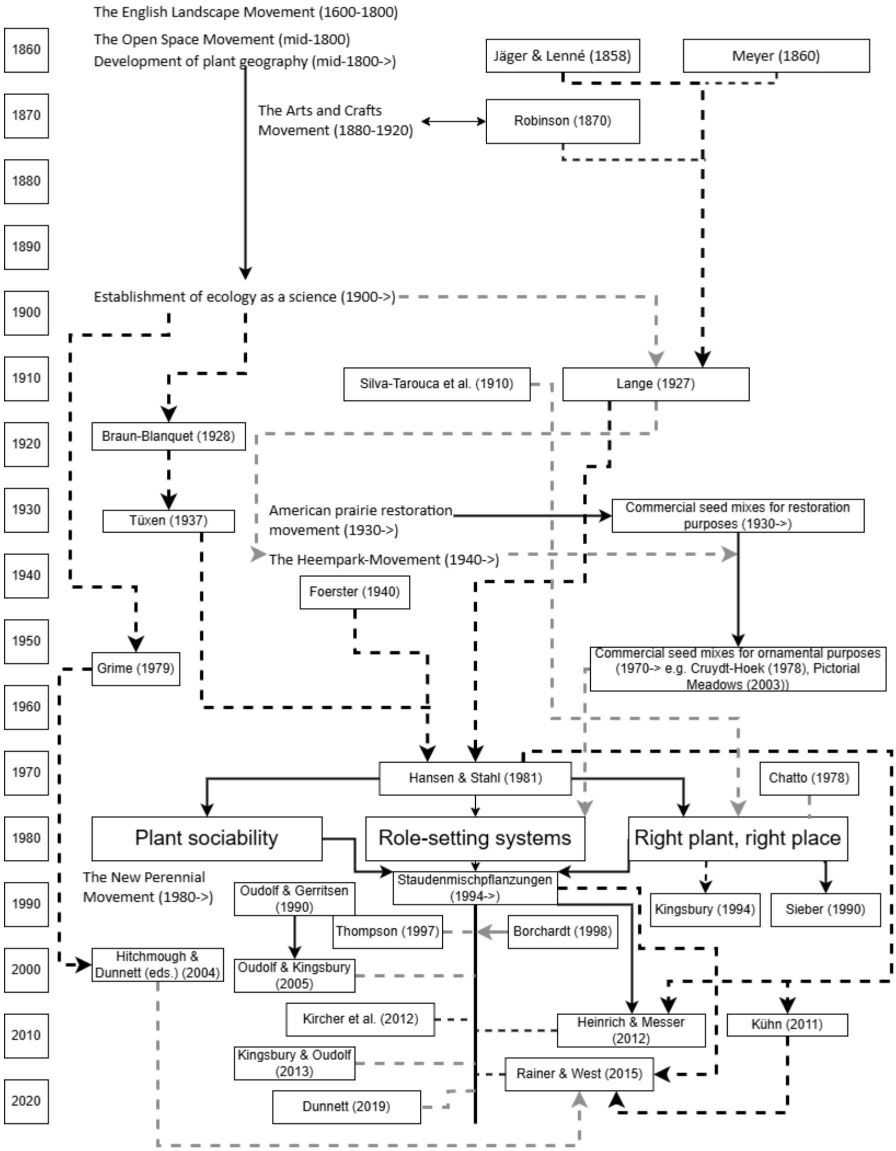

Figure 7 Rough timeline of the key influences on the three planting design tools within DPC. Continuous black lines denote direct contribution of certain publications on the development of an idea, or the development of an idea from another. Dashed lines denote the influence of one of the author's to another: Black dashed lines indicate direct influence, whereas grey dashed lines indicate lesser or indirect influence. The names and dates refer to the initial release year of key DPC or plant ecology publications. Note that the role-setting systems are the only design tool that continues to be debated and revamped.

The history of DPC is thus inextricable from the past 1,5 centuries of landscape architecture and garden design movements, which oscillate between formalism and informalism, preference for native or exotic plants, and the relative importance placed on either artistic or ecological concerns (Forbes et al. 1997; Kingsbury 2014; Woudstra 2014). Since DPC is emphatically concerned with the application of ecological knowledge on planting design, especially the early development of ecological science and later political movements of ecological awareness also give critical context for the development of DPC (Forbes et al. 1997; Woudstra 2014).

"The use of ecological knowledge" or "nature" can seem like given components of planting design, since it inevitably is about the use of living plants and thus must contend with every aspect that influences those lives (Forbes et al. 1997:70; Robinson 2016). How "ecological principles" or inspiration from nature is applied to planting design varies, as people's attitudes, beliefs and knowledge of nature inevitably influence their design work (Forbes et al. 1997:69-70,111; Woudstra 2014). Thus, the changes in how nature is viewed is also reflected in the history of DPC, especially when it comes to the relative importance placed on perceived natural patterns or ecological processes, the view of plantings as collection of individual plants or as cohesive plant communities, as well as the deeper personal and societal meanings of nature (Forbes et al. 1997:69).

However, the results of design work might be satisfactory even if the factors influencing the results aren't known by the designer (Forbes et al. 1997:72). There is evidence that the earliest applications of ecologically inspired practices like the use of nurse plants, rudimentary understanding of succession, mimicking patterns from nature and later understanding the importance of disturbance for maintaining semi-natural landscapes precede ecology as a science (Forbes et al. 1997:73-74,76-77). While some of the observations that formed the basis for these practices turned out to align more or less with current plant ecological knowledge, some observations were interpreted in ways that do not comply with today's understanding of cause and effect: For example, lupin plants growing on dry soils have been sometimes assumed to be the cause of drought, rather than interpreting their presence on a dry site as a sign of the plant's drought tolerance (Forbes et al. 1997:73-74,76-77,82).

Despite changing views on nature and ecology, there is a throughline in the history of ecological approaches to planting design that emphasizes the choice of site-adapted plant species and the use of management techniques informed by knowledge of environmental stress and disturbance to create plant assemblages that seem at home in the place where they live (Bradshaw (1983) in Forbes et al. 1997:70; Robinson & Darke 2009; Hansen & Stahl 2016). In many places and time periods, site adaptation and harmonizing with the surrounding ecosystems of the planting has been formulated into preferences or policies on the use of regionally native plants, whereas the use of exotic plants on sites where they thrive without intensive maintenance has just as often been seen as a way to work with site-adapted vegetation (Hitchmough 2011; Sjöman et al. 2016; Potgieter et al. 2017).

Possibly more than any other planting design style or application, the DPC-framework has also become increasingly interested in the developmental dynamics of vegetation, where ecological and anthropogenic processes direct changes in vegetation patterns, structure and composition (Forbes et al. 1997:108-109,111; Grosse-Bächle 2005; Dunnett 2014; Gustavsson 2014). Interest for matching plants to their site, vegetation patterns and ecological dynamics between plants has over time led to the development of different planting design tools, summarized in Figure 9.

Figure 8 Henk Gerritsen's Priona garden is a great example of the DPC dynamics of control and spontaneity: Both too much and too little maintenance can destroy the intended design and the joy of the planting.

Figure 9 Piet Oudolf is the most prominent designer of the New Perennial movement. Whether his work counts as DPC has been debated. Ichtushof in Rotterdam is one of his most naturalistic designs.

Figure 10 Queen Elizabeth Olympic Park showcases DPC plantings by Nigel Dunnett, James Hitchmough and Sarah Price.

5.2 Right plant in right place: reference landscapes, site conditions, and site adaptation

The credo of the DPC-framework is that there are suitable plants for each combination of site conditions, which makes it possible to create attractive plant assemblages for variable situations (Oudolf & Kingsbury 2005:101–103; Hitchmough 2014:160). The cliché "right plant, right place" denotes that the distribution and performance of different plant species is highly dependent on site conditions including disturbance and maintenance, as well as interactions between plants (Kühn 2011:98, 114; Hitchmough & Dunnett 2014:16–17; Hansen & Stahl 2016; Robinson 2016:19). Plant fitness to the site does not only improve their survival and development, but is also thought also decrease the need for vegetation maintenance (Hansen & Stahl 2016:13). Site conditions can be exogenous or endogenous, biotic or abiotic, vary in intensity, appear together in varying combinations and interacting each other in many ways (Kühn 2011:98–100; Hansen & Stahl 2016:13). In urban and garden settings human activity is a considerable driver of site conditions: changes in soil attributes, adding or removing shade, and sometimes complementing local precipitation with watering (Borchardt 1998:235; Kühn 2011:98; Robinson 2016:21).

Another way to approach site-adapted planting design is the use of reference landscapes to learn about plants and their habitats, and to project a coherent image of a planting (Hitchmough 2014:136; Hansen & Stahl 2016). The reference landscapes might be studied in detail for habitat restoration, conservation or emulation purposes, or used as a basis for stylizing and amplifying their most interesting features for wider public appeal (Borchardt 1998:235; Rainer & West 2015:55–59, 137–159; Robinson 2016:181). Rough habitat identification for choice of appropriate reference landscape/ "habitat archetype" can be done without expert equipment through analysis of a site's observable features (Borchardt 1998:239; Rainer & West 2015:124–137). Besides the use of native plants and plant combinations from locally relevant reference landscapes, the use of exotic plants to evoke native or foreign habitats is also possible, preferably as wild varieties or less hybridized cultivars to promote an overall naturalistic aesthetic (Borchardt 1998:236; Oudolf & Kingsbury 2013:131–132; Hansen & Stahl 2016).

5.2.1 Overview of the utilization of reference landscapes and plant tolerances to site conditions in planting design from 1600's onwards

From English Landscape Movement to Gardenesque and Arts and Crafts

The English Landscape Movement (1600-1800) might be seen as an early example of stylizing natural and semi-natural landscapes into informal garden designs (Forbes et al. 1997:71; Adler Kroll n.d.). Many of its features, such as foregrounding the designer's artistic intent by curbing spontaneous development, is at odds with later characteristics of ecological or naturalistic planting styles, including the Picturesque style of the 1700's that attempted to emulate natural patterns in gardens more accurately than its predecessors (Forbes et al. 1997:71–72; Woudstra 2014:25). The Landscape Movement's use of informally arranged meadows and woodlands as semi-natural garden elements that echoed the surrounding landscape would remain prominent features of ecologically inspired planting design, and outlast other types of naturalistic planting once the Gardenesque style took over most British Gardens (Forbes et al. 1997:72-73,85).

Figure 11 Rousham Gardens by William Kent (1685-1748) is an example of early 1700's English Landscape Movement.

Despite the reign of Gardenesque styles that abhorred the idea of nature in gardens, the Arts and Crafts movement (ca 1880-1920) preserved some of the earlier interest in and knowledge of natural patterns in planting design (Forbes et al. 1997:79–80; Kühn 2024:22–23). For example, William Robinson (1838 –1935) of the Arts and Crafts movement is known as a pioneer of naturalizing hardy exotics in native plant communities for easily maintained gardens (Forbes et al. 1997:80; Robinson 2016:315). His work was a deliberate combination of artistic ambitions and naturalistic principles, as he used field observations of the natural habitats of plants to understand the interplay of soil, precipitation, and temperature to establish explicit links between site factors and the opportunities for naturalizing specific plant species on different sites (Forbes et al. 1997:80, 82–83). From these, he created his own classification of " Garden Habitats" and corresponding plant species lists based mainly on soil types, but also habit, association with garden elements, and "*rabbit-proof plants*" (Forbes et al. 1997:83; Robinson & Darke 2009:263–278).

Early American landscape architects like Frederick Law Olmsted (1822-1903) and Calvert Vaux (1824-1895) modeled their large public parks after the English landscape park and thus gave informal garden styles wider legitimacy (Forbes et al. 1997:94–95; Beveridge 2006). But on the whole, formal garden layouts and imitation of classical European garden styles reigned in the USA as a way to tame the vast wilderness, and to show a belonging to higher social classes (Forbes et al. 1997:94–95). Even American applications of the ideas of Arts and Crafts movement were adapted to fit the overall desire for grand and tidy designs (Forbes et al. 1997:94–95). It is against this backdrop that Jens Jensen (1860-1951), Aldo Leopold (1887-1948) and Ossian Simonds (1855–1932) started working with American native vegetation in the early 1900's, and would remain very influential not only among prairie restoration and conservation circles, but also in the broader sphere of naturalistic planting design in America (Forbes et al. 1997:95; Douglas 2006; Streatfield 2006; Woudstra 2014:42–43; Olin 2021:43; *Who was Aldo Leopold?* n.d.).

The development of ecological science and its early applications in planting design

Parallel to the tail end of the Landscape Movement, Alexander von Humboldt (1769-1859) and other ecologists in Germany, UK, the USA, Sweden and Denmark developed the field of plant geography in the mid- to late 1800's and early 1900's by mapping the links between the natural distribution, appearance, and growth conditions of plants (Woudstra 2014:25–26, 28-29,50-51). Plant geography paved the way for describing interactions between plants in an assemblage, distinguishing between native and exotic plants, and determining plant adaptation to varying site conditions (Woudstra 2014:28–29). The development of naturalistic and ecological plantings in Germany was thus aided by the establishment and development of ecological sciences, i.e. "*the science of relations between organisms and their environment*" including the life cycles and trophic levels of organisms (Forbes et al. 1997:85; Woudstra 2014:27–28).

"Die Verwendung der Pflanzen in der Gartenkunst" (Hermann Jäger & Peter Joseph Lenné 1858), *"Lehrbuch der Schönen Pflanzenkunst"* (Gustav Meyer 1860), "*Gartengestaltung der Neuzeit"* (Willy Lange & Otto Stahn 1907), and *"Unsere Freiland-stauden"* (Ernst Graf Silva-Tarouca et al. 1910) were some of the early publications discussing of the use of ecological principles (plant origin, plants' demands on site conditions, ecological processes) in planting design even outside of botanical gardens (Wittke 1994 in Forbes et al. 1997; Kühn 2011:103, 2024:22; Woudstra 2014:27; Wolschke-Bulmahn (2009) and Gröning (1997) in Köppler 2017). For example, William Robinson's German contemporary Hermann Jäger (1958) was similarly interested in naturalizing exotic herbaceous plants in semi-natural garden settings, and had his own categorization of different planting situations in gardens such as flowerbeds, lawns, water features, rockeries, or pots (Woudstra 2014:29; Kühn 2024:22). Another example would be Silva-Tarouca et al.'s (1910) simple descriptions of suitable site conditions for different plants in garden settings in terms of soil moisture and light conditions (in Duthweiler 2016:X).

Humboldt, Robinson, Meyer and Jäger were especially influential on Willy Lange, who went on to publish several widely translated and distributed books on how to use plant geography, habitat archetypes and plant morphology as a basis for plant composition in gardens (Woudstra 2014:30; Duthweiler 2016:VI). Despite an avid interest for plant ecology, Lange overstated the significance of plant morphology, i.e. the appearance and visible physical adaptations of plants as a way to interpret the ideal site conditions for garden plants (Woudstra 2014:30). He also developed relatively mixed, fine-grain planting patterns inspired by observations of plant distribution in spontaneous assemblages, and called the resulting plantings "*Naturliche Pflanzengesellschaft - - - in Künstlerischer Steigerung*" ("natural plant communities - - - artistically enhanced") (Lange (1927) in Woudstra 2014:30–31). Lange became an active supporter of the national socialist party, which utilized landscape architecture, phytosociological principles, and the prominent (but not exclusive) use of native plants as a part of their effort to promote German national identity through landscape conservation (Forbes et al. 1997:85–86; Körner et al. 2016). Lange and his colleague Alwin Seifert thus prescribed native plants for use at landscape scales and exotics or rarefied natives in the private sphere of gardens, as their objective was in both cases to create outdoor spaces that look precious, harmonious and beautiful (Körner et al. 2016). Humboldt & Lange's principles of German ecological planting design also found their way to the USA in the early 1900's through the publications of the landscape architect Frank A. Vaughn (Wolschke-Bulmahn 1997:2; Woudstra 2014:42).

Similarly to Germany, there has been a strong streak of advocating the use of native plants, plant sociology and phytogeographical principles in the Dutch tradition of ecological planting (Forbes et al. 1997:92; Woudstra 2014:37). The geobotanist J.T.P. Bijhouver (1898-1974), who was knowledgeable about previous principles of ecological planting design, encouraged the study of local landscapes and plants to promote a specific Dutch style of site-adapted landscape design (Woudstra 2006, van Leeuwen & Doing Kraft (1959) in Woudstra 2014:38–39). While this encouragement did lead to the systematic study and recommendations for use of regionally native flora and habitats in the Netherlands, the results were not imposed on garden or park design, as these were seen to belong to the realm of artistic freedom and cultural expressions (Woudstra 2014:39–40). For example, the landscape architect Leonard A. Springer argued for the use of exotic plants by noting that even ecological plantings are always heavily influenced by the designers' artistic ambitions and thus are not comparable to habitat restoration (Woudstra 2014:36). Thus, the Heempark movement was emphatically focused on creating artistic renditions of Dutch native habitats (Koningen 1997).

"Wildnisgartenkunst" as a predecessor to "Lebensbereiche"

Karl Foerster (1874-1970), a nurseryman, garden writer and teacher, was another person in the early 1900's who served as a strong inspiration for naturalistic (but not so much ecological) planting design through Richard

Hansen, the nurseryman Ernst Pagels, and the garden designers Hermann Mattern and Herta Hammerbacher whom Foerster ran a design office with (Forbes et al. 1997:87–88; Dümpelmann 2006; Kingsbury & Oudolf 2015:60-61,66; Hopstock 2017; Kühn 2024:28–31). Hermann Mattern was also the main designer of the first German trial garden for perennials (Kühn 2024:31–32). Karl Foerster‘s "*Wildnisgartenkunst*" was based on the following principles: Using native plants in addition to exotics, preference for plant varieties with naturalistic appearance and habit, promoting the use of grasses and ferns in ornamental plantings, and finding plant compositions that would result in a balanced, well-proportioned design (Borchardt 1998:235; Duthweiler 2016:VI). Especially his book "*Lebende Gartentabelle*" (1940) that described plants in relation to their ideal site conditions, would inspire Hansen to develop his own study of Garden Habitats (Duthweiler 2016:X).

In their 1981 book "*Die Stauden und ihre Lebensbereiche*" Richard Hansen and Friedrich Stahl define designed plant communities ("*Pflanzgemeinschaften*") as plantings inspired by and functioning similarly to natural plant communities ("*Pflanzengemeinschaften*"), stylized using native and/ or exotic herbaceous plant species to evoke natural habitats and provide positive aesthetic experiences at low maintenance rates (Forbes et al. 1997:88; Kingsbury 2014:82; Duthweiler 2016:V–X; Hansen & Stahl 2016:5; Körner et al. 2016; Kühn 2024:12-15,31-32). Hansen and Stahl were inspired to write their book due to the perceived distance between nature and gardens, the monotony of woody plants and simple groundcover plantings of the 70's and 80's, the low status of green area design and management, as well as their assessment of poor plant knowledge among landscape designers (Duthweiler 2016:V–VI).

Hansen and Stahl had previously written the book "*Unser Garten, Seine Bunte Staudenwelt*" (1962) for professional audiences together, and thus knew how to best combine Stahl's expertise on perennials and garden design with Hansen's background in phytosociology, art history, and garden trials in the Weihenstephan gardens (Duthweiler 2016:V). Hermann Müssel, the technical director of the Weihenstephan gardens, as well as professor Josef Sieber also contributed to the development of the Garden Habitat system and to running the Germany-wide planting trials from the 1950's onwards (Duthweiler 2016:X, XIII). Trial programs for individual varieties of herbaceous perennials and later also standardized perennial mixes are still ongoing on 33 different sites in the German-speaking world, which is one of the German planting design's main backing arguments for the scientific nature of their work (Duthweiler 2016:VII, XVIII).

Hansen formulated the inherent connection between plant and its site into the principle of Garden Habitats ("*Lebensbereiche*") and utilized observations of different species' small-scale distribution patterns as one of the variables for classifying garden plants according to their sociability ("*Geselligkeitsstufen*")(Duthweiler 2016; Hansen & Stahl 2016). Both of these classification systems are still used and perpetuated as planting design tools both within and outside of Germany (Kühn 2011:102–107; Foerster-Stauden 2012; Rainer & West 2015:152–153; Duthweiler 2016:XIV; Bruns et al. 2019). A part of "*Die Stauden*" that is largely forgotten is the maintenance classifications of different types of native and exotic plants, especially natural varieties and highly bred plant varieties, according to their assumed maintenance needs (Duthweiler 2016:VI).

Figure 12 Parts of the Rock Garden at Weihenstephan Trial Gardens may be "original", i.e. they haven't undergone major replanting since their establishment in mid-1900's.

Early naturalistic planting in the United Kingdom

Beth Chatto pioneered her own version of habitat-based plantings in Great Britain in the late 1970's-early 1980's independent of Hansen and his colleagues' work (Kingsbury 2014:80,82,86-87; Kingsbury & Oudolf 2015:62,151). Her husband Andrew Chatto was an ecologist who studied flora of the world, and aided Beth Chatto in her search for suitable plants for the variable site conditions of her garden (The Beth Chatto Gardens n.d.a). She published multiple books on her garden, starting from *"the Dry Garden"* (1978) and ending with *"the Shade Garden"* (2002) (The Beth Chatto Gardens n.d.b). Other notable influences on ecological and naturalistic planting design in Britain in mid-1900's were Arthur G. Tansley's book *"British flora"* (1939), which introduced the scientific concept of plant communities and native plant assemblages to mainstream garden design (Woudstra 2014:48), and Cristopher Lloyd's garden Great Dixter (1950's >) where native-exotic meadows of "wild gardens" and Arts and Crafts-inspired borders meet (Forbes et al. 1997:103; Robinson 2016:316–317). Another contributor in the 60's and 70's was Brian Hackett, who promoted the use of ecological studies of local vegetation as the basis of planting design while also arguing for the inherently ecological nature of gardens as human-dominated ecosystems (Hackett (1962,1963,1979) in Woudstra 2014).

Figure 13 Native-exotic orchard meadow at the Arts and Crafts garden of Great Dixter.

Swedish and Finnish naturalistic planting design

In Sweden, Carl von Linné and his successors' fieldwork on plants' distribution and ecology from the 1700's onwards laid a groundwork for the use of regionally native vegetation (Woudstra 2014:50–51). Swedish naturalistic planting design can be traced back to mid-1800's, when Swedish garden textbooks referencing British and German garden literature started to promote the preservation of forested areas in gardens, and enhancing their appeal by increasing the abundance of wild, informally arranged flowering plants (Müller (1848) in Bucht 1997:61). Integration of areas with natural topography and existing vegetation into otherwise more formal parks and gardens with their exotic vegetation remained a common praxis with a long continuity until around mid-1900's, although naturalistic Swedish garden design was not without its critics in or outside of Sweden (Bucht 1997:60–120).

In the mid-1900's the use of herbaceous plants and trees in gardens became restricted, influenced by German, Dutch, and to a lesser extent British planting design (Bucht 1997:60–120; Tunnard (1937) in Woudstra 2014:51; Kingsbury & Oudolf 2015:151-156,162; Andersson 2021:197). Swedish planting design of the mid- to late 1900's was characterized by informal but utilitarian arrangements freely growing shrubs, complemented with the careful use of leafy and flowering perennials, which gave Swedish parks and gardens a somewhat naturalistic appearance (Woudstra 2014:53). The use of both native and exotic site-adapted plants worked simultaneously as symbolical and physical representations of the specific attributes of a site, as especially trees were used as visual shorthands for specific habitats (Gustavsson 2014; Andersson 2021:194).

An important strand in Swedish DPC practice is the development of "nature-like plantings", i.e. urban woodland design through the "ecological approach", which has been furthered through Nordic and British collaboration from the 1980's and 1990's (Tregay & Gustavsson 1983; Gustavsson 1986; Richnau et al. 2012). Some special features of these studies are the use of landscape laboratories and profile diagrams as methods to study the creation of social and cultural values in urban woodlands, woodland vegetation establishment, competition dynamics and woodland structural types (Forbes et al. 1997; Tyrväinen et al. 2006; Gustavsson 2009, 2014; Richnau et al. 2012; Woudstra 2014; Nielsen et al. 2017; Wiström et al. 2024). These approaches to urban woodland design are representative of the tradition of using reference landscapes to inform plant selection and vegetation configuration, but with a strong emphasis on spatial qualities and high recreational values (Gustavsson & Ingelög 1994; Gustavsson 2014; Mårtensson et al. 2025).

Similar urban forestry practices have also been explored in Finland, as has the use of reference habitats for garden design (Komulainen et al. 1995; Alanko 1996; Alanko & Kahila 2001; Hamberg et al. 2012; Räty 2014). DPC-design with herbaceous perennials has also been slowly gaining more prevalence in Sweden through landscape architectural education at SLU, and in Finland with support from the Finnish Association of Landscape Industries (Korn 2012; Karilas 2019).

Figure 14 Vargaslätten is an over 100-year-old native-exotic woodland garden influenced by Swedish national romantic ideas and the Arts and Crafts-movement. Design by Sigfrid Ericson.

Figure 15 Spring at Tor Nitzelius Park, which is a part of the Landscape Laboratory at SLU Alnarp.

Principles for matching plants to site conditions

Despite the long history of trying to understand how best to choose suitable plants for each site, individual plants' site condition tolerances are understudied. Garden literature, professional planting design literature and plant nursery catalogues teem with anecdotes of plants' performance in cultivation with regards to light, soil moisture, hardiness, pH, as well as references to observations of a plant's original habitats (climate, soil type, altitude, precipitation) (Bengtsson 1989; Alanko & Kahila 2001; Snodgrass & Snodgrass 2006; Kingsbury 2009:5; Schul 2015; Stångby Plantskola & Bellan, Patrick 2016; Bruns et al. 2019; Hansson & Hansson, 2022), which means that different books can give contradictory results (Sjöman & Busse Nielsen 2010; Kühn 2011:98–99; Köppler & Hitchmough 2015; Köppler 2017:18). Scientific methods for studying physiological indicators of stress tolerance are in an experimental phase, and large-scale research tends to be focused on trees (Sjöman et al. 2018; Tabassum et al. 2021). That means that the planting designer is inevitably dealing with approximates of plants' tolerances, no matter whether following a systematized framework or by piecing together individual considerations.

Knowledge of plant tolerances in urban situations is less readily available than information for garden settings, and for example urban applications of the Garden Habitat-system need to prioritize embedded information on site conditions over the visual archetypes (Robinson 2016:37; Heinrich & Messer 2017:37–39). Another alternative is to look for habitat analogues that match the site condition combinations of urban sites (Lundholm & Richardson 2010; Sjöman & Busse Nielsen 2010; Rainer & West 2015:124–137; Heinrich & Messer 2017:37–39; Ksiazek-Mikenas et al. 2021).

Although not usually presented as a way of matching plants to a site, J.P. Grime's plant strategy type theory, also known as the CSR-theory (first edition 1979, revised in 2001) can be used as a complementary framework for understanding how site-bound variation in productivity, stress and disturbance influence plant performance (Heinrich & Messer 2017:37–39). In short, productive sites favor plants with good competitive capacity (C-strategies); plants that can cope with extreme temperatures, a lack of light, water, nutrients or oxygen, alternatively cope with an excess of nutrients and plant toxins, can persist on stressful sites (S-strategies); and plants that reproduce quickly and effectively from seed or fragments can sustain themselves on sites where disturbance destroys or damages plants frequently (ruderal or R-strategies) (Grime 2001). Ornamental plantings have traditionally been constructed and managed for high productive capacity, making them most suitable for C-strategists and mixed strategies (Kingsbury 2009). However, substrates based on coarse mineral fractions are tested and used especially in urban stormwater management applications on green roofs and rain gardens, which increases drought- and nutrient stress and thus is more relevant for S-strategies (Heinrich & Messer 2017:52–67; Kircher et al. 2017; Schönfeld 2020; Pettersson Skog et al. 2023).

The CSR-theory has been embraced by many practitioners under the DPC-umbrella (Rainer & West 2015:172; Heinrich & Messer 2017:9-11,32-33; Dunnett 2019:100–103; Kühn 2024:58–63), although it is often considered to be lacking in explanatory power in planting design due to its generality (Kühn 2011:69), due to difficulties in applying ecological terminology into design (Dunnett 2019:100), due to a lack of research on classification of ornamental plants according to the system (Kingsbury 2009), or due to a lack of application guidelines, especially with regards to combining plants with different strategy types (Rainer & West 2015:167; Köppler 2017; Heinrich & Messer 2017; But see also Hitchmough 2017b:50;

and Rainer 2021, which discourage from mixing strategy types altogether). Additionally, DPC-practitioner's understanding of the plant strategy types and especially their subtypes is generally poor (Rainer & West 2015:167). Because of these limitations the value of the CSR-theory for planting design is currently mostly pedagogical. Thus, possibly the most important part of the CSR-theory for urban planting design is the insight that the higher stress and disturbance a site experiences, the less tenable it becomes for plant growth (Grime 2001; But see also Laughlin 2023:45–55).

5.2.2 The Garden Habitat-system for site-adapted plantings

Utilizing plants' site adaptations and site condition tolerances to create thematically coherent, healthy and low-maintenance plantings is at the heart of the German Garden Habitat-system (Hansen & Stahl 2016). Garden Habitats can be seen as analogues that cover loosely defined sets of site combinations, mental images to inspire design and rough goals for vegetation development (Kühn 2011:105). They are not recreations of any plant community typologies, but rather artistic interpretations and interpolations informed by spontaneously occurring plant assemblages (Borchardt 1998:239; Kühn 2011:98; Hansen & Stahl 2016; Körner et al. 2016). While the Garden Habitat system is not the first classification of site conditions in garden settings, it is the most widely used known system based habitat archetypes or -analogues as an aid for choosing plants on aesthetic and/ or ecological grounds for different parts of gardens, parks and other green areas even outside of Germany (Forbes et al. 1997:102; Kingsbury & Oudolf 2015:117,120; Kühn 2024:34-35,96).

The GH-system consists of seven main types of Garden Habitats: Woodland, woodland edge, open space, rockery, ornamental border, water edges & wetlands and water, each articulated further via numerous subcategories (Hansen & Stahl 2016). While the system is inspired by natural habitats, it is specifically developed for use in gardens and public urban green spaces (Hansen & Stahl 2016:44). It acknowledges the inherent differences between natural and constructed habitats, the potential adaptability of plants to site conditions that differ from their original habitats, as well as successional and seasonal changes to site conditions (Hansen & Stahl 2016:54–55). The original GH-system includes plant lists that are based on site conditions, plant attributes, and user-centric categorizations (Table 5). The first level classifications can be seen as aesthetic habitat archetypes or loose habitat associations, i.e. the Garden Habitats. The second level classifications tend to detail site conditions, site context and habitat associations, sometimes even blending in specific plant attributes. The third level classifications include for example the influence of maintenance type and -intensity on site conditions, vary wildly in content, and sometimes also include nested fourth-and fifth-level lists. Altogether, the book provides ca 130 separate plant lists at levels 1-3.

This version of the GH-system has largely been replaced in practice and education with applications of Dr. Josef Sieber's Garden Habitat system, which presents the GH independently from the associated plant lists (Kühn 2011:106; Foerster-Stauden 2012; Duthweiler 2016:XIII; Bruns et al. 2019; Staudengärtnerei Gaißmayer 2022). The number of GH presented as Sieber's can vary between 8 and 15, as some new habitat analogues have been added, and some of the lists provided by Hansen & Stahl have been expanded into their own GH-types (Kühn 2011) or subtypes (Foerster-Stauden 2012; Bruns et al. 2019; Staudengärtnerei Gaißmayer 2022). Soil moisture (terrestrial habitats) or water depth (aquatic habitats) are provided for most of the GH and their subtypes. None of the versions attributed to Sieber address light availability or soil attributes consistently within the system. Instead, plant nursery catalogues tend to provide species-specific information on plant tolerances for light and soil conditions as a complement to the GH-system. Some special characteristics are included in the descriptions of individual GH, such as soil pH (heath), microclimate (woodland edge), and soil depth (rock garden mats). Heinrich & Messer (2017) provide a slight update to the GH-system by relating Sieber's GH-classification to different urban sites and uses like green roofs or rain gardens, but do not revise or complement the GH-system accordingly.

Criteria for assigning plants into different Garden Habitats (“*Lebensbereiche*”) and different plant lists under these Garden Habitats in Hansen & Stahl (1981/2016)

First level lists: Seven Garden Habitats for herbaceous perennials						
1. Woodland	2. Wood-land edge	3. Open ground	4. Rock garden	5. Border	6. Water's edge and marsh	7. Water

Second-level lists and beyond:

Site conditions	Plant attributes	User-oriented categorizations
Microclimate: Air moisture, (Air) Temperature, wind	Geographical and/ or cultivated origin	Habitat association (e.g. woodland, rocky steppe, mature gardens)
Light conditions; Full sun, sunny, light shade, half-shade, shade	Winterhardiness, tolerance of different sites	Aesthetic categorization (e.g. visual impact, seasonal variation, color)
Soil moisture; Dry, moderate, moist, wet	Tolerance of specific maintenance regimes	Commercial availability
Other soil attributes: nutrient content, soil type, soil pH, other soil chemical properties, concentration of specific elements	Life form: Herbaceous flowering perennials, grasses, bulbs and tubers, ferns, climbers, dwarf shrubs, aquatic plants	Association with specific plants or plant types (trees, phytosociological indicator plants
Water conditions for aquatic plants: depth, movement, quality	Size: Spread, height	Function (e.g. turfgrass replacement, spatial allowance)
Temporal variation in site conditions	Habit (e.g. climbing, creeping, tussock)	Maintenance: Intensity, type
Successional stage of existing vegetation	Flowering: Intensity, timing	Planting pattern and density
	Longevity (perennials, annuals, biennials, short-lived plants)	Planting size
	Competitiveness	Role in planting (e.g. groundcover, solitary plants, thematic key plants)
	Vigor	Context: Cultural (e.g. farmer’s gardens, by built garden features), site (garden, park, rock garden), user context (plant collectors, medicinal plants)
		Focus on specific genus (e.g. *Lilium spp., Narcissus spp., Erica spp.)*

Table 5 Hansen & Stahl's Garden Habitats and criteria used for plant lists under different Garden Habitats

The GH-system is a design tool for plant species selection, mainly by contributing to finding parameters that influence interactions between plants and their sites. Hansen & Stahl's version of the system has a focus on combining plants from similar habitats to ensure a naturalistic aesthetic, whereas the Sieber-adjacent versions allow combining plants more freely according to their tolerances (see also Hitchmough 2014:134). Neither the Sieber-derivates nor Hansen & Stahl's version present site condition combinations comprehensively or systematically, which limits their useability in matching plants with their abiotic and cultural environment. Another limit to the useability of the systems are unclassified taxa, although especially German plant nurseries continue to classify new commercially available plants. The biggest limiting factor for the reliability of the GH-system in goal fulfilment is the limited scientific evidence on taxon-specific site tolerances and optimums. This weakness is not limited to the GH-system, but affects all attempts at site-adapted planting design.

Figure 16 The perennial meadow at Weihenstephan, probably representing the Garden Habitat open ground-2, is a contemporary example of the GH-system.

5.3 Utilization of ecological patterns and processes

In the DPC-framework, planting patterns are used as a way to promote a naturalistic appearance and to create impactful visual effects in small and large scales (Borchardt 1998:235). “Pattern” in a designed plant community can be considered as much of a function of the design as it is the result of processes of change in the vegetation after the planting has been created (Borchardt 1998:235; Dunnett 2014:98; Dunnett et al. 2014:247; Hitchmough 2014:134, 171, 173; Wiley (2000) in Kingsbury 2014:87). This applies equally to planted and sown designed vegetation as well as managed spontaneous vegetation, as all of them are subject to intentional anthropogenic actions (Koningen 2014). Some approaches to DPC downplay the importance of precise plant placement in favor of trusting the plant combination and the patterning force of ecological processes, although many designers have been able to create great spatial and experiential effects through careful considerations for massing lower and taller vegetation, creating concentrations of simultaneous flowering, and using solitary perennials or trees as visual foci (Oudolf & Kingsbury 2005:101, 2013; Hitchmough 2014:131; Kingsbury 2014:85).

The more complex combinations and patterns, the more knowledge about plants’ competitive traits and responses to different maintenance techniques they require (Borchardt 1998:235; Oudolf & Kingsbury 2013:34). Plant knowledge can, for example, allow the designer to mimic the spatial structures of a reference habitat, either using plants from local communities or by substituting them with exotic plants (Hitchmough & Dunnett 2014:16). While the structures and patterns of spontaneous vegetation may make a planting appear to be ecologically functional and easy to maintain, they do not necessarily lend these attributes to vegetation (Hitchmough & Dunnett 2014:16). For example, vegetation on productive soils tends to become dominated by highly competitive single-species clonal groups, no matter the initial planting composition (Suter et al. 2010; Hitchmough 2014:130). This effect is exacerbated by infrequent, invariable and non-selective disturbance patterns (Schmithals & Kühn 2014; Bjørn et al. 2019; Seidl et al. 2022). Less productive sites have finer patterns and more even distribution of different plant species across the space (Hitchmough 2014:130). The high planting densities promoted by some DPC practitioners as a way to improve the resilience of plantings also requires a good understanding of what increased density means for competitive circumstances in plantings (Oudolf &

Kingsbury 2013:236–237; Hitchmough 2014). The arguments for this approach are that denser plantings give less space for invasive weeds and seedlings, and that the plants become less prone to flopping as they can support each other, instead of requiring staking to stay upright (Oudolf & Kingsbury 2013:236–237; Rainer & West 2015:50–54).

5.3.1 Brief historical overview on the use of ecological patterns and processes in planting design

Early ideas of ecological patterns and processes in garden settings

William Robinson's planting design work in the late 1800's can be seen as a signifier of the shift from naturalistic patterns towards understanding ecological processes (Forbes et al. 1997:79–80). For example, Robinson's writing shows an appreciation for dynamic appearance, especially in terms of seasonal changes and intermingled distribution patterns, as well as gives evidence of early concerns for the effect of interspecies competition on vegetation development (Forbes et al. 1997:80–82). The maintenance of these plantings consisted of extensive methods like mowing, and Robinson also spent minimal effort on site preparations (Forbes et al. 1997:82). While Robinson's fellow Arts and Crafts designer Gertrude Jekyll continued to apply and develop Robinson's principles in her own work with woodland gardens, she clearly separated her work from the practice of "wild gardening" both in terms of plant choices and by using drifts as the basis for planting patterns (Forbes et al. 1997:84; Richardson 2021). Jekyll's work was also a precursor to the cottage garden style of designers like Vita Sackville-West or Marjorie Fish, which artistically utilizes the appearance of spontaneity without seeking to use ecological patterns or principles as its basis (Richardson 2021:80).

Driven by the Romantic notion that human intervention on nature's workings was unequivocally bad, the Open Space Movement of the mid-1800's took the ideas of working with nature even further by promoting passive nature preservation as opposed to active conservation efforts, essentially allowing succession to take over semi-natural landscapes (Forbes et al. 1997:75–77; Baigent n.d.). Besides Romantic-era view of nature, The Open Space Movement was also a countermovement to the intensification of agriculture and forestry, and the resulting loss of wilder vegetation (Forbes et al. 1997:75). Parallel to calls for using native plants and protecting nature by ceasing maintenance of coppiced, grazed and mown vegetation, the

Gardenesque movement that rejected any naturalistic ambitions in gardens was also gaining popularity during the Victorian era (Forbes et al. 1997:78). It was an intentional counterforce that attached itself to the formal tradition of pre-Landscape Movement garden styles like Renaissance and Baroque, and excluded the use of native plants in favor of showy exotic species (Forbes et al. 1997:78). The reign of Gardenesque styles was long, even though the formal designs and the tender exotic plants of the Gardenesque required much more money and work to maintain than the Landscape Garden (Forbes et al. 1997:78).

The influence of phytosociology on German planting design

The botanist Josias Braun-Blanquet's (1884-1980) work on developing phytosociology, i.e. the study of co-occurring plant species, plant abundance, growing patterns and plant distribution in spontaneously occurring plant assemblages through surveys was taken up by a fellow botanist, Reinhold Tüxen (Ewald 2003; Dengler et al. 2008; Woudstra 2014:35). Tüxen not only went on to further develop phytosociology through his surveys of natural vegetation but became also an inspiration for garden designers and supported them in applying his research to planting design (Woudstra 2014:35). One of Tüxen's notable students was the landscape designer and teacher Richard Hansen, who carried out phytosociological surveys under Tüxen during World War II and used the ideas of plant sociability formulated by phytosociologists to inform his own "*die Geselligkeit der Stauden*"-classification (Duthweiler 2016:VIII; Körner et al. 2016). The influence of phytosociology on Hansen's work is apparent when comparing Braun-Blanquet's illustrations of plant assemblages with Hansen's way of describing and presenting planting patterns based on the most suitable group sizes for each species (Körner et al. 2016). While phytosociology has mostly been replaced with more complex and often individualistic descriptions of plant community ecology and the drivers of community assembly (Götzenberger et al. 2012; Decocq 2016), Hansen's "*Geselligkeit*"-system lives on in the German-speaking planting design methods.

Naturalistic patterns in the Heempark-movement

Jac P. Thijsse, Leonard A. Springer (1855-1940), A.J. van Laren, Cees Spikes and Heimans were some of the Dutch pioneers of ecological and naturalistic planting, creating public gardens like the Heempark Thijssepark in Amstelveen, the Amsterdam bos, and Zuiderpark (Woudstra 2014:38;

Heinrich & Messer 2017:24). The Heemparks were designed to provide an idealized, stylized image of Dutch nature and native plant communities, and to give people a place where they could learn about these environments even as Dutch habitats were rapidly decreasing in the face of ongoing urbanization (Forbes et al. 1997:93; Koningen 1997; Woudstra 2014).

Heemparks needed intensive maintenance by highly skilled gardeners, which later practitioners like Ger Londo tried to avert by encouraging non-selective maintenance methods like weeding, even at the cost of lost detail in vegetation composition and structure (Koningen 1997; Londo (1977) in Woudstra 2014:40). The top-down application of the early Heemparks raised some concerns about how they were anchored in local communities' lives, which led to later Heemparks being built and managed with input from the inhabitants of the area (Forbes et al. 1997:93–94, 105).

Figure 17 Idealized Dutch nature at Jac P. Thijssepark in Amstelveen.

5.3.2 Plant sociability as a tool for determining planting patterns

The most prominent systematic approach to planting patterns within the DPC-framework is the "*Geselligkeit*"-system (Kühn 2011:122; Rainer & West 2015:152–153; Hansen & Stahl 2016:62). Inspired by phytosociology, Hansen, Stahl and Müssel (2016:62) used observations of horizontal patterns in spontaneous vegetation as a basis for their classification of ornamental plants according to their sociability ("*Geselligkeit*"), expressed as recommended group sizes for different taxa. The sociability classification tends to be misrepresented as a purely phytosociological approach (Kühn 2011:122; Dunnett 2014:108; Rainer & West 2015:151–152), although Hansen, Stahl and Müssel themselves describe the sociability classification as a tool for stylizing nature into aesthetically pleasant compositions that are stable in the long term (Hansen & Stahl 2016:61–62). Borchardt (1998:238) later proposed that the classification should be almost purely based on plant habit and visual considerations, but his view has not been popularized.

"*Die Stauden und ihre Lebensbereiche*" lists the following criteria as basis for the sociability classification (Hansen & Stahl 2016:62):

- Plant sociological assessments of typical group sizes in nature
- Inherent plant traits related to their life forms, such as spreading habit, typical seasonal dynamics and size
- Assumed effect of group size on maintenance needs
- Variability in visual performance during a growing season
- Influence of group size on visual effect (which plants look best in which group sizes).

The different factors described are independent from each other without being completely exhaustive, meaning that any of the aspects may be combined with each other for different results, and that there may be additional aspects that could impact the grouping of plants. The variables of maintenance needs and visual effect are context-dependent and thus largely subjective. The individual aspects are neither elaborated on, nor is the influence of each aspect on the overall classification provided by either Hansen and Stahl or the plant nurseries that currently are perpetuating this system, meaning that it is impossible to tell which attributes were prioritized for the class ascribed to each plant. These flaws in the classification system seem to necessitate prioritization between the different factors on a case-by-case basis in order to ascribe a class to any plant. Comparing *Macleaya cordata* and *Verbascum olympicum* gives an example of the difficulties of applying the sociability classification system (Hansen & Stahl 2016:70–71). Both plants are of sociability class is I, i.e. they are recommended for use as solitary plants or in groups of 2-3 individuals. Because these plants' life forms, spreading habits and maintenance needs are very different, the classification probably has emphasized plant size, visual habit, and relatively stable visual performance within a growing season. The classification system does not provide information on exact classification criteria to the reader, and thus the designer needs to have species-specific knowledge to make sense of the implications of the classification for each individual taxon.

While the "*Geselligkeit*"-system has been seen by some practitioners as a useful tool for assessing the competitive compatibility of plants, others have found it confusing and problematic (Hitchmough 2014:168–169; Heinrich & Messer 2017:27–28). Kingsbury (Kingsbury 2009:11) claims that the classification paves way for a dogmatic style of planting design, where following a set system may become more important than designing for ecological functionality. This critique is partly a reference to Dunnett (Dunnett et al. 2014:107–108), who points out that plants' natural distribution patterns are influenced by their environment rather than expressions of inherent plant traits. These critiques misrepresent the system by boiling it down to emulating observations on nature, fail to problematize the system itself, and as such do not engage with the reasons why the classification exists and is still used despite its flaws.

From a practitioner's point of view the attractiveness of the sociability system is that it implies a collected insight into several aspects of plant growth and life cycles, which is then used as the basis for making a recommendation for how a plant with certain attribute sets could best be used for technical-ecological function and aesthetic effect. Despite failing to provide a transparent method for assigning plants into the different categories, the sociability classification has pedagogical value in illuminating that inherent plant traits influence the extent to which plants can be expected to cover ground reliably.

5.4 Designing structurally complex plant assemblages

Plantings in the DPC-framework are often thought of in terms of plant communities that consist of different populations of multiple plant species (Hitchmough & Dunnett 2014:2; Rainer & West 2015:43–47). The idea of working with “communities” as opposed to “individuals” is seen as a way to work with ecological processes, reduce or rationalize maintenance needs, and create beauty (Hitchmough & Dunnett 2014:2; Evert [2010] in Heinrich & Messer 2017:17–18; Tabassum et al. 2020). The idea is usually to give the plant assemblages an "ecological structure", i.e. plantings should have an appropriate number of structural layers at different heights, the layers should have densities that work for the intended aesthetic goals and are useful for maintaining the layered structure (Hitchmough 2014:168). Combining plant species with different kinds of growing forms can also make plantings more resilient in the face of disturbances that decrease their canopy cover (Simon (1990) in Kingsbury 2014:85; Tabassum et al. 2020). Plant species selection is often restrained to maintain legibility of plantings, and to utilize the ecological phenomenon of few species visually and proportionally dominating any given plant community (Luz [2002] in Kingsbury 2014:85). The whole is managed above the individuals (Evert (2010) in Heinrich & Messer 2017:17–18).

Commercially produced mixtures of meadow and prairie plants originate from North American prairie seed mixes created for restoration projects at Wisconsin University in the 1930's (Heinrich & Messer 2017:14). These kinds of mixes have been further developed in the USA, Germany, Switzerland, Austria, the Netherlands and Great Britain from the 1970’s onward, and gained moderate success (Kingsbury 2009:12–13; Oudolf & Kingsbury 2013:201; Kingsbury & Oudolf 2015:52–53; Heinrich & Messer 2017:14). Despite this long history of commercial plant mixes, the “New Perennial movements’” single most important development within the DPC-framework are the “*Staudenmischpflanzungen*”, which are standardized, systematically trialled mixes of perennial grasses, forbs and bulbs, as well as recently also coppiced trees and shrubs, composed for specific Garden Habitats according to the roles each plant plays in the assemblage (Kingsbury 2009:12; Kircher et al. 2012; Heinrich & Messer 2017). Each mixture consists of predetermined plant varieties in predefined proportions and the plantings themselves can be laid out entirely randomly at even spacing, thus saving the effort of creating planting plans (Kingsbury 2009:12; Kircher et al. 2012; Dunnett et al. 2014; Heinrich & Messer 2017:16,49). Some aspects of the mixes, like planting density or placement of some plant species, can be adjusted according to site conditions and goals (Heinrich & Messer 2017:7,16,49).

“*Staudenmischpflanzungen*” or mixed perennial plantings were originally developed by Walter Kolb and Wolfram Kircher at the Bayerische Landesanstalt für Weinbau und Gartenbau (LWG) in 1994 (Kircher et al. 2012). Mixed perennial plantings apply a broad range of DPC design tools and principles, like the Garden Habitat-system, the “*Geselligkeit”*-system, and also has incorporated Grime’s plant strategy types as a more recent development (Borchardt 1998:238,245; Kircher et al. 2012; Rainer & West 2015:159–187; Heinrich & Messer 2017:31–33; Alizadeh & Hitchmough 2019). A related approach to the German “*Staudenmischpflanzungen*” is the Swiss "*Integrierte Pflanzensysteme*" from ZHAW Wädenswil, which differs from its parent by combining planting and sowing, and by integrating creative management.

Later more research institutes and universities in Germany, Austria and Switzerland joined the effort, and the development of new mixes is coordinated by the Bund Deutscher Staudengärtner (“German union of perennial gardeners”) (Kingsbury 2009:12; Kircher et al. 2012; Oudolf & Kingsbury 2013:201; Heinrich & Messer 2017:32–33). These standardized plant mixes, created for use in specific Garden Habitats, were developed as an easily applicable and maintainable alternative to shrub monocultures and seasonal bedding plants (Kircher et al. 2012; Heinrich & Messer 2017:18–19). A considerable interest and demand for mixed perennial plantings was created in Germany through frequent communication geared towards landscape professionals and public actors working with green spaces, who were attracted by the idea of having perennial plantings despite financial challenges (Kircher et al. 2012; Heinrich & Messer 2017:6). 'Silbersommer' by the Arbeitskreis Pflanzenverwendung of the Bund Deutscher Staudengärtner in 1998 is the most broadly used standard mix, which has been tested at varying site conditions in both Germany and Switzerland (Heinrich & Messer 2017:20). It has been successful even in urban condition due to its good tolerance of dry and warm conditions, as well as its capacity to sustain its visual appeal and diversity (Kingsbury 2009:86).

Figure 18 Planting trials for new mixed perennial plantings at LWG Veitshöchheim. These standardized mixtures are the first that feature trees. The chosen tree species respond well to coppicing, which helps maintain the mixtures relatively low.

Figure 19 A variation of "Silbersommer" in a very narrow streetside strip in Würzburg

5.4.1 Role-setting tools for plantings

DPC practitioners' interest in the ecological and aesthetic roles different plants can play has led to the development of a variety of role-setting systems that are used for selecting plant species and determining their initial abundance and distribution in a planting (Heinrich & Messer 2017:30). Hansen & Stahl's "*Leitstaudenprinzip*" (2016:82–87) emphasizes plants' visual attributes as a basis of organizing them into patterns, but does not provide a systematic framework for the application of this principle. Another early inspiration for visually oriented role-can be found in Borchardt's book "Pflanzenkompositionen" (1998), where the roles for plants are described in much more detail but not formulated into systematic applications. From this background, a variety of role-setting systems have been created to maintain a grip on the design process of complex, species-rich plant mixes.

The most common role-setting systems of the DPC-framework today are based on the system developed for "*Staudenmischpflanzungen*" or "mixed perennial plantings" (MPP) in Germany in the 1990's (Kircher et al. 2012; Heinrich & Messer 2017). The roles have been developed partly out of practical concerns: informing constructors of the order in which the plants would be laid out, providing a way to sort the plants in each mix according to their proportional share of the whole, and making the mixes scalable across different-sized spaces (Kircher et al. 2012; Heinrich & Messer 2017).

The role-setting systems can also be seen as a way of dictating the general principles for the visual experience of plantings, as the roles are often described based on the intended size and habit of relevant plants, as well as their percentage of the planting (Borchardt 1998:238; Kircher et al. 2012; Heinrich & Messer 2017:32–33). There is also a general idea that the proportions given for each role influence the ecological function and development of the planting, possibly most effectively conveyed by Rainer & West's decision to name their system "*layers of a plant community*" (2015:172). Oudolf & Kingsbury (2005:109) also point out that some of the roles are relative, e.g. structure vs. filler position is partially decided based on the rest of the plant selection. For example, *Anemone sylvestris, Calamintha nepeta and Luzula sylvatica* are used in some of BdS's mixes as companion plants, and in others as groundcovers (*BdS Staudenmischungen* 2025).

Variation in historical and contemporary role-setting systems

Table 6, Table 7and Table 8 present eleven different ways of approaching role-setting in designed plant communities. The role-setting systems found in the material can be roughly sorted into four categories: German proto-roles (Borchardt 1998; Hansen & Stahl 2016), explicit variations on the MPP-system (Messer 2009; Kühn 2011; Kircher et al. 2012; Heinrich & Messer 2017), implicit variations on the MPP-system (Rainer & West 2015) and independent role-setting systems (Thompson 1997; Luz 2001; Oudolf & Kingsbury 2013; Dunnett 2019). While the chronological presentation of these systems serves to imply their interconnectedness, it should not be read as a continuous development of a singular role-setting tool; rather, with the exception of Kircher et al. (2012) the material presents their own approaches as individual systems, without acknowledging (Borchardt 1998; Rainer & West 2015) or with only partial acknowledgement (Messer 2009; Kühn 2011; Heinrich & Messer 2017; Dunnett 2019) of the larger context in which they have been developed. The individuality of each system is above all implied by limited engagement or no engagement with the previous versions, as there are almost no reflections upon the number, naming or proportions of the roles in each of the systems.

The role-setting systems of the MPP category largely follow their vocabulary used by Hansen & Stahl (2016) and Borchardt (1998), although much of the contents of the contemporary terminology differs from their original use (Kühn 2011:246; But see also Robinson 2016:176–177). The independent role-setting systems either purposefully distance themselves from the MPP tradition (Dunnett 2019) or lack an explicit connection to it (Thompson 1997:117–123; Oudolf & Kingsbury 2013:80). Dunnett's approach to his "structural types" is bound to their conception as parts of a design methodology, and as such he makes no promises of this correlating with ecological function (2019). Dunnett's system is also not intended to be used for randomly mixed plantings, but rather it is a tool for deciding the individual placement of plants within mixes (2019:121). Oudolf's simplified 70-30 split between structural plants and filler plants pays clear homage to Heiner Luz's almost identical "*principle of dominant species*" (Luz 2001; Oudolf & Kingsbury 2013:80). Thompson uses the idea of "*growth forms*" to recommend combining perennials from different growth form categories to ensure easily managed, multilayered groundcover in mixed border plantings, and also gives some pointers on the visual characteristics each category brings to play (Thompson 1997:117–123). As with the proto-roles, his categories contain a fair amount of overlap, and the system is not applied consistently throughout the book or the garden settings he describes.

Although the role-setting systems are intended to simplify the design process (Rainer & West 2015; Dunnett 2019), the role-setting systems cannot be used without a thorough understanding of plant material and the socio-technological-ecological systems of the site (Heinrich & Messer 2017). In the cases where Grime et al.'s CSR-plant strategy model is incorporated, the designer must also contend with the fact that very few ornamental plants have been classified with regards to their strategy types (Dunnett 2014:103). The designer also needs to understand the implications of the plant strategy on the behavior of plants in a role, as plants that exhibit more competitive tendencies behave very differently from plants that are more emphatically S- and R-strategists (Hitchmough 2017b:49–51). Additionally, the CSR-strategy model describes continuums rather than three strict types (Grime 2001; An example of more nuanced approach to the CSR-model in planting design can be found in Kühn 2024).

While the role-setting systems with their prescribed proportions for different kinds of plants have no intrinsic truth value (Dunnett 2019:137), their numerous iterations imply that there is a demand for conceptual and practical planting design tools. Formulators of such tools might do well to use the successful BdS-perennial mixes as a basis from which to reverse-engineer a list of design factors that allow for aesthetically pleasing and successfully coexisting designed plant communities; while the design methods are not internally or externally valid, the trialing process seems to be able to produce broadly applicable plant combinations whose ecological dynamics should be studied further.

Plant role-setting systems (1980's – 2000's)				
Leitstauden, / Dominant structural plants	*Bodendecker/ ground cover plants*	*Begleitstauden / Companion plants*	*Streupflanzen / Scatter plants*	*Füllstauden / filler plants*
Hansen & Stahl ([1981] 2016) p.38, 48-49, 60, 86-87, 163, 215, 219): **Das Leitstaudenprinzip** ("The principle of dominant species")				
Leitstauden; Dominant visually, large amounts but small groups, mark the highlight of the season/ the structure. *But see also* **Solitärstauden:** a specific group of perennials that are used as singular ornaments for garden elements, not used as a part of perennial plantings. **Kernstauden:** long-lived, visually impressive.	**Bodendecker,** *But see also:* **Flächendecker**	**Begleitstauden:** Visually less important, short-lived and/ or short-season plants (as opposed to Kernstauden) *But see also* **Zugeordnete Stauden**		Between other plants to close the remaining open spaces
Thompson (1997, p. 117-118, 120-122): **Growth forms**				
See also **Settlers:** clump-forming, slow-growing and long-lived	*See also* **Carpeters:** shade-tolerant, low, sometimes seasonal groundcovers and self-seeding gap fillers. **Explorers:** Strong vegetative spreaders			**Ephemerals:** Short-lived forbs for gap filling and extra color
Borchardt (1998, p. 157, 162-164, 167, 169, 208, 237-238, 245, 253, 260-261, 263): **[no collective name]**				
Leitstauden; Repeating, durable, showy plants, varying plant and group sizes. **Gerüstbildende stauden;** Taller, characterristic and spatially important plants, long season. *But see also* **Solitärstauden:** Tall (~>1,5 m), for use as single individuals. **Kernarten:** Tall, durable, structural plants. **Gerüststauden:** Spatially functional, small groups, strong habit. **Akzente:** Spatial accents, often vertical habit	**Bodendecker:** Groundcover (preferably evergreen), low-maintenance, below knee-height, well-spreading. *But see also* **Teppichstauden:** Low height implied. **Kleinstauden:** Small "weaver" plants between different vegetation types or surfaces (p. 253)	*See also* **Staudengruppe:** Colorful perennials suitable for larger groupings. **Gruppenstauden:** Mid-height plants in mid-size groups for best visual effect, contrast between groups	Plants that do not fit the other categories, inclusion in groundcover	
Messer (2008, p. 24), based on Borchardt (1998): **Structure types**				
Structuring function	**Bodendecker:** >50%; "Mulch"; Mainly small (<30 cm) plants that are used in large swathes between structure- and fill plants		Short-lived or short-season plants, including geophytes	Character-defining species that complement the framework plants

Table 6 Plant role-setting systems, part 1: 1980's to 2000's

Plant role-setting systems (2010-2014)				
Leitstauden/Dominant, structural plants	*Bodendecker/ ground cover plants*	*Begleitstauden / Companion plants*	*Streupflanzen / Scatter plants*	*Füllstauden / filler plants*
Kühn (2011 p. 246**): Funktionsgruppen** ("Functional groups ")				
5-15% (Anhalt); long-lived, often tussocky, visually dominant	**Bodendecker:** 50% (Anhalt); visually less interesting, stable groundcover of well-spreading plants	**Begleitstauden:** 30-40% (Anhalt); short-lived gap fillers, will fade away from the planting in time	Synonym for geophytes	Synonym for/ similar to Begleitstauden
Kircher et al. (2012) (based on Messer (2008), Borchardt (1998): **Plant categories**				
5-15%; Structuring function; C-S-strategists	**Ground cover plants:** >50%; Mainly small (<30 cm) plants that are used in large swathes between structure- and fill plants; C-S-strategists	**Companion plants:** 30-40%; Character-defining species that complement the framework plants, long lived; C-S-strategists	Short-lived or short-season plants, including geophytes, but also longer-lived perennials with little mass	5-10%; Short-lived, temporary groundcover and visual effect, R, RS or CR strategists
Heinrich & Messer ([2012] 2017, p. 32**): Strukturtypen** ("Structure types")				
1-10%; Several synonyms; Tall (>80 cm), **Gerüstbildner/ structural framework plants**, C-and S-strategists	**Bodendecker**: 50-60%; Mostly small (<40 cm) plants, fill up the space between Gerüstbildner and Begleitstauden, C-S-strategists	**Begleitstauden:** 30-40%; 40-80 cm tall, define character through repetition, supporting the Gerüstbildner visually, C-S-strategists	5-10%; Synonym **Streupflanzen**; Short-lived or short season species; R-RS-CS-strategists and ge-ophytes	
Oudolf & Kingsbury (2013; p.82-86, 99-100, 103-109**): [no collective name]**				
Dominant structure plants: Strong habit, long season of interest. **Primary plants:** Main role, interesting, rhythmic repetition. *But see also* **Solitary plants:** Don't lose them among other plants with similar attributes. **Bulk structural plants:** Plants with distinct but not distracting habit over a long season	*See also* **Matrix planting:** Dominant in amount, muted in effect; effective groundcovers with a long season, often grasses or fo-liage perennials, long-lived and persistent		**Scatter plants:** Random distribution, either strong structure and long season or provide temporary accents/ contrast. **Strewing plants:** geo-phytes and annuals	**Filler plants:** Short-season and loose habit plants

Table 7 Plant role-setting systems, part 2: 2010 to 2014

Plant role-setting systems (2015-2020)				
Leitstauden/Dominant, structural plants	*Bodendecker/ ground cover plants*	*Begleitstauden / Companion plants*	*Streupflanzen / Scatter plants*	*Füllstauden / filler plants*
Rainer & West (2015, p. 172**): Layers of a plant community**				
10-15%; Large plants, long-lived, strong habit, C-S strategists (design layer)	**Ground cover plants;** ca 50%; Growing under and between other things -> shade tolerance is a must for low plants. S-strategists (functional layer)	*See also* **Seasonal theme plants;** 25-40%; medium height, highlight specific seasons but tidy even before/ after, medium heights, medium group sizes. Any strategy (design layer)		5-10%; short-lived, short term-interest plants, gap fillers. R-strategists (functional layer)
Schmidt (2017): Functional types				
1-15%; h=70-100 cm (design layer)	**Ground cover plants:** 30-50%; h=5-30 cm (functional layer)	**Companion plants:** 10-40%; h=40-70 cm (design layer). *But see also* **Aspektbildner, Seasonal theme plants:** 25-40%; h> 40 cm (design layer)	Incl. Geophytes	5-10%; "short-lived, self-sowing species" (functional layer)
Dunnett (2019): Plant structural types				
See also **Framework anchors:** individually placed; less variation in abundance accepted	*See also* **Matrix anchors:** main components of the base weave, large volume, relatively low plants; less variation in abundance accepted	*See also* **Character anchors:** Thematic key players visually; less variation in abundance. **Satellites:** Complements the anchors, a large volume distributed across the area; provide seasonal character		**Free-floaters:** Synonym to fillers, Short-lived plants and geophytes

Table 8 Plant role-setting systems, part 3: 2015 to 2020

5.5 How do designed plant communities relate to urban nature-based solutions?

While the history of naturalistic and ecological planting styles now span more than 150 years, they seem not to have been mainstream planting design practice at any point in history (Forbes et al. 1997; Hitchmough & Dunnett 2014:18; Woudstra 2014:36). Some of the reasons for this might be the high level of skill they require in their design, construction, and maintenance, which have both regulated the number of design projects as well as the number of projects that have survived until today (Hitchmough & Dunnett 2014:18; Kingsbury 2014).

Another aspect that can be read between the lines of DPC history and current DPC research is that the theoretical development of DPC, including its design tools, has been incremental at best and stagnant at worst since the early 2000's. Hitchmough & Dunnett (2014:18) identified the following research gaps relevant to DPC in 2004: Plant establishment, plant species selection for different site conditions, competitive dynamics at community and species level, and applied knowledge for practical design and management. Now, 20 years after the first publication of *"The Dynamic Landscape"*, little scientific progress has been made on these subjects in relation to ornamental planting design (See Oliveira Fernandes et al. 2025 and also paper 1). There have also been few efforts to synthesize current ecological research on these subjects (Hunter 2011; Kühn 2011; Tabassum et al. 2020; French 2021; Teixeira et al. 2022), and the effort that has been put forth hasn't been accepted into mainstream planting design practice. The need for creating evidence to aid planting designers to make informed decisions for plant selection is thus as great as ever (Ferrini et al. 2020; Stroud et al. 2022; Oliveira Fernandes et al. 2025).

Against this background, why might the DPC-framework still be interesting from an NbS point of view? Table 9 shows the critical points of connection between the DPC-framework and the demands NbS criteria place on urban vegetation (Sowińska-Świerkosz & García 2022). The most obvious contribution that the DPC-framework can have on NbS is to deepen our understanding of the requirements and dynamics of designed vegetation. While the argument that an understanding of plants' interactions between the site, other plants, and other organisms leading to lowered need for vegetation maintenance is probably sound, there simply is not enough evidence to corroborate the claim. Thus, more research is needed on the topic to assess the cost-effectiveness of DPC. The effectiveness and efficiency of the DPC-framework in delivering provisioning and regulating ESS as well as biodiversity support is underexplored in DPC literature and research, which in Table 9 shows as a blank space between vegetation attributes and DPC performance goals. Provision of cultural ESS by DPC has received more attention, although there is still a need for continuing the exploration especially with regards to the influence of scale and local context to people's appreciation and experience of urban vegetation.

The criterion "*answering to societal challenges*" is what ties the whole question of DPC relevance for NbS together: The DPC-framework is only relevant to the concept of NbS when it is explicitly used to improve societal conditions in some way, whether by improving the quality of green spaces, contributing to climate resilience, countering biodiversity loss, remediating water and soil quality, enhancing people's connection with nature, and so on. DPC created without specific considerations of societal challenges are always "random actions" according to many NbS definitions and thus are rendered irrelevant for the concept of NbS (IUCN 2020a; Sowińska-Świerkosz & García 2022; European Commission n.d.).

NbS **criteria** (Sowińska-Świerkosz & García 2022)	**Vegetation attributes relevant for the NbS criterion**	**DPC Planting design and vegetation management objectives**	**DPC performance goals for designed vegetation**
Answer to societal challenges	Contributing to the appropriate, specific, predefined aims of the NbS at relevant scales (e.g. Climate resilience, water management, green space management and urban place regeneration (European Commission 2021).		
High effectiveness and economic efficiency	Designed based on evidence; Effectiveness evaluated regularly; Governed and managed flexibly to accommodate changes in the system and functions; Suitable for the biophysical, sociocultural and policy context	Combining plants with similar and/or complementary behavior, community before individual *(Kircher et al. 2012; Oudolf & Kingsbury 2013; Hansen & Stahl 2016; Heinrich & Messer 2017; Rainer 2021)*	Low maintenance needs through self-regulation *(Thompson 1997; Hitchmough & Woudstra 1999; Kingsbury 2009; Hitchmough 2010; Kircher et al. 2012; Oudolf & Kingsbury 2013; Schwingesbauer & Plenk 2013; Hitchmough & Dunnett 2014; Rainer & West 2015; Hansen & Stahl 2016; Heinrich & Messer 2017; Dunnett 2019; Rainer 2021)*
Inspired and powered by nature	Alive; Organized in ways resembling natural patterns, or allowed to self-organize; Natural processes are more often a part of the solution than a problem	Utilization of ecological processes, patterns and change (*Hitchmough 2010; Kühn 2011; Kircher et al. 2012; Oudolf & Kingsbury 2013; Hitchmough & Dunnett 2014; Rainer & West 2015; Hansen & Stahl 2016; Bjørn et al. 2016; Heinrich & Messer 2017; Dunnett 2019;)*	
		Plant needs/ tolerances match the site conditions/ context *(Thompson 1997; Kühn 2011; Kircher et al. 2012; Oudolf & Kingsbury 2013; Hitchmough & Dunnett 2014; Rainer & West 2015; Hansen & Stahl 2016; Heinrich & Messer 2017)*	Enhancing cultural, social, and aesthetic values (*Thompson 1997; Hitchmough & Woudstra 1999; Cascorbi 2007; Hitchmough 2010; Kircher et al. 2012; Oudolf & Kingsbury 2013; Hitchmough & Dunnett 2014; Rainer & West 2015; Hansen & Stahl 2016; Köppler 2017; Heinrich & Messer 2017; Dunnett 2019)*
		Focus on naturalistic aesthetic in plant choices, overall design, and creative vegetation management *(Hitchmough & Woudstra 1999; Oudolf & Kingsbury 2013; Robinson 2016; Rainer & West 2015; Hansen & Stahl 2016)*	
Provide multiple services, incl. biodiversity benefits	Perceived as assets with possible services, disservices, and trade-offs; Based on multi-scale biodiversity considerations		Contribution to small-scale plant biodiversity and support for other organisms (*Hitchmough & Woudstra 1999; Kingsbury 2009; Hitchmough 2010; Oudolf & Kingsbury 2013; Hitchmough & Dunnett 2014; Rainer & West 2015;Robinson 2016; Hansen & Stahl 2016*)
			Provision of regulating ecosystem services (*Hitchmough 2010; Rainer & West 2015; Rainer 2021*)

Table 9 Connections between NbS criteria and DPC objectives and goals

Criticism against DPC as a planting design framework

Especially herbaceous plantings in the DPC-framework have been criticized both from within the framework as well as outside of it for being too focused on aesthetic values to be ecologically valuable, being too ecologically focused to be aesthetically valuable, requiring too much expertise to apply in design and management, and also being too formulaic to produce meaningful and actually long-lived plant compositions (Kingsbury 2009:11, Cassian Schmidt in 2014:82–83; Kingsbury & Oudolf 2015:117,120; Rainer & West 2015:162; Körner et al. 2016). Richardson (2021:84–87), for example, critiques the New Perennial movement for an overemphasis on scientific ambitions, and the pursuit of recreating pre-existing natural plant communities from around the world at the cost of design intent. Critique towards the alleged "ecology over aesthetics"-attitude of planting designers who incorporate ecological ideas to their work dates back at least into the 1950's, and continues to make strawmen of the more nuanced or explicitly aesthetic-focused sentiments in the leading literature on designed plant communities (Kühn 2011:104; e.g. Hitchmough & Dunnett 2014; Rainer & West 2015; Dunnett 2019). The strength of the DPC-framework *is* precisely in its ambitions to use ecological knowledge to create interesting and pleasing vegetated spaces that are sustainable in the long term; to be explicitly inspired by nature, yet to acknowledge the intrinsically anthropogenic nature of DPC. Whether the contrasting views and shifting priorities within the DPC-framework are seen as flexibility and a richness of perspectives (Leopold & Perennial Perspectives Foundation 1997:13–14; Kingsbury 2014) or as points of contention (Richardson 2021) will inevitably shape the way the DPC-framework continues to develop, and how its potential to contribute to NbS might be realized.

Another example of the tensions between aesthetic priorities and ecological science within the DPC-framework would be the critique of the ecological credibility of William Robinson's work, as his "wild garden" is not perceived as especially "wild" by today's standard (Forbes et al. 1997:81; Woudstra 2014:47; Gröning (1997) in Köppler 2017:8). The legitimacy of such critique can be questioned against the backdrop of knowing that the field of plant ecology as a science was starting to develop at around the same time as Robinson put out the first edition of his book (Robinson & Darke 2009; Egerton 2013), and that plant community assembly is a mystery even to plant ecologists today (Götzenberger et al. 2012). Similarly, Piet Oudolf's work was initially considered groundbreaking for his naturalistic style that highlights the seasonal ecological dynamics of designed vegetation, utilizes less-hybridized plant taxa, as well as focuses on plant habit and texture (Kingsbury 2014:91; Kingsbury & Oudolf 2015:205–213), but more recently the ecological qualities of his work have been questioned (Kingsbury 2014:91–92; Dunnett 2019:67). The lesson to be learned from both cases is that any attempts to interpret nature or apply ecological knowledge to planting design today must be done with an acceptance of the fact that current interpretations or understanding of plant ecology might be challenged in the future. Thus, the most productive way of approaching the DPC-framework from an NbS point of view might be to see it as a work in progress, or as an attempt to do our best with the information we have right now – provided that DPC practitioners are, in fact, committed to actively developing the framework as well as their own professional practice.

The three analyzed design tools (Garden Habitat-system, "*Geselligkeit*"-system, and role-setting systems) are useful for explaining complex ecological concepts and their relevance for plant selection and organization in a pedagogical and applicable way. The tools also encourage the designer to engage with the visual and experiential qualities of plantings in terms of character (Garden Habitat-system), pattern and scale ("*Geselligkeit*"-system) or space, structure, and rhythm (role-setting systems). However, the methodological applicability of the tools is limited due to their internal contradictions, and the scarcity of the ecological evidence base their use would call for. Thus, pursuit of the DPC objectives requires stronger evidence and internally coherent evidence-based approaches that could be developed into design guidelines. While there does not seem to be an established distinction between guidelines and tools, in this thesis they are defined as follows: Design tools are "instruments of inquiry" (Dalsgaard 2017), whereas design guidelines are "directions for inquiry" (Prominski 2016). In other words, while both help the designer to formulate relevant solutions to their design inquiries, design tools aid in carrying out practical, specific tasks and actions, i.e. "what to do", whereas the purpose of design guidelines is to provide the designer with general information that guides the designer towards appropriate design solutions, or "how to do" (Prominski 2016; Dalsgaard 2017). While the three DPC design tools, and especially the role setting systems, have elements of both, their specificity and prescriptiveness make them more relevant as tools. Another distinction could be that design guidelines are always abstract and ideally evidence-based, whereas design tools can also be concrete (e.g. software, pens) and usually judged by their utility (Prominski 2016; Dalsgaard 2017). According to this divide the Garden Habitat-system, "*Geselligkeit*"-system and role-setting systems are also more like tools, as their utility is not entirely dependent on the strength of the evidence behind them.

The usefulness and quality of future design guidelines or tools are still inescapably dependent on the reliability and availability of detailed plant knowledge, as well as the designer's individual design skills: Even though design tools, design guidelines or descriptions of planting design experts' design methods can attempt to describe rules for design, an expert will inevitably ignore, bend and break the rules according to the fine-tuned professional judgements their vast work experience allows them to make (Flyvbjerg 2006). Thus, expert systems like detailed design tools, plant selection algorithms or even evidence-based design guidelines are unlikely to replace practical planting design expertise any time soon (ibid). The development of design guidelines to realize DPC objectives should also not be done at the cost of neglecting to evaluate how fulfilling the design objectives might contribute to DPC performance goals. DPC performance in the long term should be the basis for judging the success of the DPC-framework, not only in reference to itself, but also with regards to its relevance for NbS.

Based on the critique that many planting designers have leveled on the "scientification of design", there are grounds for questioning the necessity of setting higher standards for planting design methods and for the performance of designed plantings, no matter if the suggested standards come from conceptual frameworks like NbS, from ecological or design researchers, or from among DPC practitioners. The main arguments for framing DPC through the lens of NbS are that it might help at lending legitimacy to the purported necessity of naturalistic and ecological planting design (Dunnett 2019; Rainer 2021) by providing tools and indicators for measuring the performance of designed plantings on similar terms that the DPC-framework uses (see Table 9). Counterarguments might include the difficulty of measuring intangible values like the intrinsic value of biodiversity, beauty, site history and creativity, or even the harm of trying to measure them. However, rejecting demands for higher accountability for design intentions and design outcomes in general is less productive than providing argumentation for the prioritization of intangible values in specific cases. In other words, wanting to maintain the right to create ornamental plantings purely for the joy of creating or experiencing them, or to refuse stormwater management-enhancing measures in existing forests or at historically significant sites, does not need to be in conflict with ambitions to promote the development of best design practices and performance evaluation methods for creating verifiably effective, multifunctional vegetated structures.

5.5.1 Possible alternatives to the DPC-framework in the context of NbS

While DPC is not truly an evidence-based design practice, it also has no real, named contenders for planting design frameworks for urban NbS. Some alternative approaches to urban vegetation can however be identified.

In urban vegetation practice the main alternative approaches stem from conventional urban ornamental horticulture, which includes a strain that is the direct descendent of private and public gardens ("horticultural approach") and a functionalistic strain ("robustness approach"). From the scientific literature two further approaches can be found: The "environmental engineering approach" that seeks to optimize specific ecosystem service delivery by studying specific plants or plant traits, and the "urban greening" approach that is concerned with vegetation at non-species-specific scales, usually studied in terms of volumes, areas or networks. In between research and practice there is also the "nature conservation approach", which includes working with remnant natural and semi-natural vegetation, development of new semi-natural vegetation as a form of ecological restoration, and promoting the exclusive use of native plants and local plant communities even in urban areas. DPC can sometimes overlap with the horticultural and nature conservation approaches, the former usually in strictly ornamental contexts and the latter in more suburban contexts like woodlands, wetlands and meadows. In these cases, the difference between DPC and non-DPC vegetation might be negligible, and usually boils down to the design methods used, or the depth of consideration for ecological factors (vs. Horticultural vegetation) or aesthetic and amenity values (vs. Nature conservation).

Horticultural approaches to urban vegetation (e.g. Asgarzadeh et al. 2014; Kamenetsky 2017; Božanić Tanjga et al. 2022) are no more evidence-based practices than DPC, and they are based on considerably narrower ecological design criteria than DPC. Although horticultural approaches may include considerations for biodiversity through provision of flower, fruit and seed resources, they rarely work with questions of structural diversity that is also important for habitat value. The strengths of horticultural urban vegetation lie in provision of cultural ESS and spatial differentiation but rarely consider other regulating ESS than possibly shading and windbreak. Depending on the skill of the design organization horticultural plantings may be sturdy, rich and maintained at reasonable costs, or demanding, fussy and expensive to maintain, or robust and easily maintained but poor in variety and ecological value.

The robustness approach can be exemplified by monocultures of low ornamental shrubs (Bengtsson & Bucht 1973). No studies on urban vegetation robustness could be found for this study, and thus it can be suspected that there is little scientific evidence to back this planting design strategy up either. It distinguishes itself from the horticultural approach by prioritizing ease of maintenance at the cost of adaptation to local social conditions beyond basic safety and security concerns and an overall neat and tidy appearance. When aesthetic values are considered further within the robustness approach, they tend to rely on mass effects of simultaneous blooming or autumn color. Sometimes large-scale variation is also used to contrast monocultural blocks of different robust plants against each other, or to spread out flowering or other seasonal variables across a longer span of time. Due to a lack of small-scale variation robustness approaches tend to produce vegetation with low habitat value, as their vegetation structures are usually simple and their windows of flower, fruit and seed resource provision tend to be narrow. While robustness approaches usually do consider biophysical site conditions to help them attain the goal of easy maintenance, the plant species and varieties used are always generalists with wide site condition tolerance amplitudes, and thus detailed site condition analyses are only necessary in extreme situations. Robustness strategies often show low adaptability and resilience and are thus susceptible to mass failures when the site turns out too extreme for the plants, or when there's an outbreak of pests that they can host.

Nature conservation approaches (McCallum et al. 2018; Suganuma et al. 2018; Wooster et al. 2022) can be great at providing both habitat value, provisioning ESS, and regulating ESS through the establishment or management of semi-natural grasslands or woodlands. However, depending on the local biophysical and social contexts, the use of native plants and local plant communities may not always be appropriate in urban areas. On the other hand, there are urban situations like biofilters by road verges, large parks or suburban parking lots where the untidiness or early mowing are completely unproblematic, and thus places where the nature conservation approach to urban vegetation is valuable. Another question is the size of the native plant species pool that can tolerate urban and especially URG conditions. While nature conservation approaches can draw on scientific studies on urban and suburban ecology, there isn't much research on establishing native vegetation in supra-urban areas or in urban NbS like URG:s. This is especially true for Northern Europe.

The environmental engineering approach can be a very valuable research field for identifying plant traits and vegetation attributes that are decisive for the delivery of certain ESS (e.g. Afshar et al. 2018; Maier 2022; Galli et al. 2021). However, ecological engineering as a planting design approach risks suboptimization, as actions that promote provision of some ESS may cause a decrease in the quality or quantity of other ESS, just as optimization for some functions can exclude other uses (Bennett et al. 2009). Thus it tends to lend itself poorly to the intentional development of multifunctional vegetation for NbS, even though incidental co-benefits or multifunctionality are probably present in most cases.

The "urban greening" approach (e.g. Amini Parsa et al. 2020; Baker et al. 2021b; Lucchezi Miyahara et al. 2022) is not practically applicable unless it is combined with one of the other approaches and is thus not relevant as an alternative to DPC. However, it is relevant for NbS, and thus should be integrated into urban green area governance and urban planning methodologies that guide planting design and vegetation management at larger scales.

5.5.2 Potential development of the DPC-framework

One of the reasons for the popularity of the DPC-framework is probably that DPC practitioners have packaged the key ideas of the framework into design tools (Garden Habitat-system, plant sociability classification, and role-setting systems) that are at least superficially approachable. Thus, developing the current DPC-tools into more comprehensive and consistent design guidelines (Prominski 2016) might be a way to update the evidence base and methodology behind the tools while maintaining the presentation style of the previous tools. Design guidelines should provide flexible but clear guidance that helps planting designers with their key tasks: Problem definition together with the client and possibly other designers, site analysis, plant selection, designing the spatial configuration of plants, considering plants' interactions with their biotic and abiotic environment, and understanding how these are influenced and changed in time (Robinson 2016:204).

The search for knowledge at the start of each project should be made relatively easy and fast, as the design guidelines should summarize and abstract information and direct the designer towards relevant design questions (Prominski 2016:220–221). Instead, the tools are sometimes treated as "theories" in the natural scientific sense of the word, i.e. as true explanations or at least the best currently available explanations of phenomena (Thompson 2016:56) that have direct bearing on design outcomes. If "theory" is understood in the sense of humanistic science, DPC theories should provide a tentative basis for interpreting sites and vegetation and explaining the apparent patterns, but they do not need to be true or testable (Thompson 2016:53; Herrington 2017:1). If "theory" is instead understood as "goal-directed instruments" (Legg & Hookway 2024), the DPC design tools can be seen as theories that, while not necessarily scientifically sound, do help designers to achieve DPC objectives and goals.

There is also something to be said about how the necessity and availability of evidence has influenced the development of the three planting design tools discussed in this thesis: The role-setting systems are constantly being reinvented and reinterpreted, as they are not so much based on evidence or systematic assessments as design judgements any planting design professional can make. The heavy and detailed Garden Habitat-system of Hansen, Stahl and Müssel (2016) was supplanted with Sieber's simplified version (1990) as the basic idea of Garden Habitats was easy to adopt, and the ongoing German perennial trials continue to produce data of plant species' performance on different sites. The plant sociability classification, in contrast, has not been developed further since *"The Perennials and their Garden Habitats"*, possibly due to the comprehensive database that would be needed to make the sociability assessments, and the unclear method of weighing the different aspects influencing the sociability categories against each other. In fact, heavy emphasis on scientific evidence is sometimes experienced as a hindrance for planting design, even among

DPC practitioners (Kingsbury 2014:83; Rainer & West 2015:168; Dunnett 2019:10, 106).

And here lies the catch: while the current DPC tools seemingly allow the designer to easily apply available knowledge, they in reality place high demands on the designer's knowledge base and knowledge-gathering skills. A better way forward would be to explicitly acknowledge the complexities of planting design, including the global, regional and local gaps in the evidence base that would be needed to design plantings in complete accordance with the DPC tools and objectives. In other words, to formulate DPC design guidelines that incorporate uncertainties and incompleteness, rather than continue with design tools that mask them.

As the development of design guidelines for the DPC-framework should, essentially, serve the needs of designers' professional practice and improve design outcomes (Robinson 2016:38; Milburn & Brown (2003) in Jansson et al. 2019:26), one alternative would be to align further development of design guidelines within the DPC-framework with Prochner & Godin's (2022; See also Stompff et al. 2022) quality indicators for research through design:

1) Traceability: The design guidelines and their development should be transparently formulated, with explicit reference to the written sources or project experiences they are based on. The information required for the use of design tools should be identified, and reliable information sources should be provided insofar these are available. Concepts used in DPC guidelines should comply with widely accepted terminology in appropriate domains (planting design, gardening, landscape architecture, plant ecology, urban ecology and so on), and be explicit about the exact meaning of DPC-specific concepts that use terminology that parallels or overlaps established terminology in neighboring domains.
2) Interconnectivity: The design guidelines and design outcomes should always be contextualized within the social, ecological and technological variables of the project site or the circumstances under which information is presented in referenced literature. Where possible, the guidelines should also explain correlative and causal connections between design parameters and design outcomes as far as they are known and be explicit about what is not known.
3) Applicability: The DPC guidelines should cover the most prevalent planting design applications within clearly delimited areas (geographical, contextual, functional). The context for which the guidelines are developed should be disclosed, and the extent and

limitations of applicability should be explicitly stated. Utility and usefulness are the ultimate tests for design guideline applicability.

4) Impartiality: Scientific objectivity should be striven for. When subjectivity cannot be avoided or where it is inherent to the guideline, possible biases should be reported and arguments motivated.
5) Reasonability: DPC guidelines must be internally sound or openly acknowledge known contradictions. Methods for verifying design outcomes should be reliable, even if it is accepted that design methods and design outcomes as such might not be replicable.

Finally, DPC guidelines must be expressed with clarity, so that they improve designers' abilities to pursue DPC objectives and their chances to attain performance goals (Robinson 2016:38). The resulting guidelines should not be seen as final truths or guarantors of desired design outcomes, but rather as best practices that are made to be revised.

6. Paper 1: Reviewing designed plant communities' potential for urban nature-based solutions

Vegetation performance in and as NbS is dependent on factors related to planting design and vegetation management, such as placement, abiotic and biotic site conditions, plant identity and combination, the spatial structure and distribution of vegetation, as well as the realized development of plants on the specific site (Sæbø et al. 2003; Williams et al. 2009, 2015; Sjöman & Busse Nielsen 2010; Aronson et al. 2016; Ferrini et al. 2020; Watkins et al. 2021; Stroud et al. 2022). Unfortunately, the specific effects of these factors on vegetation development and ESS delivery by plants are poorly known, and thus vegetated NbS performance is unpredictable (Maco & McPherson 2003; Oldfield et al. 2015; Martin et al. 2016; Widney et al. 2016). Thus, there is a risk that vegetation underperforms in terms of biodiversity support, regulating or cultural ESS provision, provides ecosystem disservices, or that intensive vegetation maintenance is necessary to maintain their health and ESS delivery capacity (Lyytimäki & Sipilä 2009; Threlfall et al. 2016; Aronson et al. 2017; Mathey et al. 2018; McPhearson et al. 2022).

While NbS design should be based on evidence, its definitions stress the effective and efficient performance of the realized solution, which may be achievable even without a perfect understanding of why the solution works (Frantzeskaki et al. 2019; Sowińska-Świerkosz & García 2022). Evaluating the underlying reasons for NbS performance is however necessary for managing NbS in the long term, learning from them for future solutions, and improving the reliability of their performance, which can necessitate an analysis of the design, construction and maintenance parameters of NbS vegetation (Dumitru et al. 2020; European Commission 2021; Sowińska-Świerkosz & García 2021). Investigating scientific evidence available for planting design and vegetation management is thus pertinent for assessing the available evidence base for creating and maintaining vegetation that can perform well in and as NbS.

The aim of this paper is to assess the extent to which the current scientific evidence on designed plant communities (DPC) might contribute to sound planting design practices for urban nature-based solutions. The delimitation to urban contexts was made in accordance with the European Union's focus on NbS as a method to improve the climate adaptation, environmental quality and financial competitiveness of European cities (European Commission 2015, 2021). The DPC-framework was chosen not only due to the focus of the thesis, but also due to its promise of working with multi-species vegetation and combining at least ecological and sociocultural sustainability (Kingsbury 2009; Dunnett 2014, 2019; Hitchmough & Dunnett 2014; Kingsbury & Oudolf 2015; Rainer & West 2015; Hansen & Stahl 2016; Robinson 2016), as opposed to planting design or vegetation management frameworks promoting the use of monocultures or only focusing on ecological OR sociocultural OR techno-economic goals. The chosen approach is to utilize the four criteria for NbS provided by Sowińska-Świerkosz and García (2022) as a framework to analyse scientific literature on or relevant to DPC.

To support the main aim of the study, the paper also includes an analysis of DPC terminology, design objectives and performance goals, as well as a description of the main characteristics of the current field of DPC research. The analysed literature on DPC research is then critically evaluated with regards to how it might support the fulfilment of the four NbS criteria 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? (Sowińska-Świerkosz & García 2022).

Choice of research methods

The literature for the scoping review was collected through a multi-phase data collection and screening process that resulted in a selection of 51 peer-reviewed scientific articles that either were explicitly linked to the DPC-framework, or that studied multi-species vegetation that is designed and managed with an explicit focus on both the ecological aspects of vegetation as well as the benefits humans can attain from it. The main analysis framework is built on the following the four criteria: (1) inspired and powered by nature; (2) Answer to societal challenges; (3) Provide multiple services, incl. biodiversity benefits; and (4) high effectiveness and economic efficiency. To improve the accuracy of mapping the evidence provided by the analyzed papers onto the four criteria, the criteria are further detailed and elaborated through their different aspects. Due to the ambiguity of the terminology within the DPC-framework, a pre-study was necessary to establish a working definition of DPC, and to motivate the use of the term "designed plant communities" over its synonyms.

Results

The literature review shows the breadth of topics that need to be considered to design and manage NbS vegetation, a variety of research methods relevant for investigating DPC, as well as the many ways in which DPC have been applied across the globe. The considerable variety of vegetation types and applications found in the research indicates that core DPC tenets are broadly applicable to urban vegetation. It also shows how small the available evidence base for urban planting design for NbS is. As most of the studies have been conducted in temperate climates of Northwestern Europe, the generalizability of the evidence can be questioned, and the results of the analysed papers already in part show how local variation influences outcomes (e.g. Nouri et al. 2013; vs. Droz et al. 2021; Hitchmough & de la Fleur 2006; vs. Schmithals & Kühn 2014; Köhler 2006; vs. Nagase & Nomura 2014). Furthermore, the scarcity of the scientific evidence base for the successful application of DPC objectives and for attaining the performance goals for DPC also shows that the DPC-framework cannot reliably fulfil its own promises, and thus its potential contributions to NbS criteria fulfilment also remain largely unverified.

Evidence in DPC research is largely concentrated on aspects of NbS criteria "*inspired and powered by nature*" and "*high effectiveness and economic efficiency*", which seems plausible as much of grey literature on DPC as well as the three design tools described in chapter two are focused on ensuring a good adaptation of plants to their biophysical environment and on finding plant combinations whose coexistence enables weed deterrence and long-term retention of plant diversity without intensive vegetation maintenance. From this perspective, it is surprising how little of the evidence feeds back to any of the design tools. Research describing planting patterns was found to be minimal, as planting or sowing density was the only pattern-related aspect investigated in the analysed studies. Coexistence between plants is mostly considered from the point of view of dominant competitiveness and weed colonization. Site conditions are largely simplified to questions of productivity, i.e. light, soil moisture and nutrient availability, without discussing suitable plant choices for less productive sites or sites with varying chemical attributes in terms of pH, salinity, available oxygen or pollution, which are important factors for vegetation development in urban areas. Vegetation surveys, which in this case give the most compelling evidence on the effects of site conditions on vegetation distribution and survival, give only rough reference on how the findings could be applied to practical planting design or vegetation management. The general trend of decreasing plant diversity in the experimental and case study sites despite certain maintenance actions also warrants more attention in the future, as it may influence vegetated NbS performance negatively over time. And as the overarching result on vegetation management is that maintenance improves plant survival and growth, it would be important to find the tipping points where maintenance no longer improves vegetation development, or where maintenance is too infrequent to maintain desired plant composition or vegetation structure.

The ecosystem service that had most related evidence was "*aesthetic appreciation and inspiration for culture, art and design*", and biodiversity support through habitat provision had a similar number of results. The more or less corresponding societal challenges of "*green space management and urban place generation*" and "*environmental degradation and biodiversity loss*" were similarly at the top of the list. These results are unsurprising, as two of the exclusion criteria for papers were a lack of consideration for human interests, and a lack of consideration for ecological aspects of designed vegetation. However, it is essential that planting design and vegetation management for urban NbS also is further explored with regards to a wider variety of societal challenges and ESS. Socio-cultural interests were mainly discussed based on how preferences and perspectives on urban vegetation vary by socioeconomical factors, while at the same time flowering performance was often considered a good proxy for aesthetic value in plantings.

Habitat value was investigated with regards to invasibility risks of exotic plants, habitat value of exotic plants, the presence and diversity of invertebrates in urban vegetation, and plant diversity as a proxy for habitat value in urban areas. While each of the topics warrant more study, looking further into the drivers of urban vegetation's habitat value for different organism groups would be especially interesting from a planting design and vegetation management points of view. Plant diversity and vegetation structural complexity are often seen as factors that increase maintenance needs in ornamental plantings, and thus the possibly increased biodiversity values need to be weighed against maintenance methods and intensity. The possible biodiversity benefits of structural complexity must similarly be assessed in relation to issues of safety, security, and appreciation of urban vegetation.

Why does this study and its results matter?

The DPC performance goals identified in this paper map onto three of the four NbS criteria: DPC should exhibit a degree of self-regulation and resilience, thus representing functional ecosystems that satisfy the definition of "nature" in the context of NbS; They should provide cultural and regulating ESS as well as contribute to plant and other organism biodiversity, and provide services from three out of four ESS categories simultaneously; And their design and management should create a basis for solutions that have low maintenance needs, which contributes to NbS effectiveness and efficiency. However, the connection between DPC and societal challenges is weak both in DPC objectives and goals, as well as in the analysed DPC research. From a definitional standpoint, DPC do not inherently contribute to all NbS criteria.

Since most DPC:s have not been created to be NbS, they might also fall under the exclusion criteria "random actions", and thus cannot be considered to be NbS even if they in practice do fulfil many of the other NbS criteria (Sowińska-Świerkosz & García 2022). However, this literature review does not aim to assess if and which DPC can be deemed to be NbS, neither does it assess the scientific merits or demerits of the DPC-framework as such; rather, the aim is to see how scientific evidence collected within or adjacent to the DPC-framework could be used in planting design and management in a way that might improve NbS performance. To achieve the aim of the study, even incidental compliance and contributions of DPC research to NbS performance is relevant: If DPC-based vegetated areas can semi-independently provide multiple ESS that contribute to locally relevant societal challenges, they provide valuable functions similarly to NbS. Additionally, it should be noted that NbS is less of a theoretical concept than a practically verifiable set of functions and performance.

The problem thus lies in assessing the performance of such "accidental" or "partial" NbS. In the analysed literature as well as in practical urban green area management, much of the performance of vegetation is measured by proxies, such as the survival rate of individual plants and species of the original assemblage (Hitchmough & de la Fleur 2006; Cascorbi 2007; Dunnett et al. 2008b; Suter et al. 2010; Bretzel et al. 2012; Hitchmough &

Wagner 2013; Köppler et al. 2014; Schmithals & Kühn 2014; Bjørn et al. 2019; Alizadeh & Hitchmough 2020a; b; Droz et al. 2021), canopy coverage rate (Hitchmough & de la Fleur 2006; Dunnett et al. 2008b; Hitchmough & Wagner 2013; Köppler et al. 2014; Schmithals & Kühn 2014; Kutková et al. 2018; Droz et al. 2021), biomass measured directly or as a function of height (Cascorbi 2007; Dunnett et al. 2008b; Suter et al. 2010; Bretzel et al. 2012; Hitchmough & Wagner 2013; Köppler et al. 2014; Hitchmough et al. 2017; Kutková et al. 2018; Bjørn et al. 2019; Alizadeh & Hitchmough 2020a; b), vitality (albeit with variable criteria)(Schmithals & Kühn 2014; Droz et al. 2021), and flowering performance (Dunnett et al. 2008b; Kutková et al. 2018; Droz et al. 2021). The correlation between these proxy values and practical ESS delivery or maintenance costs is not established in the analysed literature. This raises the following questions: Do the proxy values correlate with specific ESS? How accurate are such proxy-based evaluations, compared with more direct methods for specific ESS delivery? How efficient and approachable are such proxy-based evaluations, compared with more direct methods for specific ESS delivery? And which ESS delivery cannot be measured by proxy values from vegetation (see also Brooker et al. 2008)?

The review shows the elusiveness of the DPC-framework, as there are no agreements on common terminology or goals within the framework besides a vague idea of combining aesthetic values with knowledge of ecological patterns and processes. Still, compiling the design and management objectives and performance goals for DPC was possible due to the relative consensus on DPC core ideas between the most prominent authors of grey and scientific DPC literature.

As the reason for DPC practitioners' reluctance to define or name their planting design framework is rooted in the New Perennial Movement's insistence on welcoming people with varied opinions and interests, the repetition of ideas and principles across grey DPC literature of the past 45 years does raise the question if that variation is still a part of the framework. In terms of design methods, tools and styles variation still lives, but the trend in grey DPC literature seems to be away from diversity and with increasingly tight focus on ornamental plantings of herbaceous perennials, possibly with a skeleton of small trees and large shrubs. In contrast, DPC-adjacent research still shows a range of vegetation types from ornamental plantings to urban woodlands to prairies, meadows and lawns to wetland vegetation to spontaneous vegetation, as also exemplified by *"The Dynamic Landscape"*

(2004) and the *"Perennial Preview"* (1997). It would thus behove future DPC practice and research to embrace this variety, not only in pursuit of its own ends, but also as a means to contribute to a wide variety of NbS. Additionally, future research on DPC might gain broader legitimacy and interest, if it could show that DPC are relevant for use in and as NbS. To that end, the NbS criteria (Sowińska-Świerkosz & García 2022) and the different aspects of the criteria might be useful to guide the researchers towards salient research questions and performance indicators.

Theoretical research into DPC could further synthetize and deepen historical perspectives on the subject by contextualizing associated practitioners and practices as a part of broader schools of thought on planting design, landscape design, design theory, vegetation ecology, philosophy of science and city planning, etc. This could be helpful in sorting out the "jargon" (Dunnett 2019)of the paradigm, clarifying the lexicon of the subject, and correcting the circulating misconceptions (Körner et al. 2016) on how and where different ideas originated and developed. A common vocabulary could improve communication between DPC practitioners and scholars, leading to more effective knowledge-, and theory creation. Specifying design terminology within the paradigm could also aid in creating a shared research agenda for planting design, including systematic collection of evidence on the attributes and behaviour of plant material.

One avenue of investigation could also be to study existing DPC-plantings, including not only long-lived and otherwise successful exemplars, but also to study failed projects to identify where the failures were due to problems with design methods and tools, or due to realized conditions of the project (Körner et al. 2016; Swaffield 2016). Similarly, it could be interesting to analyse the practical discourse around urban NbS planting design and vegetation management to better understand how professionals working with policies, planning, design, construction and maintenance of urban areas relate to the four criteria of NbS (Sowińska-Świerkosz & García 2022), and which methods they use to contribute to NbS criteria fulfilment in their work with urban green areas and vegetation.

7. Study 2: The strategic management of vegetation in urban rain gardens - experience from practice in 10 Nordic cities

The aim of this paper is to describe common phenomena and trends surrounding contemporary planting design for urban rain gardens (URG), as well as the subsequent vegetation development and maintenance needs in in the Nordic context. This study should deepen the scientific understanding on vegetation management in Nordic urban rain gardens with regards to vegetation development, typical maintenance actions, and common issues. This paper then sets a baseline for planting design approaches, vegetation maintenance practices, and vegetation development in URGs as a model NbS, which can be used in comparisons with case study results (study 3).

Beryani et al.'s (2021) survey of 26 Swedish URG:s (called biofilter facilities in their study) found that only 60% of the study objects had satisfactory hydrological function due to design and construction mistakes or a lack of sufficient maintenance. Their oldest surveyed URG:s were built in 2012, and 20/26 of the facilities had been installed between 2015 and 2017, i.e. 1—3 years of age in 2018 when the surveys were conducted (Beryani et al. 2021). In the Swedish context this corresponds roughly to the common length of the warranty period for infrastructure projects, which is also the period when urban vegetation is maintained most intensively (Svensk byggtjänst 2004).

As Beryani et al. (Beryani et al. 2021) were not able to procure planting plans for most of their survey sites their results on vegetation are quite meagre, but the following observations are worth highlighting: While vegetation health, appearance and coverage were generally rated positively, there were also notable irregularities in vegetation establishment and the amount of invasive weeds in the biofilter plantings. The study also reports low plant species diversity, although due to a lack of available planting plans on URG planting plans and plant lists, include more recent example projects, and also to broaden the scope to include Finnish URG:s as well.

Choice of research methods

Qualitative, semi-structured group interviews on vegetation development and management in URGs were carried out between autumn 2023 and autumn 2024. Planning and preparing for the interviews (Kvale & Brinkmann 2014) started with the decision to work with semi-structured focus group interviews. The interviews were centered around specific URG-example projects, which provided possibilities for the researchers to familiarize themselves with realized URG:s in Sweden and Finland (Table 10).

The example projects were chosen based on recommendations from the interviewees as well as professional and research contacts, or on the basis of personal interest in certain projects. Thus, the example projects were chosen through non-random convenience sampling (Galletta 2013:33; Kanazawa 2017:316). The interviewees were contracted through “network sampling” or “snowballing” (LeCompte & Schensul, 1999 in Galletta 2013:34; Kanazawa 2017:316), where the municipal project leader of an interesting example project recommended or invited colleagues from the project organization into the group interview, or where the main landscape design contractor of an example project provided contacts to the municipal project organization. The recruitment of the last groups of interviewees was also influenced by an interest in broadening the range of the types of projects to study (based on e.g. streets vs. parks, size of the municipality). The Finnish example projects were all chosen based on recommendations from the licentiate student’s Finnish Ramboll-colleagues, but of the 10 example projects only 2 have been designed by Ramboll. The remaining example projects have all been carried out by different design consulting companies, or by municipal design organizations.

Site	Municipality size	Project form	In-ventory	Context	Design priorities	Substrate type	Major issues?
FI1	Major	Com-mission	Yes	Street (new)	Stormwater quality, long season of visual interest, ease of maintenance	Filter structure with soil-based substrate (custom)	Target vegetation supplanted after establishment
FI2	Major	Com-mission	Yes	Park (new)	Stormwater quality, spatial and visual qualities	Unknown	Target vegetation hard to establish
FI3	Major	Com-mission	Yes	Street (new)	Stormwater quality, ease of maintenance	Filter structure with custom soil-based substrate (custom)	Target vegetation hard to establish
FI4	Mid	Munici-pal	Yes	Minor street (new)	Stormwater quality, ease of maintenance, visual qualities and biodiversity	Filter structure with custom soil-based substrate (custom)	No major issues
SE1	Major	Munici-pal	Yes	Minor street (retrofit)	Local flood control, visual qualities, ease of maintenance	Biochar, macadam & compost (product)	No major issues
SE2	Major	Munici-pal + consult	No	Minor street (retrofit)	Ecosystem services, optimizing tree pit volume, stormwater quantity management	Biochar, macadam & compost (product)	No major issues
SE3	Major	Com-mission	Yes	Street (new)	Long season of visual interest, stormwater quality & quantity management	Biochar, macadam & compost (custom/ product)	URG:s receive less water than intended
SE4	Mid	Com-mission	No	Street (new)	Long season of visual interest, stormwater quality & quantity management	Sand- and compost-based URG substrate (product)	No major issues
SE5	Mid	Com-mission	No	Street (re-newal)	Multifunctional vegetation, stormwater quality management	Sand- and compost-based URG substrate (product)	URG:s receive less water than intended, notable salt damage
SE6	Mid	Com-mission	No	Park (re-newal)	Stormwater quantity, spatial and visual qualities	Sand- and compost-based URG substrate (product)	No major issues

Table 10 Overview of example projects used as the basis of the interviews. “Commission” as a project form means that external design contractors were commissioned by the municipality. The classification of municipality sizes is in accordance with Swedish Association of Local Authorities and Regions’ *“Kommungruppsindelning”* (2023). The issues were interpreted from the interview results, and may or may not have been corroborated with the site inventory results.

The interviews on the four Finnish example projects and two of the Swedish example projects were preceded by site inventories. For 8/10 example projects archival material in the form of design drawings, plant lists, written specifications, and sometimes presentations of the project were also perused for background information on the example projects and to support the site inventories. Adding an element of site inventories and archival studies into the semi-structured interview allowed for improved analysis of the interview answers, contextualization of the example projects, and made it possible to ask the interviewees to elaborate on specific observations of the site (Galletta 2013:26–25). Asking for material about the projects beforehand and doing the site surveys in preparation not only provided more data and helped to interpret answers, it also might have helped build trust with the interviewees as they could be assured that the interviewer had taken the time to get to know the project.

The interview questions and site inventory topics were formulated on the basis of professional experience in landscape architecture as well as the theoretical framework of the strategic management of urban green spaces. The interview questions regard urban rain garden governance, planting design, engineering and construction, maintenance and management, as well as the main lessons learned from each example project. Additional information on example project age, size, cost, and project type (major street, street or park; new project, renewal project or retrofit project) have been collected for reference.

The focus has been gaining information on gaining empirical information on the interviewees' experiences with their practical work (Kvale & Brinkmann 2014), including the influence of interpersonal relationships. The interviews have been explorative in nature, although the large number of relatively detailed questions is more typical for interviews that seek to prove a hypothesis (Kvale & Brinkmann 2014:148). Contrary to recommendations for semi-structured interview methodology (Kallio et al. 2016) no pilot testing of the questions was made. Instead, the first draft of the interview guide was designed together with the co-authors, and the final set of questions was reviewed by the co-authors before it was employed.

To gain a multifaceted picture of the phases of URG development and maintenance, landscape designers, urban green area managers, construction managers, stormwater engineers and city planners involved with procuring or delivering design, construction and maintenance services for URGs in

Finland and Sweden were chosen to be interviewed. In three of the ten cases municipal representatives had conducted the project within the municipality, and thus designed the example projects themselves. In the other seven cases the municipality acted as a client for external design contractors. The interviewed maintenance and construction staff were also municipal representatives.

Although the ambition was to interview the people most knowledgeable on the planning, design, construction, maintenance and monitoring of each example project, this was not always the case in practice as especially green area construction and maintenance professionals were mostly absent from the interviews, either due to scheduling conflicts or lack of contact. The idea was also to be able to analyze the answers based on the professional role of each interviewee, but this kind of analysis has not yet been made. In some example projects there had also been notable attrition in the design organization, which meant that the interviewees might not have been involved throughout the whole project. As the interviews were conducted in groups, the interviewees probably attempted to maintain harmony and come to a certain consensus, although people did also express challenging views and even challenging questions to other interviewees. In any case, finding out differences in the views of different professional roles might have been easier, had the interviews been conducted individually.

The interviews were held through Microsoft Teams, using the project's local language. The number of informants at each interview has varied between 2 and 5 people, and the total number of informants was 32. Additionally, two people answered questions by mail. Some of the interviewees answered from their own spaces, whereas others shared a physical space. Microsoft Teams' automatic, simultaneous transcription function was used in all interviews. The transcripts were controlled for accuracy and adjusted when needed. In general, the Finnish automatic transcripts were more accurate than the Swedish ones, but especially names and professional vocabulary needed to be corrected manually afterwards. As a part of controlling the transcripts the answers of different people in the same room/ using the same Teams-account were assigned to the correct interviewee.

1,5 hours were allotted for each interview, but to get more in-depth more time would have been necessary. Occasionally the allotted time was also not enough to go through all of the questions, in which case complementary information was gathered via e-mail afterwards. This was especially the case when an expert (usually from the maintenance organization) was not available for interview.

Qualitative research can be used to analyze the world as described by the interviewees (Kvale & Brinkmann 2014). The original idea for analyzing the results was thus to approach the answers at face value and report the results using the questions as the sole analytical framework. However, after the first batch of interviews had been conducted and the answers had been transferred to appropriate questions, the use of strategic management as the analytical framework to summarize key results was opted for to contextualize the interviews in the cyclical processes of urban green area development and maintenance. This prompted to an extent the inclusion of archival material to verify some of the interviewees' claims. The main example of this was searching for the stormwater strategies and guidelines of each municipality to see if such documents exist and if they had existed at the time of the example project's design process, or if the interviewee had been unaware of such documents or misremembered the timing for the publication of these documents. A similar verification through documents was made for some of the information sources the interviewees claimed they had used in the design process.

The licentiate student's experience as landscape architect meant that she was familiar with the context, terminology and typical practices of urban development and URG projects in Sweden and Finland beforehand. Due to this, the phase of thematical definition and familiarization with the topics of the study (Kvale & Brinkmann 2014) and the literature review phase that is usually carried out to support question formulation (Galletta 2013; Kallio et al. 2016) were cut relatively short. On the other hand, weaker familiarity with the professional practice might have lessened the number of assumptions made in the interpretation and analysis of the answers, and prompted more questions into how people define different concepts or how different project tasks are carried out. This might have helped to reveal more in-depth differences and similarities between the interviewees, the project organizations, and example projects.

The choice of looking into vegetation in URG:s in general, and not focusing on DPC in specific, was based on a worry that the number of suitable interviewees might have been insufficient had the example projects been defined too strictly. Including all kinds of vegetation into the study also helped to identify different kinds of strategies for URG planting design, which is also relevant for contextualizing the observations from the designed case studies (study 3).

Preliminary results

The preliminary results are presented here as they pertain to the four NbS-criteria by Sowińska-Świerkosz and García (2022), and the different phases of strategic management: Policy, planning, design, construction, maintenance and monitoring. In the final paper the exact format of how results are presented is under deliberation.

Inspired and powered by nature

Few municipalities had policies regarding urban vegetation in place. Correspondingly, space allotment for URG:s in the zoning plans was found to seldom provide sufficient preconditions for thriving urban vegetation. The poor status of vegetation in the planning phase was further exacerbated by the often weak contact between urban planners and green area designers. The interviewees reported, however, that the needs and attributes of vegetation are considered in more detail in the design phase. Site conditions (moisture, light, salt) are always considered as a part of the planting design process, and drought tolerance and variation in moisture conditions are identified as special focus for URG planting design. In some cases, however, the emphasis on moisture conditions might be at the cost of considerations for plant adaptation to other site conditions.

Specific plant expertise, internal or external, is often employed in URG projects to improve project outcomes. This has been especially important in many of the Swedish example projects, as Swedish landscape architects find URG-relevant planting design guidance harder to find than their Finnish colleagues. However, heavy reliance on tacit plant knowledge may hinder effective knowledge transfer and make grounds for design choices more opaque, which in turn makes the assessment of factors influencing vegetation success or failure more difficult. Plant diversity, “dynamic vegetation” (the Finnish synonym for DPC) and mixed planting patterns are sometimes employed to cope with uncertainty and increase vegetation resilience against unpredictable site conditions, pests and pathogens. Most of the projects try out some less used plant varieties to experiment with broadening URG plant palettes, and have also been able to find ways to pilot adjustments to engineered URG solutions to improve conditions for vegetation.

Answer to societal challenges

Stormwater quality and quantity management policies abound in both Finland and Sweden. In most cases stormwater policies and strategies can be found at municipal level, and municipal stormwater quality management is also regulated by national or local standards for environmental qualities of receiving water bodies. In Finland national guidance on stormwater quality and quantity management is also available. However, only one of the interviewee groups make an explicit connection between policies and the decision to deploy URG:s in their project. For example, few interviewees referenced directly climate resilience or urban place regeneration as reasons for working with URG.

URG placement and size is usually based on stormwater calculations, and often designated in zoning plans or encouraged in district planning. This is not always the case, however, and the designers sometimes express uncertainty about the rectitude of both volume and quality management calculations.

Provide multiple services, incl. biodiversity benefits

Aesthetic considerations and amenity values are usually prioritized and always considered in the planting design process. Stormwater quality management is another ecosystem service often considered by the designers. The interviewed designers are conscientious about enabling URG function, and plant selection and placement are thus often adjusted to decrease risks to the URG technical structures. All of the Finnish designers also report that biodiversity support is a central concern for URG vegetation design, contrary to their Swedish colleagues of whom few mention the topic. Overall, stormwater management and biodiversity are almost always considered only in the abstract in the planting design process, and detailed mentions of how the plants should contribute or which organisms are targeted are lacking. A symptom of this is the high focus on “safe” plant species, which are used to cope with uncertainty at the cost of plant biodiversity. In a similar vein, further ESS are rarely considered in the planting design process.

High effectiveness and economic efficiency

Stormwater management policies and technical URG design guidelines can improve the effectiveness and efficiency of URG:s, provided that they are based on best practice and promote solution connectivity. An example of such policies might be Finnish municipal programs for urban green spaces that include URG:s or NbS, or the inclusion of URG:s in some municipal technical handbooks in Sweden. However, as NbS as a concept is mentioned in only two of the examples, the likelihood of URG:s being employed as NbS that fulfil all four of the criteria is relatively low. This is exemplified by the fact that the Inclusion of URG:s is often decided on a project-by-project-basis, which hinders solution connectivity.

In the design phase, however, solution effectiveness may benefit from the fact that URG and URG planting design are an iterative collaboration between multiple people, who usually represent a variety of expertise and experiences. The interview results also show that planting design process always considers the social, environmental and policy conditions relevant for the project, and thus promotes the development of locally adapted solutions. Vegetation maintenance needs are almost always considered as a part of the planting design process, which may also improve the cost-effectiveness of URG:s over time.

Many of the professionals in the interviewed design organizations actively seek out and sometimes follow up URG reference projects. The interviewees also report that projects are used actively to experiment with and develop new URG solutions, fostering innovation and promoting monitoring practices. Yet, formal monitoring programs are rarely employed. While monitoring and data collection for verifying solution effectiveness and for future research are reasonable arguments for implementing a monitoring scheme, most of the interviewees were primarily interested in monitoring as a means to help identify causes of solution failure. Some of the answers suggest that allotting some of the project budget to solution adjustments during the warranty period might be enough to identify the worst risks to solution functionality and help to correct them in time.

Most of the interviews highlighted drought as a common problem with URG:s. Many of the interviewees suspected that the grading of adjacent street did not lead water to the URG:s as intended. Other possible causes of drought could be problematic inlet design, too permeable substrate, drainage pipe installation at the bottom of the URG, or too permeable subsoils. Troubleshooting underground problems is difficult, and thus monitoring the executed solution is less useful than demanding control measures during the URG construction process. Another issue that was often raised in the interviews was worries about and substrate or inlet clogging, despite the fact that these problems were not reported by the interviewees in relation to the example projects specifically. However, URG clogging has been found in other studies to be a frequent problem (Beryani et al. 2021). Clogging can often be observed aboveground, which means that visual monitoring methods can often be useful for scheduling maintenance efforts, assessing sediment sources, and adapting estimations of clogging rate. Data collected through monitoring, evaluation and controls can ideally be then used to test design hypotheses and improve future design solutions based on the observed outcomes, thus improving solution sustainability (Ahern 2011).

Why does this study and its results matter?

Based on the interviews, some of the common URG:s problems in Finland and Sweden include accumulation of debris and sediment that block URG inlets, misplacement of URG outlets that prevent aboveground runoff detention, trampling that causes soil compaction and damage to vegetation, runoff not reaching the URG:s due to grading problems or blocked inlets, unsatisfactory URG area and substrate volume due to competing interests with other types of infrastructure as well as large concrete fundaments replacing substrate, and troubled vegetation establishment due to extremely dry URG substrates. Many of the same issues have been identified by Beryani et al. (2021) and Lundy et al. (2022). Additionally, URG substrates have been found to leach nutrients in Sweden (Pettersson Skog et al. 2023). It is thus obvious that there are many hinders to URG:s working as the NbS they are meant to be.

Besides the effects of failed site analysis or other mismatches between design assumptions and realized conditions, the interview informants also report on several other possible causes of vegetation failure in urban areas. Planning, design, construction and maintenance phases can all involve unhelpful practices that hinder good vegetation development or otherwise prevent the creation or function of effective NbS. Like stormwater professionals earlier, many of the green area professionals expressed that they especially feel a lack of influence on the planning process, where the space allotment and placement of URG:s is decided (Cettner et al. 2013). Value conflicts, interpersonal issues, and unexpected/ uncontrollable events also effect realized vegetation development and NbS performance. The most notable issues regard the detrimental effects of unexpectedly severe drought, lack of space for plants above- and belowground, deprioritizing plant needs in the design process, and design and maintenance attitudes that discourage the use of species-rich planting combinations or trying out more unusual plant varieties. Still, almost all of the example projects also included trying out less common plant varieties, aimed for biological and visual variety, and could name engineering solutions that were adjusted for the benefit of vegetation. This implies a mismatch between the narrow perceived solution space for URG:s, and the real solution space which is broader.

There is often a strong perceived contradiction between creating URG substrates that provide optimal conditions for stormwater retention or pollutant removal, and that promote good vegetation development (Funai & Kupec 2017; Dagenais et al. 2018; Larm & Blecken 2019; Robinson et al. 2019; Pettersson Skog et al. 2023); Yet, vegetation has undeniable functionality in providing, enhancing and upholding stormwater quality and quantity treatment in open stormwater management structures (Le Coustumer et al. 2012; Yuan et al. 2017; Johnston et al. 2020; Skorobogatov et al. 2020). Considering that substrate stability, porosity, and a good balance between water retention and water drainage are beneficial for both vegetation and stormwater management (Glaister et al. 2017; Bakhtina et al. 2023), the main issue where plant needs and stormwater management goals contradict is the question of soil nutrient content (Funai & Kupec 2017; Shrestha et al. 2018; Larm & Blecken 2019; Pettersson Skog et al. 2023).

Urban rain gardens are sometimes conceptualized as highly productive environments where stormwater provides the plants with both nutrients and water (Glaister et al. 2017; Yuan & Dunnett 2018). Depending on the site and construction of the URG, this might be an accurate description (Funai & Kupec 2017; Corduan & Kühn 2024). However, the construction practices for Swedish URG:s with coarse substrates, poorly functioning inlets and excessive drainage systems create extremely dry site conditions, which are exacerbated by low annual precipitation and increasing heat and drought in the spring and summer (Skorobogatov et al. 2020; Beryani et al. 2021; Mantilla et al. 2023).

The ideal URG construction for Nordic conditions might thus benefit from improved water retention capacity so that plants and microbes could utilize stormwater and stormwater-borne nutrients to a considerably higher degree (Wang et al. 2019). Compost, biochar and other substrate materials that can absorb both water and nutrients and maintain them in a form that is available to plants and microbes should similarly be formulated so that they do not leach pollutants that are promptly drained out of reach for plants in the URG (Pettersson Skog et al. 2023).

8. Study 3: Vegetation development in urban rain gardens during the establishment period –a case study of four vegetation strategies

NbS should be multifunctional, economically feasible, and utilize nature as a part of the solution. Urban rain gardens (URG) are an NbS that has been gaining popularity in the past 10-15 years (Cettner et al. 2013; Chen et al. 2023), but there are uncertainties as to how one of the key natural components in them, vegetation, should be designed and managed for optimal performance (Winfrey et al. 2018). Designing vegetated NbS that perform well with regards to cultural and regulating ecosystem services (ESS) as well as provide biodiversity support must have a plant species composition that can deliver these services at a relevant quantity and quality for as large part of the year as possible.

Common vegetation types in URG tend to be trees, shrubs, herbaceous perennials and lawn, sometimes in combinations, usually in one or two layers. The urban context usually means that the space available is relatively small, and that there are relatively high expectations on the experienced safety and tidiness of vegetation in these. This is why spontaneous vegetation and multilayered woody vegetation are employed more rarely than URG in other stormwater management NbS. Thus, herbaceous perennial plants and low perennial woody plants like shrubs are commonly used in URG:s.

The success of URG vegetation hinges largely on vegetation health and well-being and resistance to invasion by undesirable plant species, even after the intensive maintenance of the warranty period is over. URG tend to be viewed as having especially tricky growing conditions due to alternating drought stress and oxygen deprivation stress, often combined with stress from salt and pollutants in the stormwater (Brooker et al. 2008). High stormwater flow rates that uproot plants or rip out shoots may also be counted as a disturbance factor. In urban situations, there may also be shade and heat stress and as well as disturbance through trampling, trash and anti-slip sand. Additionally, the different species in a planting should be in a relative competitive balance with each other to discourage quick competitive exclusion of some plant species and thus slowing down the rate of decreasing plant diversity. Choosing plants that thrive in the site conditions is thus necessary, as is considering possible adverse interactions between plants and other organisms like herbivores and plant diseases. Thus, plant selection for URG:s should ideally take a variety of plant interactions with their abiotic site conditions and biotic environment into consideration.

The first 2-3 years from planting are considered critical for further vegetation development, as it is during this establishment phase that plants are most at risk of death and damage (Leers 2013; Roman et al. 2015). During this time the planting is the most vulnerable to outside invasions and drying out due to unspecialized root systems (Levinsson 2015) and higher soil moisture evaporation rate. The establishment phase thus also determines the medium-term species composition, as possible extinctions or damage to plants during the establishment period influence later competitive and facilitative interactions between the surviving species (Köppler 2017:74). Progressing canopy closure during the establishment period these interactions between plants become increasingly intense.

In Sweden, the establishment phase coincides with the warranty period for constructed vegetation (Svensk byggtjänst 2004; e.g. Uppsala kommun 2019; Stockholms stad 2025:99,104-110). The warranty period tends to involve intensive vegetation maintenance to aid quick vegetation establishment (e.g. Uppsala kommun 2019; Stockholms stad 2025:99, 104–110), after which the maintenance frequency of urban plantings decreases significantly. Usually, vegetation maintenance during the warranty period is the responsibility of the constructing company or their subcontractor. Sometimes the client (e.g. the municipality) takes on the maintenance during the warranty period as well. However, there are no set parameters for what "plant establishment" means (Levinsson 2015), and thus it is difficult to assess whether the plant selection and the warranty maintenance have promoted vegetation establishment (Leers 2013).

This study describes and compares the establishment success of the four different planting strategies in relation to plant survival and growth, the realized site conditions, and the expended maintenance efforts. This study is a practical test of the previously identified DPC design tools, objectives and goals. The main subject of comparisons is the use of site-adapted plant assemblages as opposed to standardized, non-site-specific solutions. The two-year study has yielded a rich dataset on individual plant species' growth, health, flowering and competitive prowess in the early stages of their life, which both contribute to and are affected by the holistic development of these assemblages. The study provides material for hypothesis generation for further comparative studies and meta-analyses on urban ornamental vegetation maintenance and development on similar sites. Frameworks for site analysis and plant selection schemes for further studies are presented as possible future methods.

The planting design methodology for "designed plant communities" (DPC) promises to provide a framework and design tools that help with finding plant combinations that are fit for the site, that are relatively stable in terms of species composition, and that provide multiple functions despite low maintenance needs. The hypothesis investigated in the study is thus *"plantings designed within the DPC paradigm establish successfully within the same timeframe and same maintenance regime as comparison plantings in urban rain gardens"*. The hypothesis is tested through different metrics for vegetation establishment: Plant survival, size and coverage development, plant health, flowering and reproduction performance, and onset of autumn colouring. The results are then reflected on with regards to the influence of the initial planting design, site-specific factors, maintenance and possible disturbances on the results.

Choice of research methods

The hypothesis is investigated through designed case studies. In this thesis, the case studies have a strong element of mixed-methods evaluation (Tight 2017:103), as both the designed case studies and the inventories involve qualitative descriptions and quantitative analyses of vegetation performance, vegetation composition, site context, and URG configuration. The evaluation data may later be published as more qualitative papers that focus on subsets of data that can be analysed statistically, or that are more comparative and generalizing than the rich descriptions that can be made for each of the designed case study sites. The case study evaluations might also be presented together with the site inventories carried out in conjunction with the interview studies.

The designed case studies consist of 27 test plots in total: 8 plots at Campus Ultuna in Uppsala, 10 plots at Torgny Segerstedts Allé in Uppsala, and 9 plots at Hägerstensvägen in Stockholm. The sites Torgny Segerstedts Allé in Uppsala and Hägerstensvägen in Stockholm were assigned by collaborators at Uppsala municipality and the city of Stockholm. Despite the opportunistic site selection, the two sites are relatively comparable urban street environments, with roughly similar building density and traffic intensity. Thus, the two sites may be considered to be “stratified samples” (Flyvbjerg 2006), i.e. they represent a supra-urban and coarse-substrate sub-group of rain gardens, without claiming to represent rain gardens generally.

The two sites can also be considered extreme samples of rain gardens, as the supra-urban sites are especially prone to disturbance, chemical pollution, shade and urban heat island effect, and the coarser-than-recommended substrates exacerbate urban drought stress further. The macadam-based URG substrates used in Sweden differ notably from the sand-based URG substrates and layered filter structures that are recommended internationally (Skorobogatov et al. 2020; Beryani et al. 2021; Søberg et al. 2021; Laukli et al. 2022a; Lundy et al. 2022; Pettersson Skog et al. 2023). The benefits of macadam-based substrates in URG:s is their high infiltration rate and pore volume, which provides a high capacity for stormwater retention during flow events; they have a stable structure, which maintains porosity and thus keeps plant roots oxygenated; and the included biochar and compost can promote plant and microbial life as well as bind water and pollutants (Ulrich et al. 2017; Okaikue-Woodi et al. 2020; Biswal et al. 2022). They are also much drier and lower in nutrients than in URG:s with sand-based substrates, which in turn are drier than regular planting soils (Funai & Kupec 2017). Thus, plant selection for macadam-based substrates cannot be based on experiences from sand-based substrates or structures on soils with medium to low infiltration rate and without drainage in the substrate.

The urban test plots were laid out in rain gardens, whereas the suburban plots are in plantings without a special stormwater management purpose. Urban plots exemplify real-life conditions for urban rain gardens, whereas the plots at Ultuna represent garden- and park conditions. This setup was intended to improve understanding on whether the results are more influenced by a problematic planting design and/ or plant material, or by the conditions on site. Torgny Segerstedts Allé (TSA) and Hägerstensvägen (HSV) are further divided into two sub-sites due to some unavoidable variation in site conditions: TSA-South and TSA-North, and HSV-East and HSV-West. Detailed data on design parameters for each site is presented in Table 11(Torgny Segerstedts Allé), Table 12 (Hägerstensvägen) and Table 13 (Campus Ultuna). On each of the urban sub-sites, four to six plots have been established: one with a monospecific shrub planting, one with 7 species of exotic generalist ornamental perennials, one plot with 15 native generalist meadow perennials from plugs + sown meadow mixture, and one or more plots with a combination exotic and native species of perennials and grasses, designed in accordance with the DPC-framework (10 species in total). An overview of the plant mixes is presented in Table 15.

Analogue monitoring the case studies has been carried out by the licentiate student. Vegetation cover and height were measured twice per year: late May and at the end of August. Vegetation health was assessed with the help of plant cover and height, as well as by monitoring the plantings bi-weekly for obvious signs of plant pathogens, pests, or nutrient deficiencies (Brisson & Chazarenc 2009; Laukli et al. 2022a). Digital monitoring was primarily carried out by the licentiate student. Measurements from soil sensors at Ultuna and TSA have been transmitted automatically for each hour from December 2023 onward, although there have been some notable service disruptions. The soil sensor data is thus not complete for the duration of the study, and so comparison can only be made for the periods where the sensor setup has been at work on Ultuna and TSA simultaneously.

Maintenance costs and actions will be studied through maintenance plans and maintenance diaries. The two-year maintenance plans for all three sites were intended to follow the maintenance scheme for Torgny Segerstedts Allé:

- Weeding: Weekly during year 1, every other week during year 2
- Watering: Weekly watering during both years, 100 l/ m2/ week
- Fertilizing: No fertilizers for shrubs or perennials, although water for the trees at the subsite TSA-N and Hägerstensvägen includes liquid fertilizer
- Staking of plants as needed
- Regular trash removal
- Spring cleaning (April 15th-April 30th): Cutting down herbaceous plants (except for wintergreens), and removing most but not all organic debris. All inorganic debris should be removed.
- Autumn cleaning (October): Removing most but not all organic debris. All inorganic debris should be removed.
- Maintenance period starts 15th of April and ends 15th of October.

The maintenance diaries that describe realized management have been delivered to the licentiate student but not yet analysed.

Figure 20 Torgny Segerstedts Allé, sub-site TSA_S on the 14th of May 2025. The mix DPC1b is at the foreground.

Figure 21 The subsite HSV-E at Hägerstensvägen on the 20th of May 2025. The Top-7-mix can be seen in the foreground.

Figure 22 Reference plantings at Campus Ultuna on the 19th of July, 2024. The meadow mix and DPC1c can be seen in the foreground.

SITE ATTRIBUTES	TORGNY SEGERSTEDTS ALLÉ (TSA-S/N), UPPSALA (OKT 2023)
UNIT AREA:	TSA-S: 1,6*4,7 m =7,52 m^2, TSA-N: 2,5*2,6 m = 6,5 m^2
LIGHT CONDITIONS:	Partial shade; 3-5 hours of intense midday sun Direct light hours Dec 21st: ca 12-13; Mar 21st: ca 11-14; Jun 21st: ca 9:30-14:30; Direct light hours Sep 21st: ca 11-14 The northern parts get maybe an hour less sun in spring and fall, 1,5 h in the summer. The different sides are mostly quite equal, except by the square. At the openings from the streets and the park there is some more light as well, by the park up to 2,5 h both morning and evening.
WATER CONDITIONS:	Soil moisture probably dry to moderate, with little to no buffer for dry periods. Annual precipitation between 400-600 mm (SMHI average annual accumulation 1990-2020); Small catchment areas. Water quality not especially polluted (water only from pedestrian road). Little to no salt. Highly draining planting substrate (200-400 and up) and constructed subsoil. No infiltration to natural subsoil. The upper layer has some retention capacity both in the pores as well as in the biochar and compost. There is pretty much no capillary water movement in the lower layer despite the biochar. The constructed subsoil has an even higher infiltration capacity, and no capillary water. The designed flooding depth on top of the structure is 150 mm. Periods with standing water are assumed to be rare and short in length. The constructed subsoils and bentonite layer are drained via a length- and widthwise gradient.
SOIL ATTRIBUTES AND SUBSTRATE CONSTRUCTION:	Multi-layered, deep free-draining artificial structures of mostly coarse fractions of crushed stone, biochar and compost. Layers: 50 mm macadam 8/11 + 500 mm Regnbädd Växtjord,(macadam 2/6 75%, Compost 12,5%, biochar 12,5% + 100 mm Undre regnbäddsjord (Macadam 32/90 85%, biochar 15%). Biochar EBC-certified, 0/20, not loaded with nutrients, density ca 500 – 600 kg/m3. Subsoil consists of macadam 16/90 and is separated from the planting bed with geotextile. Soil pH 7 (neutral) assumed on average. 5,5-7,5 overall. The large span of possibilities is due to the varying stone types that make up the mineral components of the substrates in this area. Biochar has a pH of around 8-10. Compost between 6 and 8. There is no nutrient data available for macadam-based substrates. The compost in itself is very nutrient-rich: EC 7,9, whereas a normal reference soil is at 1,5-4. 5 is the maximum for planting soils. Specific elements may be overrepresented in some planting beds based on stone type or compost source, but since there is no information on these we assume there are no special concentrations.
CLIMATE CONDITIONS:	Growth zone 3 (Swedish system). USDA-Zone 7a. Köppen-Geiger climate zone: Humid continental climate of warm summer subtype. Average length of growing season 190-200 days. There is an observable UHI-effect in the area. Average wind speeds are between 2-2,17 m/s, which is the second-weakest wind class. Still weather is common. Most common wind direction is southwest by west, and this is also the direction where the strongest winds come from, especially in the winter and autumn. In the spring and summer north by northeast also has a considerable single peak. The street is oriented south-by-southwest, so it is likely that it is somewhat windy, although the forest and buildings to the west probably take the edge off of the southwest by west-winds. The wind properties are likely to change to a less windy/ more singular wind direction as the eastern quarters are built.

SITE ATTRIB-UTES	TORGNY SEGERSTEDTS ALLÉ (TSA-S/N), UPPSALA (OKT 2023)
	There are no immediate large water bodies, Fyris River is a few km away. Next to this area there is a large moist forest, which might affect the air humidity some. Absolute air moisture average in January (1996-2020): 4-5, typical for southern Sweden. Relative air moisture for same time and measurement period is 85-90, like in most of Sweden. Absolute air moisture average in July (1996-2020): 10-11, which is a bit lower than in the southern coastal Sweden. Relative air moisture for same time and measurement period is 70-75, which is the next-lowest class in Sweden during this period. The site is not especially exposed, although it does align approximately with both midday sun and main wind direction. The street is reasonably narrow, and sheltered from both east and west.
NATURAL CONTEXT:	The area is sandwiched between two nature reserves, of which the other one is moist, dark multi-layered and spruce-dominated with a clear forest feeling, and the other is somewhat lighter, pine-dominated and simpler in it's structure. The area is built on top of an important aquifer, and thus the new constructions need to be isolated from the subsoils in order to prevent polluting the aquifer.
CULTURAL CONTEXT:	The central street of a new residential area. The area has a high profile that promotes innovation, especially integrated blue-green-gray systems for stormwater management. The apartments tend to be quite expensive, although there is a mix or rental housing and privately owned apartments. The street is broad and green. The Rosendal area is in progress. The first buildings of the current zoning plan have been inaugurated in 2016. Trafficked site -> Median height of vegetation max. 1 m.

Table 11 Presentation of the three case study sites, part 1: Torgny Segerstedts Allé

SITE ATTRIBUTES	HÄGERSTENSVÄGEN (HSV-E/W), STOCKHOLM (OKT 2024)
UNIT AREA:	HSV-E: 4*1,9 m =7,3 m^2 HSV-W: 8,2*1,9 = 15,5 m^2
LIGHT CONDITIONS:	West: Light shade-Dappled shade from trees (later deep shade from buildings). 0-4 hours of early morning sun and 0-5,5 hours of evening sun. Direct light hours Dec 21st: Max 1 hour of wandering light; Mar 21st: Max 1 hour; Jun 21st: 2:45-6:45, 15:15-20:45; Sep 21st: Max 1 hour + 16:45-17:45 East: Full sun (later light shade from trees). 4-18 hours of sun, always mid-day sun. Direct light hours: Dec 21st: all day; Mar 21st: ca 9:30-13:30; Direct light hours Jun 21st: all day; Sep 21st: ca 8:15-13
WATER CONDITIONS:	Probably dry to moderate, with some buffer for dry periods. The upper substrate layer has some retention capacity both in the pores as well as in the pumice, biochar and compost. There is pretty much no capillary water movement in the lower layer despite the pumice and biochar. Unclear infiltration and capillarity in the subsoil/ bedrock Annual precipitation between 400-600 mm (SMHI average annual accumulation 1990-2020); Very small catchment areas, ony from pedestrian road. Little to no salt. Highly draining planting substrate (200-400 and up). The bottom of the planting bed probably reaches the bedrock, unclear infiltration. No designed flooding depth on top of the structure. Periods with standing water are assumed to be extremely rare and short in length. The street has a decent length- and widthwise gradient, which the street construction is expected to follow.
SOIL ATTRIBUTES AND SUBSTRATE CONSTRUCTION:	A multi-layered, relatively deep free-draining artificial structure of mostly coarse fractions of crushed stone, pumice stone, biochar and compost.400 mm mixture of 40% pumice 2-8, 35% macadam 2-6, 12,5% biochar, 12,5% compost + 600 mm mixture of 45% macadam 32-90, 40% pumice 2-8, 7,5% biochar, 7,5% compost. (%-vol.) Soil pH 7 (neutral) assumed on average.5,5-7,5 as a whole for the top layer, upper layer and lower layer of the substrate. The large span of possibilities is due to the varying stone types that make up the mineral components of the substrates in this area. Biochar has a pH of around 8-10. Compost between 6 and 8. Pumice 7. Soil nutrient content presumably moderate. There is no nutrient data available for macadam-based substrates. The compost in itself is very nutrient-rich: EC 7,9, whereas a normal reference soil is at 1,5. The biochar will be nutrient-enriched and might not absorb more from the compost. The pumice, on the other hand, might, evening out the EC across the substrate. Pumice is high in silicon. Specific elements may be overrepresented in some planting beds based on stone type or compost source, but no high concentrations are assumed.
CLIMATE CONDITIONS:	Growth zone 2 (Swedish system). USDA-Zone 7a. Köppen-Geiger climate zone: Humid continental climate of warm summer subtype. Average length of growing season 220-245 days. There is an observable UHI-effect in the area: maximum radiation temperature 2013-2021 32-35 C. Primarily low wind speeds (class 2), with regular class 3 and occasional class 4 winds from the west. Air moisture is deemed to be average for the region. The site is not especially exposed, although it does align approximately with the main wind direction. The street space is relatively broad, and will be sheltered from south. Average wind speeds are between 3,32 m/s, which is the second-weakest wind class. Most common wind

SITE ATTRIBUTES	HÄGERSTENSVÄGEN (HSV-E/W), STOCKHOLM (OKT 2024)
	direction is west, and this is also the direction where the strongest winds come from, all year. This coincides with the direction of the street. Southern winds can also be strong, but will locally be blocked by the ridge and buildings to the south. The area is close to Mälaren without any large dividing height ridges in between. Absolute air moisture average in January (1996-2020): 4-5, which is higher than in the immediate surroundings (3-4), but normal in southern Sweden and e.g. Stockholm. Relative air moisture for same time and measurement period is 90+, which is more than in the immediate surroundings and most of Sweden. Absolute air moisture average in July (1996-2020): 10-11, which is a bit lower than in the southern coastal Sweden. Relative air moisture for same time and measurement period is 70-75, which is the next-lowest class in Sweden during this period.
NATURAL CONTEXT:	The area is densely built. Much of the vegetation seems to have originated as ornamental plantings. Spontaneous establishment seems also to have occurred at various points in time. South of the street the site slopes up steeply due to a large bedrock formation. The vegetation on the slopes is primarily deciduous, and the slope top coniferous. On top of the bedrock there is a shallow layer of moraine and organic matter.
CULTURAL CONTEXT:	The plantings will be a part of a very long sight axis formed by the streets and the metro tracks. The space between the buildings on either side of the tracks is wide. Its borders are variable, mostly very dense on the southern side and somewhat looser on the northern side. The area consists of houses of varying ages, from the late 1930's to the 2010's. Newer houses dominate the southwest side, older houses on the southeast, and houses from late 1960's north of the tracks. Both the walking lane and the cycling lane are broad. The site reads very much as a suburban "bypass", i.e. not a place for leisure. It constitutes approx. 600 meters of the 4 km long street. The street will partially be rebuilt to guide water from the pedestrian street towards the test plots. Trafficked site -> Median height of vegetation max. 1 m.

Table 12 Presentation of the three case study sites, part 2: Hägerstensvägen

SITE ATTRIBUTES	ULTUNA (ULT), UPPSALA (SEPT 2023/ MAY 2024)
UNIT AREA:	2*4 m =8 m^2
LIGHT CONDITIONS:	Full sun all day; Daytime length Dec 21st- ca 9:15-14:30 ; March 21st- ca 6:00-17:45; Jun 21st- ca 3:00-21:00: March 21st- ca 5:45-17:45
WATER CONDITIONS:	Soil moisture probably moderate, with some buffer for dry periods in the surrounding sandy soil. Annual precipitation between 400-600 mm (SMHI average annual accumulation 1990-2020); Minimal catchment areas, surrounded by grass. Water retaining planting substrate and natural subsoil, so capillary activity as well as horizontal water movement are to be expected. No designed flooding depth, the plantings are on a mild slope and slightly raised at the beginning. Water quality not polluted (water only from park areas).
SOIL ATTRIBUTES AND SUBSTRATE CONSTRUCTION:	Two-layered planting beds consisting of standardized, fertilized soil-based engineered substrates. 400 mm soil type A (structure according to AMA DCL.11/1) with 5-8% organic content + 200 mm soil type A with <2% organic content. Natural sandy subsoil assumed during the design phase (based on soil maps by the Geological Survey of Sweden), but turned out to be heterogenous and densely packed mineral filler material. Soil analysis (AL-method) shows the following values: pH: 6,6 P mg/100g: 13 K mg/100g: 23 Mg mg/100g: 14 Ca mg/100g: 130 Vol.-weight kg/l: 1,2 Electric conductivity (Ledningstal): 1,8
CLIMATE CONDITIONS:	Growth zone 3 (Swedish system). USDA-Zone 7a. Köppen-Geiger climate zone: Humid continental climate of warm summer subtype. Average length of growing season 190-200 days. There is no observable UHI-effect in the area. No detailed information on wind conditions on the site, but probably quite sheltered from the south (buildings and trees) and east (the forested Uppsala esker). Fyris river is about 2 km away, but separated by the esker. Presumably normal to slightly raised air moisture.
NATURAL CONTEXT:	The north edge of the Ultuna Campus, which consists of large buildings and small green areas. It is surrounded by fields in the West and South, the forested Uppsala esker in the East, and a residential area of mostly detached houses with large gardens to the North.
CULTURAL CONTEXT:	The beds are placed in a lawn “corridor”, sparsely planted with small trees and a pedestrian path. It also borders on the main street across the campus, and neighbors a campus building with parking area. Campus Ultuna is located in a relatively loosely built suburban area.

Table 13 Presentation of the three case study sites, part 3: Campus Ultuna

Designing the case studies

Designed plant communities represent ecologically and culturally site-specific solutions in this study. Thus, their design is based on a thorough site analysis of annual precipitation, planting bed construction, wind, light, natural and cultural context, and length of the growing season. Criteria for site analysis and corresponding plant selection were formulated in concert with of the pre-study (chapter 5) with the help of gray and scientific literature (Joardar 1998; Hunter 2011; Kühn 2011; Oudolf & Kingsbury 2013; Hitchmough 2014; Van Mechelen et al. 2015; Hansen & Stahl 2016; Heinrich & Messer 2017; Dunnett 2019; Radhakrishnan et al. 2019). For application of the selection criteria, plant data was collected from a subjective spread of planting design literature (e.g. (Oudolf & Kingsbury 2013; Hansen & Stahl 2016), but also German and Swedish plant nursery catalogs (Foerster-Stauden 2012; Bruns et al. 2019; Perennagruppen 2021; Staudengärtnerei Gaißmayer 2022; Säve plantskola 2022). The German catalogs and *"Die Stauden"* (Hansen & Stahl 2016) were necessary for the application of the Garden Habitat- and plant sociability-systems, whereas the Swedish catalogs were used as a complement to account for climate-dependent variables like hardiness as well as expected flowering times and plant heights. Oudolf & Kingsbury (2013) was used as the main source for describing plant habit, longevity, and persistence.

The design did not attempt to maximize stormwater management benefits, which means that the plant selection has not aimed to maximize the root length or evapotranspiration rates (Winfrey et al. 2018). Rather, technical functionality in stormwater management is assumed in this study to be a side-effect of plant health and well-being, because there is literature that points to the fact that plant identity is the thing that makes most difference to water uptake/ evapotranspiration (size, like trees) and water quality treatment (plants with a lot of biomass like *Phragmites australis*, hyperaccumulators like *Armeria maritima*). The plant selection and placements also do not take into consideration possible variation in moisture conditions within the URG, but rather all of the multi-species plantings are arranged in mixed patterns. Mixed patterns are employed partially to decrease the effects of placement on the performance of individual plant species, partially to make the case study design more comparable to experimental studies on DPC, and to emulate the mixed, equidistant patterns of "*Staudenmischpflanzungen*" and other highly intermingled DPC plantings

(Kircher et al. 2012; Hitchmough 2014:131). Shrubs have been planted at a density of 2,78 plants/ sqm (distance c/c 60 cm) as per recommendations from Swedish plant nurseries, and the perennials at 8,16 plants/ sqm (distance c/c 35 cm). The sizes and types of transplants were as follows: Shrubs 3,5 l pots, forbs and grasses for the DPC-mixes and the top-7-mix in P9- or SQ1-pots (depending on nursery availability), and the meadow plants as 40 mm x 90 mm plugs. At Ultuna and Torgny Segerstedts Allé *Anemone blanda* was planted as corms in P9-pots, whereas at Hägerstensvägen only unpotted corms were available and were thus substituted.

Complete plant lists with plant attributes for each DPC-mix can be found in Table 17 (DPC1a), Table 18 (DPC1b), Table 19 (DPC1c), Table 20 (DPC2a) and Table 21 (DPC2b). Based on the site analysis results (Table 11, Table 12, Table 13) the site was mapped onto the Garden Habitat system (Sieber 1990; Hansen & Stahl 2016). Due to uncertainties in the analysis of light and moisture conditions, four Garden Habitat classes were found relevant: dry or dry to normal woodland (W1, W1-2) and dry or dry to normal Woodland edge (WE1, WE1-2). The choice of Garden Habitats W and WE is due to woodland and woodland edge being the only Garden Habitats that explicitly include shaded situations, like the shade from buildings and/ or trees that are factors at both Torgny Segerstedts Allé and Hägerstensvägen. All of the included plants should also have a minimum hardiness corresponding with USDA zone 6 and Perennagruppen's hardiness class B*, although plants with better hardiness were preferred. Plants that were not deemed suitable for these sites were excluded from the initial selections for DPC-mixes. Additional exclusion criteria for plants were intolerance of warm sites and recorded intolerance for salt. Plants in the expected height range between 30 and 100 cm were prioritized to create enough volume in the planting, while decreasing the risk of reducing experienced safety.

Due to the harsh site constraints the resulting shortlists of plants included relatively few, seemingly equally well-equipped species. Plant selection from the shortlists aimed to maximize variation in "*Geselligkeit*"-classification, size and habit, as well as in spreading ability and method of spreading. This selection method was used as an analog to role-setting systems, and complemented with a description of the plants' intended roles in the mixes. Plant species and cultivars of species with high longevity and persistence were promoted, as were plants that were described as robust or that had acquired a high rating in the German perennial trials. Finally, the plant selections were adjusted to attain as long continuous season of blooming as possible, and to promote variation in leaf color and texture.

Plant data was compiled from seven different sources partially due to contradicting information in some of the sources, but also because none of the sources provided the complete range of information needed to judge a plant's site condition tolerances, growth and blooming parameters. For hardiness, expected height and blooming time it was important to use Swedish sources, whereas many of the other parameters were only available in German or British sources.

The site analyses, plant selection criteria and the vegetation evaluation scheme for the DPC-mixes is presented in Figure 26.

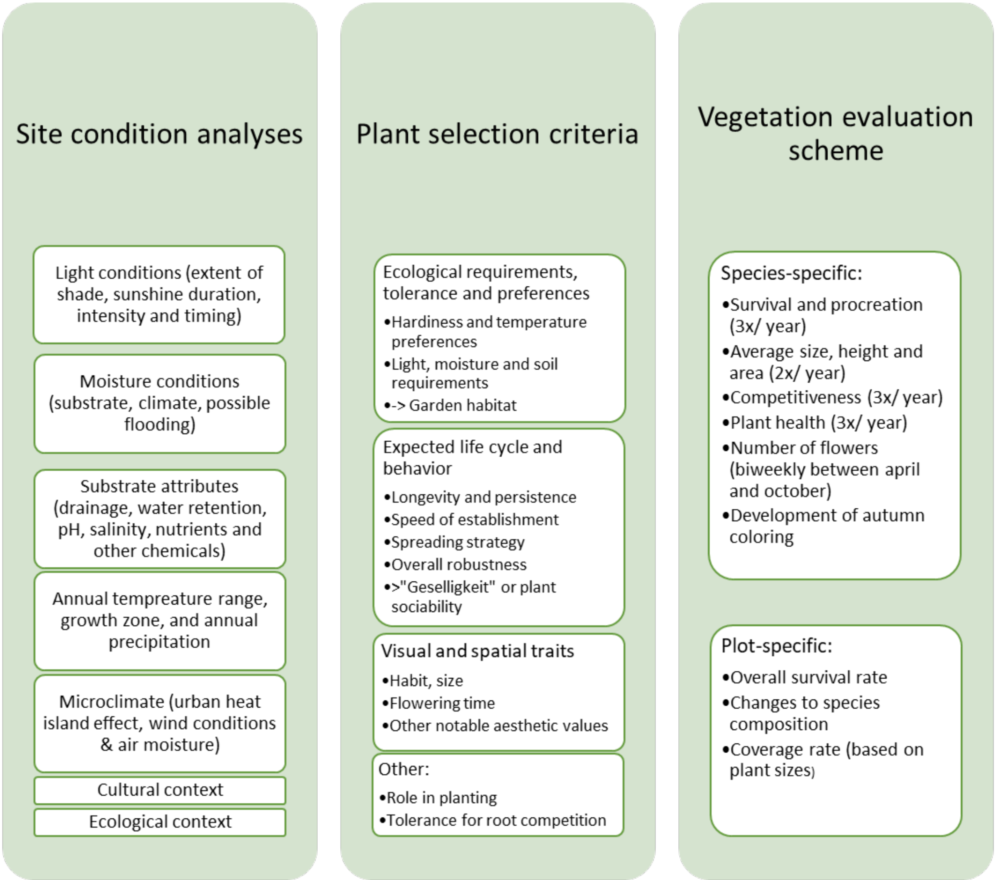

Figure 23 Planting design considerations and evaluation criteria for the designed case study

The representative plant varieties for shrub monocultures and generalist perennial forbs and grasses were chosen on the basis of sales data from five different Swedish plant nurseries that primarily cater to business clients. The shrub *Lonicera caerulea var. kamtschatica* 'Anja' E was chosen as a representative of shrub monocultures, as it was the most sold shrub in Sweden in 2019-2021. It has also been used frequently in URG:s in Uppsala, where the first test beds are located. The seven herbaceous perennials that repeated in the top 10- top 20 of all of the five nurseries' most sold-lists formed the Top-7-mix. The monoculture of *Lonicera caerulea var. kamtschatica* 'Anja' E and the Top-7 mix represent the horticultural approach to planting design. They also represent robustness strategies due to the perceived toughness and adaptability of the included plant species and varieties, although in general herbaceous perennials are not considered to be as robust or easily maintained as shrubs. To help comparisons between the habitat-matched DPC-mixes and the non-matched Top-7-mix, the GH-classifications of the plants in the top 7-mix are presented in Table 14.

Species/ cultivar	GH-classification (for sources, see legend for table 10)
Alchemilla mollis	WE *1); OG2, WE2 *2); OG2-3; WE2-3 *3)
***Calamagrostis x acutiflora* 'Karl Foerster'**	OG2, B2-3 *1); OG1-2, WE1-2 *2); OG1-2 *3)
***Geranium macrorrhizum* 'Spessart'**	WE1-2, OG, RG2 *1); WE1-2, OG1-2, SS1-2 *2); WE1, OG1, SS1 *3)
Luzula sylvatica	W1-2 *1); W2, WE2 *2),3);
***Nepeta x faassenii* 'Walker's Low'**	OG1, ST2 *1); OG1, SS1, H1, RG1 *2); B1-2, OG1-2 *3)
***Salvia nemorosa* 'Caradonna'**	OG2, B1-2 *1) OG2, H2 *2); OG1-2, B1-2 *3)
Waldsteinia ternata	W1-2 *1); W2, WE1-2 *2),3);

Table 14 Garden Habitats for plants in the Top-7-mix. Legend for sources can be found in table 17. Legend for Garden Habitat classification abbreviations can be found in English-language Bruns-catalogues, e.g. Bruns 2018/2019.

As the Nordic nurseries that specialize in native plants sell most of their stock as pre-defined, site-adapted seed mixes or pre-established vegetation mats, the meadow mix was composed based on a procedure to find 10-20 native plant species that had relatively broad site tolerance amplitudes so that the result would be as close to a composition of generalist species as possible.

The procedure consisted of compiling species lists from all of the commercial meadow seed mixes from the two largest Nordic meadow seed suppliers. For each species, the projected soil moisture, light conditions and salinity level of the mixes they were included in was recorded as indicators of the plants' site tolerances. These records were then translated into a scale of "wide tolerance - medium tolerance - narrow tolerance" for light and soil moisture conditions, and whether or not the plant is assumed to tolerate salt. However, most Nordic native meadow plants seem to have relatively narrow site condition tolerance amplitudes, the final selection also includes plants that have narrow tolerances to one or more site condition, or no recorded salt tolerance. Finally, the selection was influenced by plant availability in pre-established plugs so that they could be planted like the other ornamental plants.

Design parameters for the plant mixes can be found in Table 15. The final plant selections, including last-minute substitutions due to availability issues, are presented in Table 16.

Planting mix:	Designed plant community 1a (DPC1a)	Designed plant community 1b (DPC1b)	Designed plant community 1c (DPC1c)	Designed plant community 2a (DPC2a)	Designed plant community 2b (DPC2b)	Native meadow mix (ÄNG)	7 most sold perennials in Sweden (TOP7)	Most sold shrub in Sweden (ANJA)
Design intention:	Pine forest understory. GH: WE1(-2)	Oak forest understory. GH: WE/1(-2)	Spruce forest understory. GH:W(/WE)1-2	Shaded North-facing rock cliff. GH: WE/ ST1-2	Sunny South-facing rock cliff GH: WE/ ST1-2	Nature conservation	Horticultural	Robust
Intended site:	Southern Rosendal, Uppsala; Median strips between sidewalk and driveway			Hägerstensvägen, Stockholm; Median strips between sidewalk and driveway		N/A	N/A	N/A
Replicates:	**2** (TSA-S, ULT)	**4** (All subsites but HSV-E)	**2** (TSA-S, ULT)	**2** (HSV-W, ULT)	**2** (HSV-E, ULT)	**5** (All subsites)	**5** (All subsites)	**5** (All subsites)
Light conditions(in midsummer (expected):	Partial sun, 3-5 hours of midday sun	Semi-shade to moderate shade, 3-5 hours of midday sun. Will get progressively shadier as the trees grow.		Semi-shade, 4 h morning and 5 h evening sun	18 hours of full sun/ dappled shade	Any	Any	Any
Moisture conditions (expected):	Average precipitation, dry to average soils (on the drier side). Well-drained soils, short periods of flooding possible in extreme cases.			Average precipitation, dry to average soils. Well-drained soils, short periods of flooding possible in extreme cases.		Any	Any	Any
Soil conditions (expected):	Constructed gravel-based substrate, pH neutral or slightly alkaline, nutrient content average to poor, little to no salt			Constructed gravel- and pumice-based substrate, pH neutral or slightly alkaline, average to poor in nutrients, little to no salt		Any	Any	Any
Climate (expected):	Growth zone 3 (on the warmer side), average air moisture for the area, low winds			Growth zone 2 (+ some UHI-effect), average air moisture for the area, low winds		At least growth zone 3 (Riksförbundet Svensk Trädgård)		
Distribution	Uneven taxon abundances					Even abundances		

Table 15 Basic attributes and design parameters for the designed case study planting mixes

Planting mix:	Designed plant community 1a (DPC1a)	Designed plant community 1b (DPC1b)	Designed plant community 1c (DPC1c)	Designed plant community 2a (DPC2a)	Designed plant community 2b (DPC2b)	Native meadow mix (ÄNG)	Mix of the most sold perennials in Sweden (TOP7)	Monoculture of the most sold shrub in Sweden (ANJA)
Species in the mix:	*Symphyotrichum laeve* 'Calliope' *Campanula glomerata* 'Superba' *Centaurea montana* 'Grandiflora' *Digitalis ferruginea* *Geranium renardii* 'Philippe Vapelle' *Geranium* x *cantabrigiense* 'St. Ola' *Malva moschata* *Phlomis russeliana* *Phedimus kamtschaticus* *Sesleria autumnalis*	*Anemone blanda* 'Blue shades' *Eurybia divaricata* *Campanula persicifolia* *Carex caryophyllea* ´The Beatles´ *Geranium nodosum* *Lamium galeobdolon subsp. flavidum* 'Herrmann's Pride' *Lamium orvala* *Luzula nivea* *Tellima grandiflora* *Waldsteinia ternata*	*Aruncus* 'Fairy Hair' *Asarum europaeum* *Euphorbia amygdaloides* 'Purpurea' *Fragaria vesca* 'Rödluvan' E *Geranium macrorrhizum* 'Bevan's Variety' *Geranium phaeum* 'Album' *Hesperis matronalis* *Lamium maculatum* 'Beacon silver' *Luzula pilosa* 'Igel' *Waldsteinia geoides*	*Anemone tomentosa* 'Robustissima' *Eurybia herveyi* ´Twilight' *Bergenia cordifolia* 'Möja' *Buglossoides purpurocaerulea* *Carex oshimensis* 'Evergold' *Carex umbrosa* *Epilobium angustifolium* 'Album' *Helleborus foetidus* 'Wester Flisk' *Lamium galeobdolon* 'Florentinum' *Polystichum aculeatum*	*Anaphalis triplinervis* *Calamagrostis brachytricha* *Calamagrostis* x *acutiflora* 'Cheju-Do' *Centaurea dealbata* *Geranium sanguineum* 'Max Frei' *Hieracium aurantiacum* *Euphorbia polychroma* *Phlomis tuberosa* *Phuopsis stylosa* *Veronica teucrium* 'Knallblau'	*Achillea millefolium* *Anthoxanthum odoratum* *Briza media* *Campanula rotundifolia* *Centaurea jacea* *Dianthus deltoides* *Festuca ovina* *Galium verum* *Hypericum maculatum* *Hypericum perforatum* *Knautia arvensis* *Leucanthemum vulgare* *Linaria vulgaris* *Lotus corniculatus* *Plantago lanceolata*	*Alchemilla mollis* *Calamagrostis* x *acutiflora* 'Karl Foerster' *Geranium macrorrhizum* 'Spessart' *Luzula sylvatica* *Nepeta* x *faassenii* 'Walker's Low' *Salvia nemorosa* 'Caradonna' *Waldsteinia ternata*	*Lonicera caerulea var. kamtschatica* 'Anja® E

Table 16 Plant lists for each of the plant mixes in study 3

Taxa	%	Hardi-ness	Garden Habitat	Moisture	Light	*Gesellig-keit*	Longevity & persistence	Visual features	Role	Size (cm)	Bloom (mo)	Habit	Spreading strategy	Soil	Other
DPC1a (Pine forest understory. GH: WE1(-2))															
Aster laevis– 'Calliope'	6%	A *4) ; USDA 3*2) or 4 *3)	OG, B *1); WE1-2, OG2 *2); OG1-2, WE1-2 *3)	Moderate to temp. dry *1); ~ to dry *2),3)	Sun *1); ~ to half-shade*2),3)	II *1); I *2); I *3)	True perennial *5); Persistence + *5)	Contrasting color [PO];Structure + *5)	Lead role	130-150 *7)	8-10 *7)	Upright habit *5)	Self-seeding ± *5); Vegetative spread - *5)		
Campanula glomerata 'Superba'	7%	A *4); USDA 2*2),3)	OG *1); OG1-2, WE 1-2*2),3)	Moderate to mod. dry *1); ~ to dry *2),3)	Sun *1),3); ~ to half-shade *2)	II*2),3)	True perennial *5); Persistence + *5)	Showy cul-tivar [PO];Structure - *5)	support role	40 *7)	6-7 *7)	Upright stem mound *5)	Self-seeding ± *5); Vegetative spread ±/+ *5)	pH >7 *2); Drainage+, productive +, humus+ *3)	
Centaurea montana 'Grandiflora'	7%	B *4); USDA 3*2),3)	WE *1); WE1, OG1 *2); WE1-2, OG1-2 *3)	Dry *2); Mod-erate to dry *3)	half-shade *1); Sun *2); ~ to half-shade *3)	I *2); I-II *3)	True perennial *5); Persistence + *5); Robust *3)	Structure + *5) Short season for pleasant expression [PO]	support role	60 *7)	6-7 *7)	Stem mound *5); Loose mound *2)	Self-seeding - *5); ~ ± *3); Vegetative spread ±/- *5); Short ramets *2)	Nutrient (+), humus + *3)	
Digitalis ferruginea	5%	B* *4); USDA 6 *2) or 5 *3)	W *1); WE1-2*2),3)	Moderate *1); ~ to dry *2),3)	Sun to half-shade *3) Half-shade *2); ~ to shade *1);	I-II *2),3)	Short-lived *1),2),3); >5 years *5); Persistence + *5)	Structure + *5)	Lead role/ scatter/ filler	120 *7)	7-8 *7)	Emergent habit *5)	Self-seeding ++ *5); Vegetative spread 0 *5)	Nutrient + *1); Loam + *1),3); Humus+, Drainage+*3)	
Geranium renardii 'Philippe Vapelle'	15%	A *4); USDA 5*2),3)	WE *1); RG1-2, SS1-2, WE1 *2); RG1, SS1 *3) OG1-2 *2)*3)	Moderate to temp. dry *1); ~ to dry *2),3)	Sun *3) ~ to half-shade *2); Half-sun to half-shade *1);	I *2); I-III *3)	Long-lived *3)	Structure [PO]; Inter-esting leaf texture *2)	support role	40 *7)	6-7 *7)	Leaf mound [PO]; Clump-forming habit *3)	Short ramets *2)	Drainage+, coarse sub-strates+, Nutrient (+) *3)	Robust va-riety *3); Warm sites +*3)
Geranium x cantabrigiense 'St. Ola'	15%	A* *4); USDA 5*2),3)	SS1-2, WE1-2, OG1-2, H1-2*2),3)	Moderate to dry *2),3)	Sun *3) ~ to half-shade *2);	II-III *2),3)	Robust *2); Perennial [PO]	Wintergreen leaves*2),3)	Groundc over	20 *7)	5-6 *7)	Mat-forming habit*2),3)	Short ramets *2)	Sandy,stony *2); Humus (-), Nutrient (-) *3)	Warm sites +*3)
Malva moschata	10%	B *4); USDA 3*2) or 5 *3)	OG1-2, WE1-2*2),3)	Moderate to dry *2),3)	Sun*2),3); ~ to half-sun *1)	I *2); I-II *3)	Short-lived *2); <5 years [PO]	Structure - [PO]; Long blooming time [PO]	support role	50 *7)	6-9 *7)	Upright habit [PO]	Self-seeding + *2); Vegetative spread 0 [PO]	pH<7+ *2)	Warm sites +*2)
Phlomis russeliana	5%	A *4); USDA 6 *2)	OG *1); OG1, SS1, WE1 *2)	Moderate to mod. dry *1); Dry *2)	Sun *1),2)	I; takes a lot of space *2)	True perennial *5); Persistence + *5)	Structure ++ *2),3),5); Wintergreen *2)	Lead (ground-cover)	70 *7)	7-8 *7)	Emergent habit *5); Mat-forming habit *2)	Self-seeding ± *3),5); Vegetative spread ± *5)	Loam + *1)	Slow to es-tablish *2)
Sedum kamtschaticum	15%	A* *4); USDA 6 *2)	RG1-2*2); OG1-2*6) WE1-2,, SS1-2*2),*6)	Moderate to dry *2)	Sun to half-shade *1),6)	II-III *2)	True perennial [PO]; Persistence ± [PO]	Structure - [PO]	Groundc over	15 *7)	7-8 *7)	Low cushiony habit *2)	Vegetative spread ± [PO]; Self-seeding ± [PO]	Coarse sub-strates + *2)	
Sesleria autumnalis	15%	A *4); USDA 6 *2) or 4 *3)	OG, SS *1); SS1-2, H1-2, RG1-2 *2); OG1-2*3) WE1-2*2),*3)	Moderate to dry*2),3)	Sun *1); ~ to half-shade *2),3)	I *2); I-II *3)	True perennial *5); Persistence + *5); Robust*2),3)	Structure ++ *5); Winter-green *2)	Groundc over	30/50 *7)	8-10 *7)	Mat-forming habit *5); Clump-forming habit *3)	Self-seeding - *5); Vegetative spread ± *5)	Nutrient + *1); Sand+, coarse sub-strates+ *2); pH>7+ *3)	Tolerates root com-petition well *2),3); Warm sites +*3)

Sources: *1)(Hansen & Stahl 1981), *2)(Foerster-stauden 2012), *3)(Gaissmayer 2020 [DPC2a/DPC2b Gaissmayer 2023]), *4)(Perennagruppen 2021), *5)(Oudolf & Kingsbury 2015), *6)(Bruns 2018/2019 – also the source for Garden Habitat-abbreviations!) *7)(Säve 2022 [DPC2a/DPC2b Säve 2023]), *8)(Stångby 2022), *9)(E-planta 2022), *10)(SLU Artfakta), *11)(Vegtech 2023) [PO] personal observation. Legend: Structure ++/ +/- (Long season/several months of/ Short season of structural interest), Self-seeding ++/ +/ ±/ - (High/ Reliably/ Moderate/Low self-seeding ability); Vegetative spread ++/ +/ ±/-/ 0 (Very high/High/ Moderate/ slow/ no vegetative spreading ability); Persistence +/ ±(High/ medium persistence). Soil and other preferences: + (high value preferred), (+) (high value) beneficial, - (low value beneficial); "~" indicates agreement with previous source, with additions.

Table 17 Designed plant communities and plant attributes for study 3: DPC1a

Taxa	%	Hardiness	Garden Habitat	Moisture	Light	*Geselligkeit*	Longevity & persistence	Visual features	Role	Size (cm)	Bloom (mo)	Habit	Spreading strategy	Soil	Other
DPC1b, Oak forest understory. GH: WE/W1(-2)															
Anemone blanda 'Blue shades'	15%	- *4); USDA 6*2) or 5 *3)	W *1); W1-2, RG2, SS2*2); OG1-2, B1-2 *3) WE1-2 *2),3)	Moderate to mod. moist *1); ~ to dry*2),3)	Deep shade *1); Sun to half-shade*2),3)	II-III *2); II; *3)	Perennial [PO]	Spring aspect [PO]; Geo-phyte *2),3)	Scatter/ filler plant	15 *7)	5-6 *7)	Leaf mound habit [PO]	Vegetative spread ± [PO]; Self-seeding ± *2)*3)	Humus+*2),3)	Warm sites +*3)
Aster (Eurybia) divaricatus	7%	A *4); USDA 3 *2) or 5 *3)	WE *1); OG1-2 *3); W1-2, WE1-2 *2),3)	Moderate to dry *1),2),3)	Sun to ~ (to ~) *3)half-shade *1); ~ to shade *2);	II-III; vigorous *2); I-II *3)	True perennial *5); Persistence + *5)	Structure ++ *2), 5); winter seedheads *3)	Lead role	50-70 *7)	9-10 *7)	Upright habit *5); Leaf mound, good groundcover *2)	Vegetative spread ± -*5) or *2); Self-seeding ± /++ *2),5)	(Sand +) *1); Humus+, highly produc-tive+ *3)	Tolerates root compe-tition well *3)
Campanula persicifolia	5%	A *4); USDA 3*2),3)	WE *1); W1, WE1*2); B2, WE1-2 *3); OG1-2,*2),3)	Moderate to mod. dry *1); ~ to dry*2),3)	Sun to half-sun *3) ~to half-shade *2); ~ (to shade) *1);	II; vigorous *2); II; *3)	True perennial *5); Low persis-tence *5)	Structure - *5)	support role	60 *7)	6-8 *7)	Emergent habit *5)	Vegetative spread ± *3),5); Self-seeding -/± *5), *3)	pH>7, *1); sand+ *1),3); Loam + *1),2),3); Well-drained *3)	Warm sites +*3)
Carex caryophyllea ´The Beatles´	5%	A *7); USDA 7*2) or 5 *3)	WE1 *3); ~ OG1 *2)	Dry *2),3)	Sun to half-shade *2); Half-sun to shade *3)	II*2),3)	[Perennial] *3)	Wintergreen *2)	support role	20/30 *7)	5-6 *7)	Low cespitose*2); Wide clump-forming *3); Mat-forming *7)	Short runners *3)		Warm sites +*3)
Geranium nodosum	10%	A *4); USDA 6 *2)	W1-2, WE1-2 *2)	Moderate to dry *2)	Half-shade to shade *2)	II *2)	True perennial *5); Persistence + *5)	Structure - *5); Long-flowering [PO]	support role	40 *7)	6-9 *7)	Leaf mound habit *5)	Vegetative spread ± *5); Self-seeding ± /++ *2),3),5)		
Lamium galeobdolon 'Herrmann's Pride'	20%	A *4); USDA 5*2) or 4/6 *3)	W *1); W1-2, WE1-2*2),3)	Moderate to mod. moist *1); ~ to dry*2),3)	half-shade-shade *1),3); sun to half-shade *2)	V; *1); III-IV; *2); I-II;*3)	Persistent *2); Long-lived *3)	Variegated leaves *2);	Ground cover	25 *7)	5-6 *7)	Fast-growing carpet *2)	Long ramets *2) Aggressive *1); Cultivar is less ag-gressive *2	Nutrient + *1),2); pH<7+, Loam + *2);	Info from *3) on 'Flo-rentinum' and 'Silber-teppich'.
Lamium orvala	6%	A *4); USDA 6 *3)	WE1-2, W1-2 *3)	Moderate to dry *3)	Half-shade to shade *3)	I-II *3)	Long-lived *3)	Leafy *3)	Lead role	50 *7)	5-6 *7)	Clump-forming habit *3)	Self-seeding ± *3)		
Luzula nivea	5%	A *4); USDA 6 *2) or 5 *3)	W *1); W1-2 *2); W2 *3) WE1-2*2),3)	Moderate to mod. moist *1); ~ to dry*2),3)	half-shade to shade *1),2),3)	II *1),2); II-III *3)	True perennial *5); Persistence + *5)	Structure - *5); Winter-green *3)	support role	20/40 *7)	6-7 *7)	Mat-forming *5); Clump-forming *2); Loose clump-forming *3)	Vegetative spread ± *5); Self-seed-ing – *5) or ± *2),3)	Loam + *1),2),3); pH 7+, humus+, sand + *2); pH <7+ *3)	Tolerates root compe-tition well *3)
Tellima grandiflora	7%	USDA 6*2),3)	W1-3, WE1-3 *2); W2, WE2 *3)	Dry to moist *2); Moderate *3)	Half-shade to shade *2),3)	II-III *2),3)	True perennial *5); Persistence + *5); Robust*2),3)	Structure - *5); Winter-green *2)	support role	40 *8)	5-6 *8)	Leaf mound habit*2),5)	Vegetative spread - *5); Self-seeding ±/++ *3),5)		Tolerant *3)
Waldsteinia ternata	20%	A *4); USDA 3*2),3)	W2, WE1-2 *2),3);	Moderate to dry *2),3)	Half-shade to shade *2),3)	III-V *2),3)	True perennial [PO]; Persistence + [PO]; Vigorous *3)	Winter-green*2),3)	Ground cover	20 *7)	5-6 *7)	Dense mat-forming habit *3)	Vegetative spread ± *2)	Humus+, well-drained + *2)	

Sources: *1)(Hansen & Stahl 1981), *2)(Foerster-stauden 2012), *3)(Gaissmayer 2020 [DPC2a/DPC2b Gaissmayer 2023]), *4)(Perennagruppen 2021), *5)(Oudolf & Kingsbury 2015), *6)(Bruns 2018/2019 – also the source for Garden Habitat-abbreviations!), *7)(Säve 2022 [DPC2a/DPC2b Säve 2023]), *8)(Stångby 2022), *9)(E-planta 2022), *10)(SLU Artfakta), *11)(Vegtech 2023) [PO] personal observation. Legend: Structure ++/ +/- (Long season/several months of/ Short season of structural interest), Self-seeding ++/ +/ ±/ - (High/ Reliably/ Moderate/Low self-seeding ability); Vegetative spread ++/ +/ ±/-/ 0 (Very high/High/ Moderate/ slow/ no vegetative spreading ability); Persistence +/ ±(High/ medium persistence). Soil and other preferences: + (high value preferred), (+) (high value) beneficial, - (low value beneficial); "~" indicates agreement with previous source, with additions.

Table 18 Designed plant communities and plant attributes for study 3: DPC1b

Taxa	%	Hardiness	Garden Habitat	Moisture	Light	*Gesellig-keit*	Longevity & persistence	Visual features	Role	Size (cm)	Bloom (mo)	Habit	Spreading strategy	Soil	Other
DPC1c, Spruce forest understory. GH:W(/WE)1-2)															
Aruncus 'Fairy Hair' (Hybrid! Only information from *7) is specific to this cvr)	8%	A *4); USDA 3/6 *2) or 3/4*3)	W *1); W2, WE2, RG2 *2),3);OG2 *3)	Moderate *3) ~ to mod. moist *1); ~ to temp. dry *2);	half-shade to shade *1); Sun to shade*2),3);	I (A. dioicus), II (A. aethusifolius) *2)	Long-lived [A. dioicus]*2),5); Persistence + *5)	Structural interest ++ *5)	Lead role	50 *7)	6-7 *7)	Stem mound habit *5)	Vegetative spread ± *2); Vegetative spread 0 *5); Self-seeding ± *5) ; Self-seeding ±/+ *2)		Prefers cool sites with high air moisture *1) ; dioecious?
Asarum europaeum	10%	A *4); USDA 5*2),3)	W *1); W1-2, WE1-2 *2); W2, WE2 *3)	Moderate *3) ~ to mod. moist *1); ~ to dry *2);	Deep shade *1); Half-shade to full shade *2); Half-sun to shade *3)	III-IV *1),*3); III *2)	True perennial *5); Persistence + *5)	Structural interest + *5); Evergreen *2)	Ground-cover	10 *7)	(5) *7)	Broad basal leaves *5)	Vegetative spread ± *5); Self-seeding - *5); Slow-growing *3)	Loam + *1); Humus+, pH>7+ *3)	Wintergreen; establishment critical *2); Tolerant *3)
Euphorbia amygdaloides 'Purpurea'	7%	B* *4); USDA 7*2),3)	OG2 *2);, W1-2 *3) WE1-2 *2),3)	Moderate to dry*2),3)	Sun to half-shade *2); Half-sun to ~ *3)	I*2),3);	<10 years *5); Persistence + *5); Robust *2)	Structural interest + *5); Wintergreen *3);	support role	60 *7)	6-8 *7)	Upright *5)	Vegetative spread - *5); Self-seeding ± *5)		Prefers sheltered sites with no winter sun *3)
Fragaria vesca 'Rödluvan'	15%	A *4); USDA 5*2),3)	WE *1); OG2, *3); WE2, W2 *2),3)	Moderate*2),3)	Sun to half-sun *1); ~ to half-shade *2),3)	III-IV *2),3)	Perennial [PO]; Persistence ± [PO]	Structural interest - [PO];	Ground-cover	15 *7)	5-6 *7)	Loose mat-forming [PO]	Vegetative spread ++ *3),9);	Humus+, loam+, sand+, Nutrient + *3)	
Geranium macrorrhizum 'Bevan's variety'	15%	A *4); USDA 4*2),3)	WE *1); WE1-2, OG1-2, SS1-2 *2); WE1, OG1, SS1 *3)	Moderate to dry *2); Dry *3)	Sun to half-shade*2),3)	V; Vigorous *1); III-IV *2); II-IV*3)	Perennial [PO]; Persistence ± [PO]	Autumn coloring in leaves *2),3)	Ground-cover	40 *7)	6-7 *7)	Dense mat-forming 2),3)	Vegetative spread ± *2); or + *3); Self-seeding - [PO]	Compacted soils -, humus+ *2); Drainage +, nutrient - *3)	Warm sites +*3); The cultivars differ in vigor *3)
Geranium phaeum 'Album'	10%	A *4); USDA 5*2),3)	WE *1); OG2-3, W2 *2); OG2 *3) WE2 *2),3)	Moderate *1),2),3)	Sun to half-shade *2); Half-sun to half-shade *3) ~ to shade *1);	II-III *2),3); Good competitor *3)	True perennial *5); Persistence + *5)	Structural interest - *5)	support role	60 *7)	6-7 *7)	Leaf mound*5); Phalanx, slow *2)	Vegetative spread ± *5); Self-seeding ±/++ *5); or ++ *3)	nutrient + *1),3); Deep soils+, loam+ *3)	Tolerates occasional drought *2); Robust cultivar *3)
Hesperis matronalis	7%	B* *4); USDA 3*2),3)	WE *1); WE1-2, OG1-2 *2); WE2, OG2 *3)	Moderate *3) ~ to dry *2);	Half-sun to half-shade *1); Sun to half-shade *2),3)	II*2),3)	Biennial / <5 years *2),3)	Structural interest - *5);	Scatter/ filler	70 *7)	5-6 *7) 5-7 *3)	Upright habit *2)	Self-seeding ± *2); or ++ *3); Vegetative spread 0 [PO]	pH >7+ *2); Well-drained +, humus+. Nutrient+ *3)	
Lamium Maculatum 'Beacon silver'	10%	A *4); USDA 4*2),3)	W *1); WE2, W2 *2); W1-2, WE1-2 *3)	Moderate *1),2); ~ to dry *3)	Half-shade *2) ~ to shade *1),3);	II *1); II-III *2),3)	True perennial *5); Persistence ± *5); The pure species is less persistent *2)	Structural interest - *5)	Ground-cover	15 *7)	5-6 *7)	Branching procumbent *5); Fast phalanx *2)	Vegetative spread - *5); Self-seeding - *5)	Nutrient + *1),2); Loam + *2)	
Luzula pilosa 'Igel'	8%	A *4); USDA 6 *2) or 5 *3)	W *1); W1-2, *2); W2, *3) WE1-2*2),3)	Moderate to mod. moist *1); ~ to dry*2),3)	half-shade-shade *1),2),3)	II-III*2),3)	True perennial *5); Persistence + *5)	Structural interest - *5); Wintergreen *3)	Ground-cover	15/25 *7)	5-6 *7)	Mat-forming habit *5); Tussock or mat *2)	Vegetative spread ± *5); Self-seeding - *5)	pH <7> *1); pH<7 *3); Humus+ *1),3); Loam+ *3)	Tolerant *1); Tolerates root competition well *3)
Waldsteinia geoides	10%	- *4); USDA 3 *2)	W *1); W1-2, WE1-2 *2); W2, WE2 *3)	Moderate to dry *1),2); ~ (to dry) *3)	Half-shade *3) ~ to shade *1),2);	II-V *1); II *2); II-IV *3)	Reliable *3); Perennial [PO]	Evergreen *6)	Ground-cover	20-30 *3)	5-6 *7) [*G.ternata*]	Clump *1),2),3)	Vegetative spread - *2)	sand +, Loam +*1); drainage +, humus +, Nutrient + *2)	Warm sites +*2); Tolerant *3); Tolerates root competition well *3)

Sources: *1)(Hansen & Stahl 1981), *2)(Foerster-stauden 2012), *3)(Gaissmayer 2020 [DPC2a/DPC2b Gaissmayer 2023]), *4)(Perennagruppen 2021), *5)(Oudolf & Kingsbury 2015), *6) *6)(Bruns 2018/2019 – also the source for Garden Habitat- abbreviations!), *7)(Säve 2022 [DPC2a/DPC2b Säve 2023]), *8)(Stångby 2022), *9)(E-planta 2022), *10)(SLU Artfakta), *11)(Vegtech 2023) [PO] personal observation. Legend: Structure ++/ +/- (Long season/several months of/ Short season of structural interest), Self-seeding ++/ +/ ±/ - (High/ Reliably/ Moderate/Low self-seeding ability); Vegetative spread ++/ +/ ±/-/ 0 (Very high/High/ Moderate/ slow/ no vegetative spreading ability); Persistence +/ ±(High/ medium persistence). Soil and other preferences: + (high value preferred), (+) (high value) beneficial, - (low value beneficial); "~" indicates agreement with previous source, with additions.

Table 19 Designed plant communities and plant attributes for study 3: DPC1c

Taxa	%	Hardiness	Warden habitat	Moisture	Light	*Geselligkeit*	Longevity & persistence	Visual features	Role	Size (cm)	Bloom (mo)	Habit	Spreading strategy	Soil	Other
DPC2a:Shaded North-facing rock cliff. GH: WE1-2/ ST1-2															
Anemone tomentosa 'Robustissima'	15%	A* *4); USDA 3*2),3)	WE1-2, OG1-2 *2),3); B1-2 *3)	Moderate to dry*2),3); Drought-tolerant *3); ~ cultivar *2)	Sun to half-shade *2),3)	I *2); I-II *3)	Long-lived *5); Persistence + *5); Vigorous *2)	Structural interest + *5)	Lead role	60/90 *7)	8-10 *7)	Emergent *5)	Vegetative spread ± *5); Self-seeding - *5)		Warm sites +*2); Slow to establish *5)
Eurybia herveyi 'Twilight'	20%	A *4); USDA 6*2),3)	WE1-2, OG1-2 *2),3)	Moderate to dry*2),3)	Sun to half-shade *2),3); Shade-tolerant *3); half-shade *3)	II *2); II-III *3)	True perennial *5); Persistence + *5); Extremely robust *2); Healthy culti-var *3)	Structural in-terest + *5)	Lead role	60 *7)	7-9 *7)	Upright, stem mound *5)	Vegetative spread ±/+ *5); Self-seeding - *5); Vegetative spread - *2); or±*3)	Undemanding *3); Free-draining soils + *3); Nutri-ent-rich + *3)	Insect-friendly *3); Low-maintenance *3)
Bergenia cordifolia 'Möja'	12%	A *4); USDA 6 *2) or 4 *3)	WE1-2, B1-2 *2); WE2 *3); OG2, RG2 *2),3)	Moderate to dry*2),3); Drought-toler-ant *2),3)	Sun to half-shade*2),3); Shade-tolerant *2)	II-III*2) ; I-II*3)	True perennial *5); Persistence + *5)	Structural in-terest + *5)	Ground-cover	35 *7)	5-6 *7)	Broad basal leaves *5)	Vegetative spread ± *5); Self-seed-ing - *5)		
Buglossoides purpurocaerulea	10%	[Unclassified] *4); A *7); USDA 6*2),3)	W1*3);OG1, *2); WE1, RG1, SS1 *2),3)	Dry*2),3); Drought-toler-ant *2),3)	Sun to half-shade*2),3); Shade-tolerant *2)	III *2); III-IV *3)			Ground-cover	50 *7)	5-6 *7)			Tolerates calcareous soils *3)	Tolerates root competition *3)
Carex oshimensis 'Evergold'	6%	A *7); USDA 6*2),3)	W1-2, WE1-2 *2); WE1-2 *3);	Moderate to dry*2),3)	Half-shade*2); ~ Half-shade to shade *3)	II *2),3)			Ground-cover	30 *7)	6-7 *7)				Prefers cool, sheltered sites *3)
Carex umbrosa	6%	[Unclassified] *4); A *7); USDA 5 *2) or 4 *3)	W2, WE1-2*2),3)	Moderate to dry*2),3); Very drought-tolerant *3)	Half-shade to shade *2),3)	II-III *2),3)			Ground-cover	10/20 *7)	4-5 *7)				Very tolerant of root competi-tion*2),3)
Epilobium angustifolium 'Album'	7%	A *4); USDA 3 *3)	OG1-2, WE1-2 *3),6);	Moderate to dry*2),3)	Sun to half-shade *3),6)	II *3)			Lead role	150 *7)	7-9 *7)				
Helleborus foetidus 'Wester Flisk'	6%	B* *4); USDA 6*2),3); establishment improves*2)	WE1-2, W1-2, OG1-2 *2),3)	Moderate to dry*2),3); Sen-sitive to wet soil *3); Prefers dry sites *2)	Half-shade to shade *2); Half-sun to half-shade *3)	I *2); I-II *3)	True perennial *5); Persistence + *5)	Structural in-terest + *5)	Scatter/ filler	50 *7)	12-4 *7)	Broad basal leaves *5)	Vegetative spread - *5); Self-seeding ±/++ *5)	poor soils + *3); Calcare-ous + *3); Tolerates stony soils *3)	Warm sites +*2); Single-stemmed -> shorter-lived *5); Dislikes change *3)
Lamium galeobdolon 'Florentinum'	8%	A *4); USDA 4 *3)	WE1-2, W1-2 *2),3)	Moderate to dry *3)	Half-shade to shade *3),6); Sun to half-shade *7)	IV *3); Aggres-sive*6)	Long-lived *3);		Ground-cover	20-30 *3)	5-6 *3)		Vegetative spread + *3)	Undemand-ing *3)	
Polystichum aculeatum	10%	A *4); USDA 5*2),3)	W2, WE2, RG2 *2),3);	Moderate*2),3) ; Drought tol-erance im-proves with es-tablishment *3)	Half-shade to shade *2); Half-sun to half-shade *3)	I-II *2),3)			Support role	60 *7)	- *7)			Free-draining + *3); humus + *3)	

Sources: *1)(Hansen & Stahl 1981), *2)(Foerster-stauden 2012), *3)(Gaissmayer 2020 [DPC2a/DPC2b Gaissmayer 2023]), *4)(Perennagruppen 2021), *5)(Oudolf & Kingsbury 2015), *6)(Bruns 2018/2019 – also the source for Garden Habitat-abbreviations!), *7)(Säve 2022 [DPC2a/DPC2b Säve 2023]), *8)(Stångby 2022), *9)(E-planta 2022), *10)(SLU Artfakta), *11)(Vegtech 2023) [PO] personal observation. Legend: Structure ++/ +/- (Long season/several months of/ Short season of structural interest), Self-seeding ++/ +/ ±/ - (High/ Reliably/ Moderate/Low self-seeding ability); Vegetative spread ++/ +/ ±/-/ 0 (Very high/High/ Moderate/ slow/ no vegetative spreading ability); Persistence +/ ±(High/ medium persistence). Soil and other preferences: + (high value preferred), (+) (high value) beneficial, - (low value beneficial); "~" indicates agreement with previous source, with additions.

Table 20 Designed plant communities and plant attributes for study 3: DPC2a

Taxa	%	Hardiness	Garden Habitat	Moisture	Light	*Geselligkeit*	Longevity & persistence	Visual features	Role	Size (cm)	Bloom (mo)	Habit	Spreading strategy	Soil	Other
DPC2b: Sunny south-facing rock cliff GH: WE1-2/ ST1-2															
Anaphalis triplinervis	16%	A* *7); USDA 5 *2) or 5 *3)	OG1-2, RG1-2, SS1-2 *2),3)	Dry to moderate *2),3); Not for too dry sites *3)	Full sun *3) ~ to half-shade *2);	I *2); I-II *3)		Seedheads persist after bloom*2)		40 *7)	7-8 *7)	Clump-forming *2)		Nutrient-rich - *3)	
Calamagrostis brachytricha	7%	A *4); USDA 5*2),3)	OG1-2, WE1-2, SS1-2 *2); B2, OG2, WE2 *3)	Dry to moderate *2); Moderate *3);	Full sun*2),3)	I *2),3)	True perennial *5); Persistence + *5)	Structure + *5)		50/80 *7)	9-10 *7)	Cespitose *5)	Vegetative spread 0 *5); Self-seeding ±/++ *5)	Undemanding, Free-draining + *2); Light soils + *3)	Tolerates summer drought *3)
Calamagrostis x acutiflora 'Cheju-Do'	7%	A *4); USDA 3 *2) or 4 *3)	WE1-2 *2); OG1-2 *2),3)	Dry to moderate*2),3)	Full sun *2),3)	I *2),3)	True perennial *5); Persistence + *5)	Structure ++ *5)		40/70 *7)	7-8 *7)	Clump-forming *5)	Vegetative spread ± *5); Self-seeding - *5)		
Centaurea dealbata	10%	A *4); USDA 3*2),3)	OG1, WE1 *2); OG1-2, WE1-2 *3)	Dry *2); ~ to moderate *3); Prefers dry sites *2)	Full sun *2),3)	I *2),3)				50-80 *3)	6-7 *3)	Leaf mound *2)		Free-draining + *2),3); Light soils + *3); humus + *3)	Warm sites +*2),3)
Geranium sanguineum 'Max Frei'	12%	A* *4); USDA 5*2),3)	SS1*2); RG1*3); WE1, OG1, H1*2),3)	Dry*2),3); Very drought-tolerant *3)	Full sun *3); ~to half shade *2);	II-III *2),3); Vigorous *3)	True perennial *5); Persistence + *5)	Structure - *5)		20 *7)	6-7 *7)	Leaf mound *5)	Vegetative spread - *5); Self-seeding ± *5)	Undemanding *2); Free-draining + *3)	Warm sites +*2); Fairly safe from pests *3)
Hieracium aurantiacum	7%	[Unclassified] *4); Native *10); USDA 6 *2)	OG1-3, WE 1-3, H1-3 *2); WE1-2, OG1-2, SS1-2 *6)	Dry to moderate *6); ~ to moist *2); Very drought-tolerant *2)	Full sun *2); Sun to half-sun *6)	III *2); Agressive *2)				20-60 *11)	6-7 *11)	Rosette-forming *2)	Vegetative spread ± *2); Self-seeding ++ *2)		
Euphorbia polychroma	11%	[Unclassified] *4); A* *7); USDA 5*2),3)	OG1-2 *3) M1, H1, RG1, OG1 *2),3);	Dry *2); ~ to moderate *3);	Full sun *2),3)	I *2); I-II *3); Vigorous *3)	Robust *3)			30 *7)	7-9 *7)	Compact-shrubby *2)		Free-draining + *2),3); Light soils + *3); Calcareous + *3)	Warm sites +*2)
Phlomis tuberosa	12%	A *4); USDA 6 *2) or 5 *3);	H1, *2); OG1, WE1 *2),3)	Dry*2),3); Extremely drought-tolerant *2);	Full sun *2),3);	II *3)	True perennial *5); Persistence + *5)	Structure ++ *5); Seedheads *2)		100 *7)	7-8 *7)	Emergent *5)	Vegetative spread - *5); Self-seeding - /++ *5)	Free-draining + *3); Tolerates poor soils *2)	Extremely hardy *2)
Phuopsis stylosa	11%	[Unclassified] *4); A* *7); USDA 7 *2) or 5 *3)	OG1-2, SS1-2, B1-2 *2); OG2 *3); WE1-2 *2),3)	Dry to moderate*2),3)	Full sun *2); ~ to half-shade *3);	II-IV *2),3); Vigorous *3)				20 *7)	6-8 *7)		Vegetative spread ± *2); Mat-forming *3)	Free-draining + *2),3); Light soils + *3)	Adaptable *3) Doesn't tolerate deep shade *3)
Veronica austriaca 'Knallblau'	7%	A *4); USDA 6 *2) or 4 *3)	OG1, WE1, H1 *2); OG1-2, WE1-2, H1-2 *3)	Dry *2); ~to moderate *3)	Full sun *2),3)	II *2),3)	True perennial *5); Persistence + *5)	Structure - *5)		30 *7)	6-7 *7)	Upright *5)	Vegetative spread - *5); Self-seeding - *5)	Free-draining + *3); Calcareous +*2),3); loam +*2),3); Macadam + *2)	Warm sites +*2)

Sources: *1)(Hansen & Stahl 1981), *2)(Foerster-stauden 2012), *3)(Gaissmayer 2020 [DPC2a/DPC2b Gaissmayer 2023]), *4)(Perennagruppen 2021), *5)(Oudolf & Kingsbury 2015), *6)(Bruns 2018/2019 – also the source for Garden Habitat-abbreviations!), *7)(Säve 2022 [DPC2a/DPC2b Säve 2023]), *8)(Stångby 2022), *9)(E-planta 2022), *10)(SLU Artfakta), *11)(Vegtech 2023) [PO] personal observation. Legend: Structure ++/ +/- (Long season/several months of/ Short season of structural interest), Self-seeding ++/ +/ ±/ - (High/ Reliably/ Moderate/Low self-seeding ability); Vegetative spread ++/ +/ ±/-/ 0 (Very high/High/ Moderate/ slow/ no vegetative spreading ability); Persistence +/ ±(High/ medium persistence). Soil and other preferences: + (high value preferred), (+) (high value) beneficial, - (low value beneficial); "~" indicates agreement with previous source, with additions.

Table 21 Designed plant communities and plant attributes for study 3: DPC2b

Preliminary results

This thesis presents the preliminary results for the main question of the study, which is the differences in establishment success between the four planting design strategies at the different sites and sub-sites. A simple analysis of plant survival and plant growth in terms of vegetation coverage and height development is presented here for each strategy and site. Future analyses will include data on plant health, reproduction, flowering, intra-species dynamics, vegetation maintenance, dynamic substrate attributes and weather during the study period. Additionally, a description of the planting design process within the DPC paradigm as it relates to the quality and availability of site analysis methods and plant data as well as the theoretical correspondences between site and plant attributes is planned to be discussed in a separate paper.

	Avg. survival (2023)	Avg coverage (2023)	Avg height dev. (2023)	Avg survival (2024)	Avg coverage (2024)	Avg height dev. (2024)	TOTAL (2023)	TOTAL (2024)	(pcs 2023)	(pcs 2024)
1) DPC (all)	73%	67%	44%	73%	107%	49%	0,61	0,77	7	12
1) DPC1a	86%	93%	47%	89%	104%	67%	0,75	0,87	2	2
1) DPC1b	68%	44%	38%	62%	75%	52%	0,50	0,63	3	4
1) DPC1c	67%	76%	49%	63%	138%	44%	0,64	0,82	2	2
1) DPC2a	N/A	N/A	N/A	88%	123%	25%	-	0,78	0	2
1) DPC2b	N/A	N/A	N/A	76%	126%	53%	-	0,85	0	2
2)Meadow	91%	66%	81%	82%	106%	86%	0,79	0,91	3	5
3) Top-7	92%	151%	59%	88%	148%	62%	1,01	0,99	3	5
4) Anja	94%	44%	66%	95%	77%	70%	0,68	0,80	3	5

Table 22 Survival and growth of plantings belonging to the four plant selection strategies: 1) Designed plant communities 2) Polyculture of native meadow plants 3) 7 most popular herbaceous perennials in Swe-den 4) monoculture of shrubs (Lonicera caerulea 'Anja')

Table 22 shows the survival and growth of plantings for each of the strategies, as well as the survival and growth in each of the 5 DPC-mixes separately. Survival is measured against initial number of plants at planting.

Coverage is measured as the total coverage of plants in a planting against the area of the plantings, and thus can be over 100% as it includes areas where plants layer on top of each other. Height development compares the median height of the planted species (median calculated from average heights of each species) against the expected median height of the same species combination. The totals are calculated from an unweighted average of the three factors and expressed as decimal numbers. Last columns present the number of each mix. The data was collected during week 35 in 2023 (30^{th} of August – 2^{nd} of September) and week 35 in 2024 (28^{th}-31^{st} of August).

Using 75% as the cutoff point for acceptable vegetation development by its third year from establishment (Beryani et al. 2021) and 90% as the cutoff point for good development, all case study plantings reached acceptable development during 2024, and can thus be considered to have established during the 2-year warranty period. Out of the 73 plant varieties included in the case studies, the overwhelming majority (56 species) showed acceptable performance (total rating min. 0,75) and 38 showed good performance (total rating min. 0,90), indicating that a broad variety of plants can perform acceptably in URG:s. The Top-7-mix showed good development and DPC1a and the meadow mix attained acceptable development already year 1. Height development is clearly lagging behind in all strategies and mixes, with the exception of the meadow mix that reached acceptable height development both first and second growing season. Another noteworthy result is that plant survival and coverage do not necessary correlate directly with each other, at least not in multi-species mixes. The poor development of the mix DPC1b both years and across metrics shows that using the DPC-framework for planting design does not automatically yield good performance. The rest of the DPC-mixes have shown good development in terms of coverage. Future analyses will go more into detail on other performance metrics and possible reasons for the measured results.

	Avg. survival (2023)	Avg coverage (2023)	Avg height dev. (2023)	Avg survival (2024)	Avg coverage (2024)	Avg height dev. (2024)	TOTAL score (2024)	TOTAL score (2024)	(pcs 2023)	(pcs 2024)
ULT	86%	111%	65%	83%	132%	67%	0,87	0,94	6	8
TSA-N	84%	46%	50%	78%	81%	65%	0,60	0,75	4	4
TSA-S	83%	75%	46%	83%	96%	69%	0,79	0,90	6	6
HSV-E	N/A	N/A	N/A	81%	103%	53%	-	0,98	-	4
HSV-W	N/A	N/A	N/A	83%	113%	53%	-	0,92	-	5

Table 23 Plant survival, vegetation coverage and height development in Ultuna (ULT) Torgny Segerstedts Allé North and South (TSA-N/S) and Hägerstensvägen (HSV-E/W)

A comparison of the five subsites shows that on average each of them provided necessary site conditions for acceptable vegetation development and thus vegetation establishment (Table 23). Torgny Segerstedts Allé North sticks out as the worst of the class and is the only site where good coverage is not reached. Another noteworthy result is that plots in Ultuna and Hägerstensvägen have on average been able to develop a more than complete coverage already during the first year from planting. The reasons for this will be further investigated in the future, but one possible contributing factor could be that the substrates on these three sub-sites is more productive than at Torgny Segerstedts Allé.

Adjacent to the interviews, vegetation inventories were conducted on 40 urban rain gardens of variable ages at 24 different sites. Of these, around 25 URG:s had achieved a target species coverage rate of 75% or above, and 3 more URG:s fulfilled an acceptable coverage rate if non-target species were included (unpublished data). The coverage rates for these inventories were assessed by eye and are not as accurate as for the case studies. With this caveat in mind, it is interesting that of the 21 of the 27 case study test plots achieved a cover of 75% or more by their second year, giving a single-factor success rate at 78%, compared with the inventories' overall success rate at 63%.

Why does this study and its results matter?

Literature within the DPC-framework sometimes suggests that its planting design tools can be used to improve vegetation performance even in more extreme urban site conditions (Kircher et al. 2012; Rainer & West 2015; Heinrich & Messer 2017), which these supra-urban URG:s with coarse substrates represent. However, the results show that herbaceous plantings composed within the DPC-framework are not necessarily superior to plantings composed through other planting design strategies in the short term, although they do establish and perform successfully on average during the first 2 years from construction. The hypothesis of the study was thus corroborated. However, as the DPC in the study did not generally perform better than the other plantings, it calls to question how successful DPC-design tools are for improving design out comes. This is especially with regards to the Garden Habitat-system, which was the most consistently applied design tool in this study. The reasons behind the results were probably manifold, and one of the possible reasons for especially the poor performance of DPC1b was due to a misrepresentative site condition analysis for TSA and subsequent mismatch between plants and site conditions.

The design phase of the study also further emphasizes the impossibility of following the DPC-framework for planting design as it is intended. “Proper” plant selection and composition for DPC would require access to large amounts of quality plant information that is not available at the moment, as well as expertise in picking the sources and traits or ecological functions that can be assumed to be of highest relevance for site fitness, community assembly, and community dynamics (Hunter 2011; Van Mechelen et al. 2015; Tabassum et al. 2020, 2021; Watkins et al. 2021). Planting design literature, including the DPC-framework also provides little guidance on urban site condition analysis, which further showed the impossibility of making optimal plant choices for urban NbS. Further analyses will provide detailed information on the design process, realized site conditions, maintenance, and vegetation development.

Wide tolerance to site conditions seems to have aided the establishment of ‘Anja’, the top-7-mix and the meadow mix. Of all the tested strategies, the meadow mix shows by far the best dispersal ability on all sites (largest number of successfully self-seeding species) (See Niemelä 1999). The main drawback of the native meadow mix was its untidy appearance in the late summer and autumn, especially during year 2. In the supra-urban sites where the TSA and HSV test beds lie they will probably also not be mown, which risks quicker decrease in forb density. But if they were to be mown in mid-August, their spatial functions would be missed for more than two months. The 15 tried species had generally good development in variable urban conditions, but how much bigger might the useable species pool be?

Additionally, native species may in some cases be more vulnerable to native, co-evolved plant illnesses and pests than exotic plants.

Best practice for the design and management of urban vegetation and urban NbS cannot be developed without functional methods of evaluating and monitoring. The challenge is less about technology as such, and more about what is practical (Kingsbury 2009:3–4). The case studies, inventories and interviews show how valuable information can be collected "manually", by visiting sites, taking observations, and discussing with professionals. These laborious and detailed research practices should be complemented with large-scale and cost-effective automated monitoring solutions that aid in data collection and preliminary analysis. The case studies used wireless soil sensors connected to cloud services to collect hourly data on soil temperature, moisture and electrical conductivity. The monitoring service then arranged the data into easily legible graphs. These helped us understand the differences between the different substrates, but also to see how different rainfall patterns affected soil moisture. However, the sensors were a very expensive investment, and installing the sensor base station into densely built urban areas required the use of an aerial access platform to find a placement that would be safe from vandalism and to cover as large an area as possible. Thus, for continuous monitoring of urban areas even more accessible methods would be preferred.

9. Discussion: The five paradoxes of DPC, and how they can inform the development of vegetated urban NbS for stormwater management

The DPC paradoxes highlight how contradicting thoughts on nature, vegetation, and humans and different professional roles make it difficult to take informed design or management decisions for NbS. Without a clear understanding of our own understandings and biases on these subjects, evaluating design outcomes and interpreting possible causes and effects becomes difficult. Each paradox is described as it appears in DPC-literature, and an explanation of how it pertains to the design and management of vegetated NbS is given. Then, the reason and reasoning behind the opposing views expressed by the paradox are elaborated on. Then, the relation of the studies in this licentiate thesis to the paradoxes is reflected on, including the implications of the results of the study and the paradox for the design and management of vegetated NbS.

9.1 The DPC-designer is an artist that bases their decisions on scientific knowledge

The DPC-framework often emphasizes the value of cultural ESS, and aims to ignite people's love for plants and wider nature through impactful design choices (Rainer & West 2015; Hansen & Stahl 2016; Hitchmough 2017b; Dunnett 2019). DPC has also gained wider popularity due to the artistic skill displayed in many DPC projects (Kingsbury & Oudolf 2015; Rainer & West 2015). At the same time, the DPC-framework often refers to its scientific background and ecological literacy as further arguments for the framework's merits over other planting design approaches (Hitchmough & Dunnett 2014; Duthweiler 2016). Further, landscape design, and especially planting design, are often seen as pursuits that combine ecology with aesthetic concerns, and form with function (Luz 2001; Oudolf & Kingsbury 2001:12, 2005:16–18; Köppler & Hitchmough 2015; Hansen & Stahl 2016; Körner et al. 2016; Robinson 2016:26; Lenzholzer et al. 2017).

Thus, the DPC practitioner often tries to embody three professions at once: designer, artist, and scientist. Each of these professions have different objectives: Designers solve specific practical problems to create experiences, products or services, artists explore form, meaning and expression, and researchers make systematic inquiries into reality to gain new knowledge (Cross 2001; Bonsiepe 2007; Creswell (2009) in Lenzholzer et al. 2013). Another division could be made with regards to the validity of intuition as a basis for decision in each of the fields. Where an artist is allowed to base many of their professional decisions on intuition and tacit knowledge, a scientist should be able to motivate their decisions and interpretations based on sound methodologies, hard evidence and precedents (Gaver 2014). Designers work between these positions, using the best knowledge available to them to select among possible solutions according to their experience, vision and preference (Oudolf & Kingsbury 2001:66,69; Durmus Ozturk 2020; But see also Gaver 2014).

While DPC is a design framework, not a scientific practice, the DPC-framework has been developed with scientific inspirations and ambitions (Woudstra 2014). The tradition of systematic inquiries of and for DPC:s can be traced back to the trial gardens in Britain and Germany in the early 1900's (Duthweiler 2016:V–VII). Germany has also a strong tradition of national, non-peer reviewed DPC research, including the continuing trials of perennials and development of standardized perennial planting mixes, but also doctoral theses and small-scale experiments (Grosse-Bächle 2005:17–18; Schmidt 2006; Eppel-Hotz 2009; Hansen & Stahl 2016; Heinrich & Messer 2017:16; Kircher et al. 2017; Schönfeld 2020). Unfortunately, some of the data and results haven't been made public, including much of Hansen and his colleagues' experiments in Weihenstephan (Kühn 2011:105). From the 1990's onward much of the development of DPC has been done by people in the academia, or by DPC practitioners who have pursued academic research as a part of their career (e.g. Dunnett (2008b), Hitchmough (1999) and Kingsbury (2009) at Sheffield, Kircher (2012) at HS Anhalt, Kühn (2024) at TU Berlin, Gustavsson (1986) and Ignatieva (2011) at SLU). Thus, it would be reasonable to expect that the DPC-framework would be promoting the development of evidence-based planting design, which is essential for improving the reliable development and performance of biotic components in NbS (Brown & Corry 2011; European Commission 2015; Frantzeskaki et al. 2019).

However, designers both within and outside of the DPC-framework have raised concerns of the “scientification” or “technocratism” of planting design at the cost of both artistic integrity and cultural values of designed landscapes (Forbes et al., 1997, s.100; Clark (1959) via Ruff (1985) in Forbes et al. 1997:101; Dunnett 2019:63–64; Richardson 2021:84–90). For example, the Garden Habitat-system has been critiqued as too limiting for creative planting design, (Oudolf & Kingsbury 2001:73), while Hansen and Stahl (2016) themselves argue that artistically skilled designers can benefit from the restrictiveness of the GH-system as a tool for creating harmonious and aesthetically pleasing vegetation (Hansen & Stahl 2016:13,49,54). Other designers have instead critiqued giving priority to cultural values and aesthetic ambitions in the design and management of vegetation, and promoted wilder and more spontaneous vegetation instead (Le Roy (1983) in Kühn 2006; Kowarik 2021). Further, some DPC designers have posited that since anthropogenic green has a history of ideological and cultural drivers, because urban vegetation is intentionally created ("artificial"), and because urban vegetation is placed in a “cultural habitat” as well as in an ecological context, there should be space to explore both the more and less ecological, more and less artistic forms of plantings (Walser in Plenk (1998) via Kingsbury 2014:83–84). There is thus no consensus on the relationship between artistic and ecological concerns within the DPC-framework, and how these aspects are prioritized varies between DPC-practitioners.

Both artistic and ecological knowledge are necessary in the process of abstraction and stylization from reference landscapes to plantings, irrespective of whether the planting is meant to be mostly ornamental or to serve as restored habitat (Kingsbury 2014:84; Morrison 2014:121–122; Robinson 2016:28,32,34). For example, choosing relevant “signature plants” to evoke certain ecosystems requires intimate knowledge of these ecosystems at different times of the year (Hunter 2011; Morrison 2014; Dunnett 2019). Interpretation of nature, however, is not simple for the ecologist or the designer (Forbes et al. 1997:110). Studies of vegetation dynamics, for example, are hindered by inconsistencies in terminology and disregard to questions of scale (Schulze et al. 2019:621). There is also evidence that even the extremely formalistic baroque garden of late 1600’s Versailles was, in part, an attempt to showcase the most beautiful things nature had to offer, at a reasonable price (Norton (1980) in Woudstra 2014:23). The modern public would be hard pressed to understand The

Versailles landscape architect André Le Nôtre's and his contemporary British Landscape Garden movement counterparts' opposing approaches to superficially similar goals is a great example of how cultural and personal beliefs as well as context influence planting design based on interpretations of nature and natural landscapes.

Another observed issue is that scientific ecological knowledge is often difficult to apply to planting design, especially by design professionals without an extensive background in research or ecology due to the specific terminology used (Hitchmough 2017a; Dunnett 2019:100), but also because research can and often does produce seemingly contradictory results. Ecological research may also prioritize abstract, general results over specific ones, which can make the results difficult to apply in the site-specific, species-specific context of practical horticulture (Hitchmough 2010; Köppler & Hitchmough 2015). Since design is not science, an application of ecological knowledge that gives "good enough" results might be perfectly adequate (Köppler & Hitchmough 2015). Still, it would be beneficial for the DPC-framework to update its design tools and methodologies based on current research on plant ecology, urban ecology, environmental psychology and environmental engineering to make them more relevant for NbS design, or other evidence-based design beside NbS.

According to Brown and Corry (2011), evidence-based landscape architecture, and by extension planting design, can be practiced in design projects through a process of 1) formulating specific and relevant goals and questions to frame the design tasks, 2) collecting information that is intended to aid in reaching the set goals or in answering the given questions, 3) critically assessing the validity and practical relevance of collected information, and to 4) transforming the information into knowledge that can be applied to questions or to contribute to goals. It is also important to involve planting designers, green area managers and other urban development professions when developing design guidelines from research to avoid applicability issues. Evidence relevant to planting design must thus be communicated in a way that is approachable and applicable for landscape design professionals (Brown & Corry 2011). A key factor in this communication is the development of easily applicable site analysis methods whose results can directly be related to plant selection. While for example Hansen & Stahl (2016), Heinrich & Messer (2017) and Hitchmough (2017b) do provide lists of site conditions to assess, few site condition variables are provided in measurable terms. For example, if plant light requirements could be expressed as hours of direct sun per day, they could be assessed with the help of shadow analyses. Being able to work with site conditions quantitatively might in the future also enable developing a deeper understanding of how multiple and simultaneous or consequent site condition variation influence plant performance. However, that would also require a better understanding of the possible interactions between site variables, as well as a possible lack thereof.

Developing DPC or planting design in general into an evidence-based practice requires further research on urban vegetation in general and ornamental vegetation in particular, both on plant species and -variety levels, but also on a community level. This research could be carried out as a combination of controlled field and laboratory experiments, case studies and case study syntheses on completed planting design projects. Meta-analyses of professionals' and amateurs' empirical studies as well as horticulturally oriented systematic reviews on relevant ecological research could also help to move DPC research forward.

If plant ecological research is to be further utilized as a basis for DPC methodologies, it needs to be contextualized in the larger philosophical debates like the division between holistic and individualistic views of plant communities. Otherwise, there is a risk of biased or incomplete assessments of current state of research and misrepresentation of how widely accepted which scientific theories are. For example, plant sociology in the tradition of Braun-Blanquet and Tüxen has largely been replaced with alternative ways to study and describe plant communities. Grime's plant strategy model as presented in the second edition of his book (2001) is neither the only plant strategy model used in contemporary plant ecology, nor has the development of applications of the theory or complementary theories ended with the publication of the book (e.g. Craine 2007; Maestre et al. 2009; Reich 2014; Pierce et al. 2017; Laughlin 2023). Gray DPC literature tends to present these approaches to plant community ecology as definitive (e.g. Rainer & West 2015; Hansen & Stahl 2016; Heinrich & Messer 2017; Dunnett 2019), which can discourage DPC practitioners from further inquiries into plant ecological theory, which in turn hinders the incorporation of contemporary plant ecological research into the DPC toolbox.

The literature review results (paper 1) show that current evidence base for species-rich urban planting design is insufficient to create vegetated NbS with predictable enough development to guarantee that design objectives are attained in the short and medium terms. From this point of view, objective and methodical plant selection schemes cannot guarantee successful plantings any more than subjective and intuitive design methods of competent designers. This is especially notable in cases where the designer needs to make a judgement based on contradictory information sources. For example, the plant selection scheme used for DPC design for the case studies involved finding information on each plant based on at least three sources, and when contradictions arise, the information that two or more sources reported was accepted as evidence. However, this kind of majority rule does not necessarily give the most truthful result, as the variation in data might be due to different climates, variable number of observations, different original information sources and other factors that are not known for the designer while they work.

The limits of purely methodical plant selection schemes also become apparent when the method results in a larger palette of relevant design choices than what is suitable to use in a specific space. Indeed, where scientific questions seek to find a definitive solution, design is about choosing among several relevant solutions. But how should a designer make their decisions between two or more seemingly equal design choices? Or how should a designer react when objectively and methodologically composed plant lists do not fulfil all project goals? From these standpoints, it seems that a part of the design process is always in a “black box” (Durmus Ozturk 2020) which cannot be completely rationalized. Still, making an effort to document and motivate design choices as far as possible would be greatly beneficial for improving project monitoring and evaluation, and thus for developing planting design and vegetation management methods for future NbS designers (European Commission 2015, 2021; Dumitru et al. 2020; Sowińska-Świerkosz & García 2021).

9.2 Native and exotic urban vegetation both support and threaten biodiversity

As a rule, the DPC-framework emphasizes aesthetic concerns as well as plant interactions with their site, other plants, and other organisms as a basis for plant selection, rather than the geographical origins of plants (Thompson 1997:20; Gerritsen & Oudolf 2000; Oudolf & Gerritsen 2003; Hitchmough

2010; Hansen & Stahl 2016). Combinations of exotic and native species have been a part of the DPC heritage since William Robinson's work with naturalizing exotic plants in different garden settings in the late 1800's,, albeit with variable results (Robinson & Darke 2009; and similar projects undertaken by Hitchmough & de la Fleur 2006; Kühn 2006; Cascorbi 2007; Hitchmough & Wagner 2013; Köppler et al. 2014; Schmithals & Kühn 2014; Hitchmough et al. 2017). In other words, the goal of DPC is often to create novel ecosystems of exotic and/or native plants to increase the ornamental value of native semi-natural vegetation without increasing maintenance costs (Oudolf & Kingsbury 2013:18; Hitchmough & Dunnett 2014:8; Kingsbury 2014:74–79; Van Mechelen et al. 2015; Hansen & Stahl 2016:55). However, the concept of context-sensitive use of native vs. exotic species in planting design has been significant for a long time: In the early 1900's Willy Lange, Jens Jensen, Brenda Colvin all encouraged the use of exotics in urban and garden settings, but excluded them from rural projects like roadsides or nature restoration (Woudstra 2014:48). Similar sentiments of prioritizing the use of exotic and showy plantings in more densely built areas and the use of natives in rural settings are echoed in contemporary DPC literature and research (Hitchmough & Wagner 2013; Oudolf & Kingsbury 2013:41; Hitchmough 2014:133; Hitchmough & Dunnett 2014:10; Kingsbury 2014:61; Morrison 2014:122). Hansen & Stahl (2016:45–49), as another example, give recommendations for when and how natives and exotics could or shouldn't be mixed, although their recommendations are mainly based on the perceived similarities or dissimilarities between different plant groups' maintenance needs.

DPC practitioners sometimes show a certain apprehension towards the use of native plant species and especially towards recreating spontaneously occurring plant assemblages, usually due to concerns for lost aesthetic and cultural values, a lack of public support for vegetation with understated appearances, or distrust in the fitness of native species in urban site conditions exacerbated by climate changes (Oudolf & Kingsbury 2013:41, 73; Hitchmough 2014:134; Hitchmough & Dunnett 2014:10; Kingsbury 2014:63–64; Alizadeh & Hitchmough 2019). Especially the native flora of Northern Europe and the British Isles is seen as too limited in its species diversity, low-profile appearance and short season of interest to provide a sufficient basis for urban vegetation (Oudolf & Kingsbury 2005:42-43,62; Hitchmough 2010; Morrison 2014). Researcher arguments against native-only policies in Northern Europe point out the small species pool, poor fitness, and susceptibility to many known plant diseases and pests pose risks for the resilience and biodiversity of native urban trees in the Nordic countries (Sjöman et al. 2016). Some also argue that native vegetation requires more space to succeed both ecologically and aesthetically and is thus not always appropriate for garden or urban settings (Kühn 2006; Oudolf & Kingsbury 2013:41; Hansen & Stahl 2016:48; Robinson 2016:319). Additionally, the Heemparks of the Netherlands are often cited as an example of how labour-intensive native-only vegetation can be (King (1997) in Kingsbury 2014:72). Still, many DPC practitioners working with large public parks have encouraged the use of native plants to a larger extent than has been the norm (Morrison 2014; Woudstra 2014; Rainer & West 2015), but many also defend a judicious use of exotic plants instead of or as a complement to native plants especially in highly urbanized spaces (Hitchmough 2011; Hansen & Stahl 2016; Sjöman et al. 2016; Dunnett 2019). Arguments for both positions are often motivated by referring to aesthetic considerations, support for pollinators and frugivores, and resilience in a changing climate (Hitchmough 2011; Buckley & Catford 2016; Sjöman et al. 2016; Chitchak et al. 2024; Tartaglia & Aronson 2024).

Figure 24 Visually impressive DPC:s applied to demanding urban streetside conditions in Mannheim. These plantings consist mostly of exotic species, but also includes some natives. Design by Bettina Jaugstetter.

Figure 25 A mixed perennial planting, possibly "*Blütentraum*" in Karlstadt. The planting is partially overrun by native grasses but has retained some of the target species.

Increased awareness of the influence and even harm that invasive alien plant species have caused for native ecosystems and people's property has made many governments reconsider the use of exotic plant species even in urban environments, as they pose a risk of becoming invasive (Kowarik 2011; Vilà et al. 2011; Roy et al. 2024). The use of exotic plants in urban areas is a historically significant phenomenon of human cultures, which has given some exotic plant species prominent status not only due to visual and olfactory pleasure provided by them, but also due to food or raw material provision (Potgieter et al. 2017). Exotic vegetation has also been promoted as a way to improve the climate-adaptedness of urban vegetation and thus NbS (Hitchmough 2011; Sjöman et al. 2016; Alizadeh & Hitchmough 2019). Urban areas show both notable evidence of co-existence between exotic and native flora, but also the negative effect of aggressive exotic plant species on native plant diversity (Vilà et al. 2011; Seitz et al. 2022). While many ornamental herbaceous perennials have shown to be able to reproduce even in Nordic climates and thus risk becoming invasive (Kaukoranta et al. 2019), the proportion of invasive plants out of all introduced plant species overall has been relatively small thus far (Boltovskoy et al. 2018; IUCN 2020b; Roy et al. 2024:XVI; European Alien Species Information Network 2025). This is probably because exotic and native plants are subject to the exact same environmental pressures, especially in demanding urban areas where few species can thrive, let alone dominate (Daehler 2003). Still, depending on the source, native plants are described as the victims of climate change and exotics as the champions of resilient and diverse urban green spaces, or alternately native plants are promoted for their superior fitness and ecological value, whereas exotic plants must be coddled to survive (Snodgrass & Snodgrass 2006; Hitchmough 2011; Hansen & Stahl 2016; Sjöman et al. 2016).Thus, questions of if and how native and exotic plant species should be used is an important question for securing NbS functionality and possible trade-offs of using either category of plants.

The practical issues with using exotic and native plants can be summed up as follows:

1. Invasion risk – exotic plants risk invading native habitats and outcompeting native species, which is a threat to native biodiversity. Invasions of unwanted plants, i.e. native or exotic weeds in urban designed plantings can also decrease their biodiversity and supplant plant species that provide important services locally. In both cases, ESS delivery and biodiversity are threatened, albeit on different scales.

2. Habitat provision – both native and exotic plant species do provide habitat to other organisms in urban contexts (Chitchak et al. 2024; Tartaglia & Aronson 2024), although the habitat value of exotics can be compromised due to their lack of phenological adaptation or other co-evolved structures that are important for local organisms (Buckley & Catford 2016; Abdallah et al. 2021; Jensen et al. 2022; Tartaglia & Aronson 2024). Yet, harsh urban conditions can weaken or even exclude many unfit native plant species, which diminishes the species and structural diversity they might be able to provide in some urban settings. In both cases, the breadth and quality of urban biodiversity support is compromised.
3. Ecosystem service provision – Both native and exotic plant species provide ESS (Potgieter et al. 2017). Current research shows no difference between the regulating ESS delivery capacity of vegetation based on geographical origin, although this is partially due to a lack of available data (Potgieter et al. 2017; Dagenais et al. 2018). In terms of provisioning services exotic plants on one hand are important providers of food and materials, but on the other hand invasive alien plants have also reduced crops (Meyer et al. 2012; Khoury et al. 2016; Paini et al. 2016; Fried et al. 2017). Results on cultural ESS delivery by exotic or native plant species is unconclusive, although there is an indication that people prefer more visually intense plantings in urban settings (Hoyle et al. 2017; Threlfall & Kendal 2018). Plant fitness to site and to their cultural or natural context might thus be more significant for ESS delivery than whether the involved plants are native or exotic (Daehler 2003; Sjöman & Busse Nielsen 2010; Buckley & Catford 2016; Sjöman et al. 2016; Dagenais et al. 2018; Alizadeh & Hitchmough 2020a).
4. Occasionally, the use of non-reproducing exotic plants has been suggested as a compromise between invasion risk and missing out on the sociocultural benefits of exotics (Ekologigruppen 2019). This approach, however, does not always guarantee actual sterility or non-spreading of the plant, and might also come with at least four more conceivable drawbacks to vegetation maintenance needs, urban vegetation diversity and food provision to non-human organisms: Loss of ornamental vegetation resilience and adaptability, risk of promoting less “robust” ornamental plants, risk of narrower ornamental plant diversity, and decrease in nectar, pollen and fruit resources, (depending on the sterility-causing mechanisms are used to remove plant reproductive capacity).

While the interviewees in this study (study 2) rarely discussed specific species, plant lists, site visits and drawings of the example projects showed that both native and exotic species are used in Swedish and Finnish URG:s, although the majority of used plant species are exotic. When native plant species were used, they most often formed a small portion of herbaceous perennials or shrubs, alternately native meadow and shoreline species were used exclusively. No respondents reported trouble with exotic escapees in the area, but rather many experienced problems with dominant target native species like *Leymus arenarius* or *Lysimachia vulgaris*, or strong invasions of native weeds like *Cirsium vulgare*. In the designed case studies the native meadow mix performed well on all metrics, although it was slower to establish and had a shorter flowering season than many of the herbaceous mixes that also included early- and late-flowering exotic perennials. The native plant species in the case study DPC-mixes also performed well, with the exception of *Campanula persicifolia* that faced several obstacles (possibly dead on arrival at Ultuna, late delivery, planted in wrong area) and did not survive on any site. As a rule, the native species also were the most effective at reproducing themselves. The reproduction of some non-native plant species was essential for achieving canopy cover targets in situations where some of the other target species failed to establish. However, the often vegetatively aggressively spreading *Eurybia divaricata* was able to produce a plentiful number of seedlings at Ultuna, which was not anticipated. This behavior must be monitored further to assess possible invasion risk.

9.3 Designed plant communities should be dynamic, but also stable enough to fulfil design intentions

All landscape designers and green area managers need to contend with the unpredictability of vegetation establishment or development one way or another. The concept “designed plant communities” seems to assume that it is possible to define what a plant community is (in terms of e.g. species composition, relationships between plants, and relationships between plants and site), and to create such a community through design. This suggests that the designer should be able to determine causal relationships between “correct” design decisions and plant community assembly, and so the design objectives and -tools of the DPC-framework are employed to attain the desired state of “plant communities”(Although there is no consensus about what assembly rules are and how they work. See: Götzenberger et al. 2012; Denslow 2014; Escudero et al. 2021). In the case of DPC and other designed vegetation, design itself becomes akin to an assembly rule, as the choice and placement of plants, as well as maintenance actions, dictate and influence which plant species are present on a site (Oudolf & Kingsbury 2013:201). Besides plant-soil interactions and competition between plants, the influence of structural diversity, functional redundancy and response diversity are factors that planting design for DPC should consider (Hunter 2011; Tabassum et al. 2020). Ideally, a better understanding of these assembly rules would improve the chances of creating vegetation where the chosen plant species have good prerequisites for long-term coexistence, persistence, resilience, resistance to invasion, and high biomass production (Thompson 1997:11; Tabassum et al. 2020). The DPC-framework thus tries to prevent detrimental change to assemblage plant species composition and -abundances through initial design choices by combining species with similar size and competitiveness (Thompson 1997:32; Hitchmough 2014:168–169; Hansen & Stahl 2016:53) or by combining plants with different sizes and competitiveness to fulfil different roles (Kingsbury 2009:18; Kircher et al. 2012; Hitchmough & Wagner 2013; Oudolf & Kingsbury 2013:182; Rainer & West 2015; Hansen & Stahl 2016:63; Heinrich & Messer 2017); choosing plants with similar site condition tolerances to improve overall composition fitness (Thompson 1997:32; Hitchmough 2014:134; Hansen & Stahl 2016), or sometimes with variable site condition tolerances to account for variation in site conditions and encourage layered vegetation structures (Thompson 1997:33; Oudolf & Kingsbury 2013:228; Rainer & West 2015; Hitchmough et al. 2017; Köppler 2017:17); to prioritize long-lived plants (Oudolf & Kingsbury 2001:80; Kingsbury & Oudolf 2015:66) or to combine plants with different life cycles (Rainer & West 2015; Heinrich & Messer 2017); and adapting propagule size and type (e.g. seeding or transplant, young whip or semi-mature shrub) (Morrison 2014:120; Bjørn et al. 2016).

The line between acceptable and unacceptable change in DPC:s is explained seemingly pragmatically by Oudolf & Kingsbury (2005:40): Changes in proportions between species in a planting can be accepted if they increase ecological stability of the assemblage, whereas changes that have adverse effects on design intentions are unacceptable. This approach, however, implies that "ecological stability" and "realized design intentions" are interconnected (Kingsbury 2014:70; Hansen & Stahl 2016:53), which in turn implies that DPC are a result of "right" or "optimal" design choices rather than an interplay between the design choices, the realized site conditions, and ecological processes (Thompson 1997:33,36; Hitchmough 2014:174; Köppler & Hitchmough 2015; Heinrich & Messer 2017:6; Köppler 2017; see also Treib (1999) on McHarg, cited in Herrington 2017:231; but see also Grosse-Bächle 2005:290–291; Hansen & Stahl 2016:44). The criteria of NbS effectiveness and efficiency similarly necessitates a level of vegetation development predictability that is "stable enough" (Schulze et al. 2019:649) to ensure the reliable delivery of ESS within the intended maintenance budget. Thus, from an NbS point of view, a suitable level of change in vegetation is defined through its maintained ability to deliver the intended ESS at a quality and quantity that matches at least the minimum expectations of each project. This definition of predictability allows for a pragmatic judgement of the success of the design on a project-by-project basis, provided that the thresholds for acceptable performance are clear and can be verified through evaluation and monitoring.

Figure 26 While Rosemarie Weiss's 1980's perennial meadow at Westpark still retains a decent species diversity and is attractive especially at close quarters, it has lost some of its immediate visual impact due to loss of tall and large-flowered species.

Plant selection is one of the ways in which designers can control design outcomes. Plant appearance, phenology, longevity and behaviour are influenced by complex interactions between traits, site conditions, and the plants' life histories including plant pests, illnesses and vegetation density, which means that plant performance is never completely predictable (Kingsbury 2009:5; Allaby 2010b; Marris 2013:33–34; Oudolf & Kingsbury 2013:175-176,196; Hitchmough 2014:173; Hansen & Stahl 2016:36–38; Robinson 2016:19). While the aboveground morphological traits of ornamental plants are well-known and relatively predictable, (Oudolf & Kingsbury 2013:196; Köppler & Hitchmough 2015), traits like root morphology, plant longevity, reproductive and competitive abilities, and strategy types are much harder to find in garden literature or plant nursery catalogues (Cascorbi 2007; Kingsbury 2009:18; Hitchmough 2010, 2014:156; Oudolf & Kingsbury 2013:188–192; Köppler & Hitchmough 2015; Hansen & Stahl 2016:36–38; Köppler 2017:81; Bjørn et al. 2019). Even habitat matching, which is the most prevalent method for improving the predictability of ornamental plantings, has been minimally studied in the field of urban vegetation research (Kingsbury 2009; Hitchmough & Dunnett 2014:13–14; Hansen & Stahl 2016; Robinson 2016:314). Habitat matching would also necessitate reliable methods for site condition analyses, which are not prioritized in ornamental horticulture, including DPC literature despite a consensus on their importance.

Planting design also involves selecting or manipulating plant density and abundance of specific species to influence design outcomes (Kingsbury 2014:70; Hansen & Stahl 2016:45). The manipulation of relative abundance is especially prevalent in the "*Geselligkeit*"- and role-setting systems, but also in the search for "*aspektenbildner*" or "signature species" (Luz 2001; Kircher et al. 2012; Dunnett 2019; Kühn 2024). Studies show that initial abundances have less influence on which plant species become dominant over time than species identity (Suter et al. 2010; Hitchmough et al. 2017; Kutlvašr et al. 2019), which is against the oft-cited idea of including vigorous species in lesser abundances to control their spread (Hitchmough & Wagner 2013; Hansen & Stahl 2016:62). Additionally, relative abundance of plant species does not necessarily indicate their importance for the ecological processes of an assemblage, although it might influence the provision of ESS (e.g. number and distribution of shade trees, crop-producing plants, plants of different sizes or visually dominant showy plants) (Hooper et al. 2005).

Unlike many DPC practitioners today (Hitchmough & Wagner 2013; Oudolf & Kingsbury 2013:78; Morrison 2014:121–122), Hansen & Stahl (Hansen & Stahl 2016:61,63) were also worried about herbaceous plantings becoming too dense, and thus emphasize the importance of suitable planting distances as a stabilizing design factor that diminishes competition. In the case studies (study 3), a completely randomized planting pattern and uniform density of 8,16 plants per square meter was applied to all of the herbaceous planting mixes, and thus the case studies produce no comparative results on these topics. However, the chosen density allowed for canopy closure within the establishment period despite plant mortality, which indicates that these can be successful design choices at least in the short term.

Further, biodiversity is often raised as a factor that increases ecosystem stability, productivity, resilience and overall functioning within the DPC-framework (Kingsbury 2009:19; Hunter 2011; Hitchmough & Wagner 2013; Robinson 2016:163–164; Heinrich & Messer 2017:17). This view stems from the 1950's and 1960's, when several prominent ecologists started to correlate ecosystem stability with the functional redundancy provided by higher biodiversity (DeLaplante & Picasso 2011:186). This view was overturned in the 1970's and 1980's by ecologists, whose findings from theoretical analyses of model communities rather indicated that ecosystem instability is the result of higher species diversity, only for experimental research in the 1990's to again provide evidence on the positive effects of biodiversity on overall community stability, although possibly at the cost of individual species or populations (DeLaplante & Picasso 2011:187–189). The difference between these conclusions is partially due to differing definitions of stability: Is stability about the diversity of pathways for energy flows (Odum 1953 and MacArthur 1955), returning to the exact same species composition and population size as before after smaller disturbances (May 1973), the ability of a species composition to withstand the removal of one species (Pimm 1980), resistance to invasion, temporal stability of biomass production, or retained site productivity (Tilman & Downing 1994, Tilman et al. 1996) (via DeLaplante & Picasso 2011:187–189). Another influence on the results is whether biodiversity is defined at a habitat-level, species-level, functional level, genetic level and so on (DeLaplante & Picasso 2011:189,193; Ziter 2016). Thus, plant ecologists continue to attain at least seemingly contradictory results in their studies (Hooper et al. 2005; Weiskopf et al. 2024) Thus, there is yet no certainty such effects in designed vegetation either (Oudolf & Kingsbury 2013:215). Some planting designers also believe that higher species diversity increases maintenance needs (Hitchmough & Dunnett 2014:2; Hansen & Stahl 2016:52,58,63). Yet, there are also indications that the capacity of vegetation to provide multiple ecosystem services may be connected to diversity metrics including plant species richness, functional trait diversity, but also specific species composition and vegetation structure (Harrison et al. 2014; Ziter 2016; Schwarz et al. 2017). In this light, the clear tendency of biodiversity decreasing with time in designed herbaceous plantings (Suter et al. 2010; Hitchmough & Wagner 2013; Hitchmough et al. 2017; Kutlvašr et al. 2019) might still pose a risk for long-term NbS performance, even though decreasing biodiversity doesn't necessarily correlate with decreasing functional diversity (Winfrey et al. 2018). Besides diminishing biodiversity in plantings over time, changes in plant arrangement and abundances can also negatively influence not only the formal and spatial qualities as well as other aesthetic design intentions, but also the breadth and quality of provisioning and regulating ESS (Harrison et al. 2014; Hitchmough et al. 2017; Schwarz et al. 2017; Soga et al. 2021).

Unpredictability is not always derided in the DPC-framework, but rather promoted in the context of culturally evocative spontaneous vegetation (Kühn 2006; Mathey et al. 2018; Li et al. 2019). Spontaneous vegetation can also be enhanced through complementary planting, maintenance actions or long-term management schemes to favour certain species or create desired vegetation structures (Kühn 2006; Robinson 2016:12). The risk with spontaneous development of vegetation is that it may take a long time to develop and fail to incorporate possible target species (Hitchmough & Dunnett 2014:7), or that it is perceived as unattractive or experienced as unsafe (Lis et al. 2022; Cooper et al. 2024). However, people's tastes may change, and some influential projects like Schöneberger Südgelände and Gleisdreieck in Berlin, Landschaftspark Duisburg-Nord in Duisburg-Meiderich, and to an extent Tåsinge plads in Copenhagen are all examples of projects where spontaneous vegetation has been incorporated into well-used urban recreational spaces (Jorgensen 2014; Kingsbury 2014; Threlfall & Kendal 2018). Urban semi-natural remnant or even new habitats like urban woodlands, meadows, and stormwater ponds or wetlands are similarly spaces where active work with spontaneous vegetation can thus be a cost-effective and efficient approach for multifunctional DPC in or as NbS.

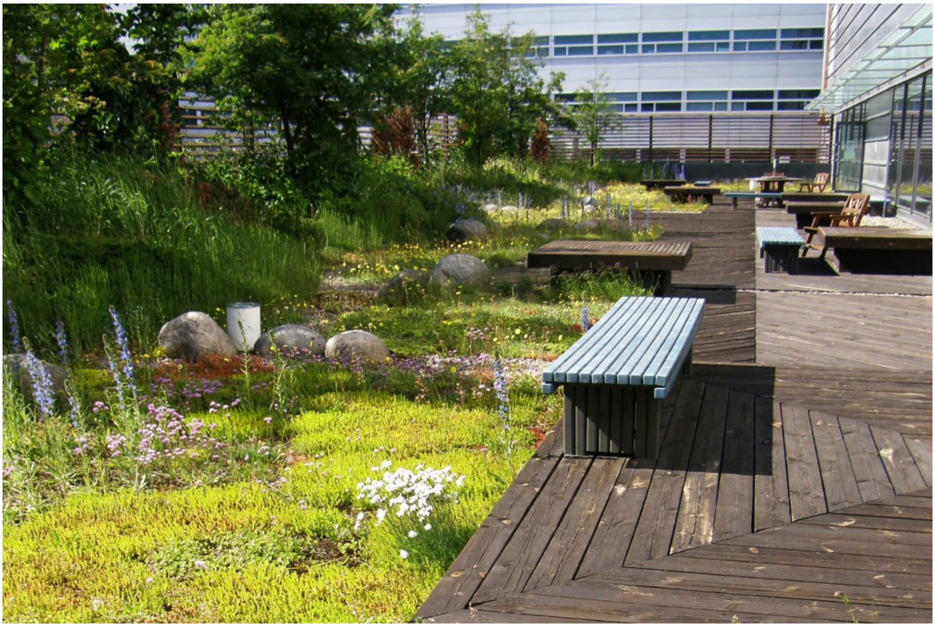

Figure 27 A green roof with planted and spontaneous native vegetation in Matinkylä.

Figure 28 Which plants are planted, which have established spontaneously here? A stormwater pond in Huddinge.

In the interview studies (study 2) two broad and non-exclusive planting design strategies to cope with uncertainty could be distinguished: Prioritizing robust solutions and prioritizing adaptable solutions. Robust solutions in the studies of this thesis were primarily associated with the use of a narrow palette of broadly used, broadly tolerant species ("robust" plants) in large group sizes, whereas adaptable solutions were associated with more species-rich compositions that could include previously less known plant varieties. "Robust" plants are those considered to be "safe choices" in a multitude of situations due to their plasticity or broad tolerance for different site conditions, longevity, tolerance for competition, non-aggressiveness, persistence under extensive and non-selective maintenance regimes, and low to no susceptibility to plant pests, pathogens or grazing (Hunter 2011; Hitchmough 2014:157; Hitchmough & Dunnett 2014:13; Morrison 2014:117; Köppler 2017:77). Thus, well-known, regionally "robust" plant species and varieties may become overused as designers "play it safe" and don't broaden their plant palette (Bengtsson & Bucht 1973; Walser in Plenk (1998) via Kingsbury 2014:84; Morrison 2014:117). Yet, there are no specific measures of "robustness", which remains a purely anecdotal descriptor; rather, the predicted success of different ornamental species should rather be seen as a continuum of higher and lower chances of successful plant establishment and performance (Oudolf & Kingsbury 2001:73).

The four strategies used in the designed case studies (study 3) echo the same basic ideas of robust solutions versus adaptable solutions: The monoculture of *Lonicera caerulea var. kamtschatica* 'Anja' E and the mixture of the 7 most popular herbaceous perennials in Sweden are obvious examples of prioritizing robust solutions, whereas the DPC:s were designed for adaptability. The meadow mix forms a kind of a middle ground: It is species-rich, which should provide adaptability, but the plant species are chosen for their broad tolerances, which is more in line with the robustness concept. In both the case studies and the interviews, including adjacent URG vegetation inventories, the different strategies showed much variability in results: On some sites (study 2), "robust" choices were suffering due to extreme site conditions or heavy weed invasions, whereas on other sites they showed acceptable development or were even thriving. Similarly, "adaptable" choices proved very successful on some sites (papers 2 and 3), whereas on others they have shown poor establishment. In both cases, the biggest hindrance for vegetation development was presumably due to extreme drought, deep shade, lack of oxygen, or exposure to salt, especially if two or more of these stressful site conditions were combined. The 10 best performing plants in the case studies (of those plant varieties that were used on 4 or more sub-sites) did include the top-selling *Calamagrostis x acutiflora* 'Karl Foerster' and *Nepeta x faassenii* 'Walker's Low' and *Lonicera caerulea var. kamtschatica* 'Anja' E ("robust plants" or high chance of success), but otherwise consisted of less-popular species like *Hypericum perforatum, Achillea millefolium, Eurybia divaricata, Centaurea jacea, Lotus corniculatus, Antoxanthum odoratum and Lamium orvala*.

All in all, the strategies employed by DPC practitioners to attain stable, reliable plant compositions are not only contradictory, but also based on incomplete or inconclusive evidence. Thus, from a theoretical standpoint, "right" or "reliable" choices that would ensure attaining the intended objectives for effectiveness and efficiency are not possible to make for the time being. But just because it is impossible to make "right" choices, making objectively wrong choices is still possible, as exemplified by the large-scale failures in establishing or maintaining vegetation in many of the interviewees' projects (study 2), some of the inventoried sites, and in the DPC1b-mixes at Torgny Segerstedts Allé (study 3). This is due to the fact that design not a truth-seeking practice like science, but a solution-seeking practice: All designs are not equally suited to answer to the challenges of a site, but there is usually more than one way of solving those challenges satisfactorily. In order to find satisfactory solutions it is thus essential to avoid making wrong choices, which in turn necessitates successively bringing questions of "*unknown unknowns*" to "*known unknowns*" to "*known knowns*" (Loxdale et al. 2016). It is not enough that few NbS-relevant disciplines or few DPC-practitioners do this work, but rather the understanding of what we don't know and what we do know must be effectively communicated across all disciplines and practitioners working with urban vegetation so that risk management and effective knowledge creation become possible.

Practically speaking, the level of detail needed for functional design solutions is one that allows for a result that is "good enough" (Hunter 2011; Köppler & Hitchmough 2015), provided that "good enough" for each project is defined in precise enough terms to be verifiable through methods available for the project organization. Without clear definitions and verification of results the successes of a project are non-transferable, the failures remain unavoidable, and the justifications for project objectives are undebatable.

9.4 Designed plant communities were developed for Northern European private gardens, but are also applicable in public settings and in semi-natural landscapes globally

While private and public gardens can contribute considerably to ESS delivery in urban areas, especially when considered as a part of the comprehensive urban green infrastructure (Cameron et al. 2012; Seitz et al. 2022; Delahay et al. 2023; Pan et al. 2023; Ariluoma et al. 2024), urban NbS are usually placed in public spaces. Much of DPC literature is written to primarily serve private garden settings, although often also with a nod towards public gardens or urban green areas (e.g. Thompson 1997; Gerritsen & Oudolf 2000; Oudolf & Gerritsen 2003; Oudolf & Kingsbury 2005; Gerritsen 2008; Robinson & Darke 2009; Hansen & Stahl 2016; Hopstock 2017). More recent DPC literature has catered more to professional audiences and public settings (Hitchmough & Dunnett 2014; Duthweiler 2016:XVIII; Heinrich & Messer 2017). Public urban areas have their specific patterns of abiotic stress, which is often compounded by infrequent maintenance (Kingsbury 2009:15; Kingsbury & Oudolf 2015:319; Robinson 2016:37). Human influence on landscapes is a gradient that increases in magnitude from unmanaged and unplanted, "natural" landscapes towards urban landscapes with a high density of built areas (Forman & Godron (1986) in Niemelä 1999; McDonnell et al. 2008; Kowarik 2011; Avolio et al. 2021).

Except for Heinrich & Messer's work (2017:37-39,45) there has been little effort put into characterizing urban habitats within the DPC-framework, although the subject has been further explored by urban ecologists and urban forestry (Lundholm & Marlin 2006; Sjöman & Busse Nielsen 2010; Lososová et al. 2012; Sjöman et al. 2018; Hirons & Sjöman 2019; Droz et al. 2021). The types and extent of disturbance are also different between private and public areas, the latter of which are more influenced by the actions of people and pets and thus might require protective measures (Kingsbury 2009:15; Hansen & Stahl 2016:50,131).

Public green areas for recreation are often designed to prioritize robustness, utility, safety, security, and the municipal maintenance budget, and thus complex vegetation structures and flowering herbaceous plants have been less prominent there than in garden settings (Pelz 2004; Oudolf & Kingsbury 2005:7,10). Management and maintenance budgets for urban public green spaces have been declining in many Western countries (Randrup & Persson 2009; Hitchmough & Dunnett 2014:1; Heinrich & Messer 2017:21; Persson et al. 2020; Randrup et al. 2021; The Association for Public Service Excellence 2021). This has often led to urban vegetation being treated as "green cement" that doesn't require special skills to design or maintain (Bengtsson & Bucht 1973; Pelz 2004; Oudolf & Kingsbury 2005:16; Duthweiler 2016:V). Still, many DPC-practitioners emphasize the importance of providing pleasant experiences through vegetation even in public spaces, which is one of the reasons behind the frameworks' interest in lowering the maintenance costs of herbaceous perennial plantings (Hitchmough & Dunnett 2014:5; Hansen & Stahl 2016:5,50; Heinrich & Messer 2017). Lowering maintenance costs is also seen to be a prerequisite for applying DPC at large enough scales to provide proper NbS functionality and biodiversity support (Hitchmough 2010).

Another important factor that separates vegetation in public urban spaces from private gardens is that while the latter can largely develop according to the tastes of its inhabitants (although in some places of the world, social norms and even formal regulations can restrict private gardens to an extent), the former must enjoy broad acceptance and even appreciation, especially in cases where urban vegetation is to function as NbS. In other words, NbS must be adapted to the social and environmental contexts of their site (European Commission 2015; IUCN 2020b; Sowińska-Świerkosz & García 2022). Research shows that people's views on outdoor space and vegetation preferences varies by context and demographic variables, which to an extent means that no solution can satisfy everybody (Hoyle 2015; Mathey et al. 2018; Nam & Dempsey 2019; Suppakittpaisarn et al. 2019; Fumagalli et al. 2020; Nazemi Rafi et al. 2020; Li et al. 2022; Lis et al. 2022; Phillips et al. 2023). In some cases, people's preferences might even run counter to NbS vegetation attributes that improve their habitat value and regulating ESS delivery.

The DPC-framework suggests "*enhanced nature*" and "*messy ecosystems, orderly frames*" as concepts for making peace with natural processes and the public's expectations on vegetation (Nassauer 1995; Kingsbury & Oudolf 2015:331; Threlfall & Kendal 2018). By adding especially attractive and clearly designed features to urban vegetation, people should learn to accept the wilder elements of these spaces. A relatively extreme example of this is the Japanese Tokachi Millennium Forest by Dan Pearson, which, despite ostensibly being a nature conservation project, incorporates large swaths of exotic perennials to re-introduce nature to highly urbanized visitorship (Oudolf & Kingsbury 2013:203). Another example would be the multitude of efforts to increase native or exotic forb richness in urban grasslands and ruderal sites.

An alternative approach to catering to local clientele has been the promotion of representing the natural conditions of the place in urban vegetation (Heinrich & Messer 2017:24). While this idea has in some cases been used in extreme manner to create landscape styles that echo an exclusionist nationalism, it also has potential to showcase the diversity of local histories and contemporary realities. Local adaptation of vegetated NbS should also reflect the varying priorities for NbS and ESS delivery: In some places provision of dense shade and cooling might be prioritized, whereas in others light and high legibility of a space are more important (Robinson 2016:320).

The delivery of each vegetation-mediated ESS and each non-human beneficiary of urban vegetation has multiple and sometimes conflicting requirements from vegetation and context, and simultaneously maximizing selected services requires considerable knowledge and skill on the specifics of the site as well as on the drivers of those services (Gaston et al. 2013). The complexities of vegetation design for urban NbS are then further expounded by the need to contextualize each service-providing unit in the larger SETS they are a part of. While the level of detail at which planting designers and other professionals working with urban vegetation engage with each of the SETS will vary from project to project, every actor involved with urban vegetation management is inevitably a part of and interacts with these SETS (McPhearson et al. 2022). An intentional approach to the social, ecological, and technical aspects of the built environment is thus key to attaining desired design outcomes for urban vegetation in general, and for vegetated NbS in specific. As future research on DPC and urban vegetation should provide a nuanced understanding of each of the interconnected SETS and how they influence design outcomes and research results, employing both qualitative and quantitative methods from different ontological and epistemological research traditions is necessary to outline each system at relevant scales. Future research on urban vegetation should also openly disclose the assumptions underlying research design, including rationale for planting designs or case study site selections, to allow for more accurate assessment of the applicability of research results to different sites.

Interviewing people on their perceptions has not been a part of the designed case studies, but several passers-by have expressed their opinions unprompted. The most common opinion voiced has been appreciation of flowering plants on all three of the sites, although one Rosendal resident complained about the flowers being “wasteful” and that “everybody would be happy enough if we just had reliable greenery on the streets”. Another opinion by visitors to Rosendal and Ultuna is that the meadow plantings have become unattractive towards the autumn. However, the meadow plantings have shown very good performance on all of the establishment metrics measured, and their flowering performance has been satisfactory.

Some aspects that might native meadow vegetation to become more acceptable for the public is to find measures to keep the plants healthier, and to keep them from flopping over due to overgrowth. The overgrowth issue has been most notable at Ultuna and will probably decrease as watering and fertilizing ends after the establishment period. Another option would be to combine the most successful species of the meadow mix with some of the most successful ornamental species, including the native *Malva moschata* but also the exotic *Calamagrosti*s ‘Karl Foerster’, *Nepeta* ‘Walker’s Low’ and *Euphorbia polychroma* and *Aster* ‘Calliope’ to not only increase the showiness of the mixes but also to extend the flowering season both towards the spring and autumn. Adjusting the relative abundances of each variety could also help to make the planting more legible and thus more acceptable (Rainer & West 2015:149–151; Li & Nassauer 2021).

Figure 29 Urban "green cement" consisting of Spiraea betulifolia 'Tor' and Spiraea japonica 'Little Princess' in Skarpnäck.

Figure 30 An "elevated robustness approach" to an urban rain garden in Rosendal, where 3-5 common shrub and grass species are planted in a relatively fine-grain pattern.

Like NbS, the DPC-framework is site- and context-oriented, although the full breadth of potential applications of the DPC-framework are not reflected in the framework's design tools. The main example that is relevant for urban NbS is the lack of guidance for supra-urban conditions where plantings are placed among impermeable surfaces in densely built areas. Since the tools only cover the use of herbaceous plants and subshrubs, their application to woody vegetation requires further investigation.

A good example of this are urban rain gardens and other supra-urban plantings, which are difficult to compose with the help of the Garden Habitat-system. In the case studies the excessive drought of the macadam-based substrate and the assumed shade directed the plant choices towards plants from the Garden Habitats dry woodland and dry woodland edge that are hardy enough in Uppsala and also tolerant of heavy shade, ambient heat, low air moisture, high pH, salt and trampling. The final species pool of viable plants was very narrow, and most of the plants that had all of the desired tolerances are very small or have a short period of interest. These attributes make plants less suitable for urban areas where plantings need to have enough volume to fulfil their spatial and amenity functions, and enough biomass to contribute effectively to regulating ESS like microclimate regulation. The scarcity and attributes of plants in these two Garden Habitats is not so much a problem of the design tool, however, but an indicator that these kinds of habitats are veering dangerously close to conditions untenable for plant life. Instead, the problem of the design tool in this case is that the habitat archetypes of dry woodland and dry woodland edge are too far from the actual conditions of the site of application – supra-urban URG - to provide information on any more aspects than moisture conditions, and to an extent light. Similarly, shaded supra-urban URG:s with a more moisture-retentive substrates like in the case study plots at Stockholm are not represented by any of the habitat archetypes either, even though the number of suitable species is larger than at a more stressful site.

The GH-system is anchored in gardens of the temperate broadleaf biome, reflected in its applications on plant categorization in nursery catalogues. This limits its relevance especially in biomes with vastly different moisture- and temperature patterns where local habitat archetypes and analogues with their own representative plant types are likely to be more appropriate both visually and ecologically. Applying the system in its broadest sense might help practitioners in differing biomes to identify comparable local references

(Heinrich & Messer 2017:37–39). On the other hand, there has been a suspicion that the GH-system is mostly interesting in more extreme climates in terms of temperature and precipitation patterns than in milder and wetter climates, as on the British Isles or in the Netherlands (Kingsbury & Oudolf 2015:317,319). The global applicability of the Garden Habitat-system should be further evaluated both in terms of site conditions, social and ecological contexts, and depending on the results it might need to be further developed to include more habitat archetypes from different biomes and detailed with a unified categorization on moisture and light conditions.

Figure 31 Urban areas can be difficult for plantings. Here, Piet Oudolf's planting at Ichtushof has been overexposed to sun, wind, drought, and possibly mechanical wear.

9.5 Designed plant communities should serve human interests, and be largely independent from human interventions

Working with vegetation intentionally as opposed to allowing for completely spontaneous establishment and development of vegetation enables adjusting vegetation to human needs and urban environments, as well as creating, maintaining and mending relationships between humans and the natural environment (Grosse-Bächle 2005:11; Hitchmough 2014:167; Rainer &

West 2015:137–159; Robinson 2016:7; Dunnett 2019). In other words, human interests trump over spontaneous ecological processes of urban vegetation; indeed, human influence is the dominating starting point for urban ecological processes (Thompson 1997:23; Robinson 2016:12), just as fulfilment of human needs is the goal of DPC and also NbS (Oudolf & Kingsbury 2013:75). Yet, both the DPC-framework and type 3 NbS strive to develop vegetation (or, more broadly, nature) that is self-sufficient enough to require little maintenance and self-organizing enough to be resilient (Eggermont et al. 2015; Hansen & Stahl 2016:16; Rainer 2021). Both approaches to urban nature also demand that vegetation fulfills set goals, which can be difficult to attain without a clear long-term management strategy and well-planned maintenance.

This contradiction of "do what you want, but also do as I say" is inbuilt in both the definitions of DPC and NbS. "Designed plant communities" and "nature-based solutions", are at their core aspirational concepts that describe a desired goal state, rather than the design process or even the constructed facility. The goal state of NbS is problem-solving, otherwise actions are "random" or failed attempts at solutions. The DPC-framework hopes to produce attractive and self-perpetuating vegetation, otherwise it is not a DPC but a purely horticultural planting or an overgrown mess. Another way to frame the focus on desired design outcomes rather than realized design outcomes for NbS and DPC would be to characterize them as prescriptive design approaches, rather than descriptive scientific methods (Finger & Dixon 1989; Dixon & French 2020).

In order to better understand how self-regulating vegetation might contribute to NbS criteria or DPC goal fulfillment, it is necessary to investigate how self-regulation of vegetation is understood, and how much maintenance can be accepted as necessary for upholding the desired delivery of cultural, provisioning and regulating ESS, as well as biodiversity support. However, not all urban vegetation needs to be conceptualized as an NbS (Randrup et al. 2020). Similarly, ornamental urban plantings that are optimized only for cultural ESS can be valuable in their own right (Cazzani et al. 2022). The key then is to be transparent about which urban vegetation does fulfil criteria for NbS, and which vegetation attains DPC goals, and which do not. Additionally, NbS and DPC are not the only frameworks that set demands on urban vegetation, but rather much of the pressure to find a good balance between control and freedom in urban nature comes from urban dwellers and green space maintenance budgets.

What are human interests in urban areas, and how can planting design and vegetation management help to fulfil them?

User-orientation is seen as the ultimate justification for urban plantings in general (Hitchmough & Dunnett 2014:5,15; Kingsbury 2014:58–59; Rainer & West 2015; Dunnett 2019), and is also the key to creating NbS that are adapted to local social and policy contexts. Catering to human needs is not only important for answering to obvious societal challenges like climate adaptation or human health and well-being, but also to for sustainable urban transformation (Cohen-Shacham et al. 2016; Randrup et al. 2020). Consequently, professionals working with vegetated urban nature-based solutions must find ways to combine regulating, cultural and provisioning ESS with habitat for diverse flora and fauna.

Many DPC practitioners are thus interested in creating people-oriented, meaningful designs: vegetated spaces that are emotionally evocative, aesthetically pleasing or even striking, seasonally variable and sometimes also informative (Oudolf & Kingsbury 2001:12; Kühn 2011:47; Hitchmough & Dunnett 2014:18; Kingsbury 2014:92; Robinson 2016:7,14-16). Nassauer's principle of "*messy ecosystems, orderly frames*" (1995; Li & Nassauer 2020; Li et al. 2022), together with stylization and visual enhancement of spontaneous plant assemblages, are often cited as an ideal model for combining the wilder, more dynamic aspects of DPC with people's needs (Kühn 2006; Hitchmough 2014:135; Rainer & West 2015). Some examples of the combination of spontaneous-looking, intermingled planting patterns with formalistic elements, can be found in Sissinghurst, Mien Ruys Tuinen, and many of Piet Oudolf's earlier works (Oudolf & Kingsbury 2013:35).

Maintaining a pleasing appearance is also seen as a prerequisite for the longevity of DPC, as vegetation that doesn't serve the needs of the people is at risk of being removed (Köppler 2017:10–13). While "wilder" appearances may be appreciated in some contexts and might also become more acceptable in time in other contexts, there are sites where certain plant species and vegetation structures carry valuable and specific cultural and historical meanings. It is thus important to consider that cultural ESS and aesthetic goals are rarely objective, and that maintaining and developing them should be done with regards to site user's needs, cultural context, and design intentions.

Urban biodiversity metrics influence regulating, provisioning, and cultural ecosystem service delivery, and also form a part of the SETS of any given site (Chapin III et al. 2000; Dearborn & Kark 2010; Zari 2018; McPhearson et al. 2022). Urban biodiversity has also conservation value as a habitat reserve, as a part of ecological corridors and networks, as an environmental indicator, and for its pedagogical value (Dearborn & Kark 2010). Hence, upholding urban biodiversity does not only have intrinsic value, but it also has instrumental value for the effectiveness and socio-cultural values of NbS (Zari 2018).

The DPC-framework also recognizes the importance of plant species diversity for habitat provision and habitat connectivity (Oudolf & Kingsbury 2013:62–63; Hitchmough 2014:134; Hitchmough & Dunnett 2014; Hansen & Stahl 2016). For example, Hansen & Stahl (2016) expressed their interest in using perennials to allow urban dwellers to experience diverse and rich nature where they live, and to combine beauty and artistry with space for rare plants and shelter for a variety of animals.

In addition to improving the habitat value of ornamental vegetation, upholding urban biodiversity is also dependent on the provision of diverse environmental niches and wilder urban vegetation (Dearborn & Kark 2010; Kowarik 2011; Ives et al. 2016). Thus, provision of urban biodiversity must be managed at large scales, and consider how and where concerns for different habitats should be met. This can require maintenance actions that limit the spread of aggressive exotic plant species to more natural areas, removing invasive weeds that would smother nectar-rich ornamental plants, and allowing thickets to form in some places and removing them from others.

While the topic of regulating ecosystem service provision hasn't been explored in depth in the context of DPC yet, some DPC practitioners have branched out to develop suitable vegetation for green roofs and rain gardens as a means to improve the provision of regulating ecosystem services in addition to providing biodiversity support and aesthetic value (Dunnett & Nolan 2004; Dunnett & Clayden 2007; Dunnett et al. 2008a; b; Dunnett & Kingsbury 2008; Dunnett 2010; Hitchmough & Wagner 2013; Yuan et al. 2017; Yuan & Dunnett 2018). Recent DPC literature also refers to the provision of regulating ecosystem services like stormwater management, erosion control and phytoremediation as possible uses of DPC (Oudolf &

Kingsbury 2013:11–12; Rainer & West 2015:180; Heinrich & Messer 2017:37,47-48; Dunnett 2019:170–179). Some examples where DPC has been applied to urban rain gardens are the rain garden plant trials at LWG Veitshöchheim (e.g. Eppel-Hotz 2009, 2019) and Sheffield Grey to Green project by Nigel Dunnett, Zac Tudor, Sheffield City Council with Robert Bray Associates (Dunnett 2019).

Just as specific plants provide specific social, ecological or economical functions, services and values, the functionality and value of multi-species vegetation units is also dependent on the specific attributes of the whole plant composition (Hooper et al. 2005). However, the understanding of which specific vegetation attributes promote diverse ESS delivery is still elementary, and thus designing vegetation that delivers the desired ESS at reasonable capacity and effectiveness is difficult. In fact, it might sometimes be easier to notice the loss of an ESS-delivering function, rather than its presence. Thus, maintenance might be needed to retain and develop the features that are crucial for target ESS delivery, which in turn necessitates the identification of such features and their indicators.

Figure 32 Rain gardens by Bettina Jaugstetter, built for the Bundesgartenschau 2023 in Mannheim.

Figure 33 Cottage garden opulence in orderly frames at Sissinghurst, an Arts and Crafts Garden from the early 1900's.

What does independence from human interventions mean for urban vegetation?

Hansen & Stahl's definition of designed plant communities is rooted in the holistic view on nature and natural plant communities as "superorganisms" popular in the 1950's and 60's (DeLaplante & Picasso 2011; Kühn 2011:105). Consequently, to work with "*Pflanzgemeinschaften*" is to find plant combinations that are close to being self-organizing units. Although later DPC-practitioners' are more familiar with the individualistic and aut-ecological understandings of plant community ecology, the basic tenet of "community before individual" remains central to the DPC-framework (Hitchmough 2010; Hunter 2011; Köppler & Hitchmough 2015). For example, while Rainer & West recognize the plant community as a fundamentally arbitrary concept developed primarily for organization purposes, the idea of finding a sustainable "optimum" through right plant choices still remains; combinations of plants are only considered to form a community if they are able to coexist on a specific site for an indefinite period of time (Rainer & West 2015:30-38,41).

DPC aspirations towards "plant communities" as both the goal state and the provider of all envisioned benefits of the DPC-framework over alternative planting design approaches is almost tautological: if a planting fulfils the design goals with little maintenance, it has become a self-regulating designed plant community; if a planting self-regulates itself to a state that doesn't fulfil design goals unless maintained intensively, it is not a designed plant community. This contradiction is not specific to the choice of using "designed plant communities" as the umbrella term instead of opting for the popular synonyms "naturalistic planting design" or "ecological planting design", as the ideal of "self-regulating, goal-fulfilling vegetation" persists within the DPC-framework independent of the used concept.

How should DPC for NbS be maintained?

Allowance for change in species composition and plant distribution patterns is possibly the aspect where DPC differs the most from conventional planting design (Thompson 1997:32; Kingsbury 2009:3; Hitchmough 2014:176; Hitchmough & Dunnett 2014:18; Morrison 2014; Hansen & Stahl 2016:13-14,16,36-38). Since the long-term management of DPC is envisioned to mainly consist of non-selective interventions aimed at maintaining the diversity of herbaceous perennials, control over species' placement and abundances is largely relinquished to ecological processes rather than adjusted through selective maintenance actions like intensive weeding, cutting back plants, staking, fertilizing, and mulching, or removing aggressive target species during the growing season (Schmidt in Oudolf & Kingsbury 2005:155; Kingsbury 2009:13; Hitchmough 2014:174–175; Hitchmough & Dunnett 2014:15–16; Hansen & Stahl 2016:45; Dunnett 2019:162).

However, successful DPC should only exhibit small-scale "*carousel dynamism*" (Schulze et al. 2019:639–640) that is largely predictable and excludes significant changes in species composition and successional community development, while allowing for changes in pattern (Kingsbury 2009:8,13,17; Bjørn et al. 2016; Köppler 2017:73–78). Such limited dynamism is often likened to an overall ecological stability and resilience of herbaceous plant assemblages, i.e. self-regulation as defined through minimal maintenance needs (Kircher et al. 2012; Oudolf & Kingsbury 2013:12; Hitchmough 2014:134; Schulze et al. 2019:649).

In other words, DPC vegetation management aims to steer the development of the plant mix according to long-term design intentions (Hitchmough 2014:132; Rainer & West 2015:61–62; Robinson 2016:13; Dunnett 2019:162) through "minimal maintenance" (Oudolf & Kingsbury 2013:123; Hitchmough 2014:132; Kingsbury 2014; Duthweiler 2016:XVIII; Hansen & Stahl 2016:131; Robinson 2016:13; Köppler 2017:78). The species selection must then comply with the chosen intensity of maintenance, which in the case of "minimal" non-selective maintenance has often included the promotion of semi-natural grasslands like meadows or prairies as references for forb- and grass-dominated DPC:s (Kircher et al. 2012; Oudolf & Kingsbury 2013:41,78; Hitchmough & Dunnett 2014:15–16).

The ability of herbaceous plant assemblages to persist with the help of only non-selective maintenance by less-skilled staff is sometimes highlighted as an overall criterion for DPC, as it is seen as a sign of self-regulation (Hitchmough 2014:131,175-176). Some studies, however, have noted that mowing might not provide strong enough disturbance by itself to maintain species diversity, but should be complemented with selective weeding or scarifying soils for better target species retention and vegetation development (Hitchmough & Wagner 2013; Bjørn et al. 2016, 2019).

Maintaining the spatial qualities and the overall desired "image" of designed vegetation are also important for many in the DPC-framework (Borchardt 1998:239; Oudolf & Kingsbury 2013:123; Gustavsson 2014;

Köppler 2017:14). For example, canopy cover, layered vegetation structures and retained species diversity are often priority concerns for upholding design intentions (Richnau et al. 2012; Oudolf & Kingsbury 2013:123; Hitchmough 2014:131, 2017b:145–165; Hansen & Stahl 2016:14; Dunnett 2019:162; Robinson 2016:163; But see also Heinrich & Messer 2017:17).

While the appearance of DPC can be somewhat resilient against invading plants in smaller quantities, large-scale weed invasions will "collapse" DPC by removing their capability to fulfil design intentions (Thompson 1997:32; Oudolf & Kingsbury 2013:123; Hitchmough 2014:164; Morrison 2014:118,127). Loss of plant diversity, and especially the loss of target species diversity, might thus be the root of the widespread belief that herbaceous perennial vegetation requires renovation every 10 years in spite of succession-hampering maintenance efforts (Oudolf & Kingsbury 2013:40).

This view was echoed by the interviewees (study 2), although only one of the interviewed municipalities had practical plans for executing regular renovations. Many of the interviewees also expected URG vegetation to be shorter-lived than in other plantings, partially due to the challenging site conditions and partially due to the invasive maintenance methods planned for removing trapped sediment from URG:s. On the other hand, few of the interviewees had planned for specific timeframes for URG vegetation besides wishing for the included trees to be allowed to live out their full lifecycles. Thus, if field-layer vegetation longevity up to or beyond the rough expectation of 10 years for herbaceous perennials is a desirable goal, the goals must be explicit, and the prerequisites for ornamental shrub, forb and grass vegetation should be further investigated.

The eldest known surviving DPC that stem from Richard Hansen's work or teaching are some areas of the Weihenstephan rock gardens, Water garden and Hazel corner by Hansen himself (established between 1947 and 954), as well as some areas of herbaceous plantings by his students Urs Walser and Rosemarie Weiss in Westpark in Munich in the 1980's (Wittke (1994) in Forbes et al. 1997:88; Kingsbury 2014:82) Duthweiler, personal communication June 2024). Other DPC-adjacent plantings of perennial forbs more than 10 years of age can be found in a variety of places: LWG and Waldfriedhof at Veitshöchheim and Peter Gaunitz' plantings in Laholm, for example, or the woodland DPC of Vargaslätten in Simlångsdalen, Arboretum Mustiala in Elimäki and the Landscape laboratories at SLU

Alnarp that only seem to get better with time. One suggestion has been that specifically more stressful sites like woodlands or rockeries provide better prerequisites for composition longevity than more productive sites. The strength of this possible correlation is and whether it also applies to highly stressful urban situations like URG:s with gravel-based substrates should be studied in detail in the future. For example, many of the case study URG plantings fulfilled their immediate design objectives during the establishment period, but how long they will keep their species richness, structural complexity, coverage and floriferousness is anybody's guess.

Figure 34 The Hazel Quarter at Weihenstephan trial garden might be one of the eldest surviving representatives of the Garden Habitat-based DPCs.

Figure 35 Urs Walser's woodland edge plantings consist of many plants that are either self-seeding or long-lived, and might partially be "original" to the 1980's.

As the species composition and structure of vegetation are at the top of the ESS cascade model, understanding both the individual plants (reductionist view of ecosystems, see e.g. Gleason 1939, Simberloff 1980, Botkin 1990) and the whole of vegetation (holistic view of ecosystems, see e.g. Clements 1916) (in DeLaplante & Picasso 2011:190–191, 199–200) is necessary to manage multifunctional, efficient and effective NbS through a suitable combination of non-selective and selective maintenance interventions. As such, further research into vegetation management and maintenance on the plants' own terms is crucial.

Further, NbS management that only stresses the service dimensions of the ESS cascade cannot remain relevant without staying sensitive to changes in the SETS the NbS belong to (Randrup et al. 2020), including the effects of these changes on vegetation. Conventional maintenance of plantings that aims at indefinitely maintaining a singular goal state or pure nature conservation approaches to urban vegetation could be examples of a rigid vegetation management strategies that may lose their relevance over time (Grosse-Bächle 2005:290; Morrison 2014:118). Correspondingly, the DPC-framework promotes "*creative management*", i.e. adjusting management goals and maintenance actions to suit changing needs and unexpected vegetation development trajectories (Oudolf & Kingsbury 2005:155–156; Gustavsson 2014; Koningen 2014). This approach to vegetation management is meant to restrict the use of natural resources and time spent on maintenance, but it requires skill and good planning from the management staff (Richnau et al. 2012; Hitchmough 2014:171; Walser in Plenk (1998) via/ Schmidt in Kingsbury 2014:93–94; Nam & Dempsey 2019). It is similar to the concept of "*adaptive management*", i.e. managing environmental resources through flexible working methods where both failures and successes are used to inform future actions (Ahern 2011; IUCN 2020a).

Despite long-term vegetation management being key considerations for the effectiveness and efficiency of urban vegetation as provider of ESS, academic research on urban vegetation maintenance is scarce. In the DPC-framework, some studies on maintenance exist, although many of these are not academically published (Schmidt 2006; Plenk et al. n.d.). Thus, it is difficult to judge the actual differences between DPC management, conventional urban vegetation management, and the management of semi-natural vegetation like meadows or urban woodlands in terms of the costs, frequencies and types of maintenance actions (Forbes et al. 1997:110).

Figure 36 "Weedy" vegetation has been integrated into Ebertpark at Ludwigshafen am Rhein to decrease maintenance while retaining an attractive enough appearance.

9.6 Reflections on study methods and results

Due to resource constraints and an excess of ambition, this thesis consists of a pre-study (Chapter 5), one finished study (paper 1), two studies in progress (studies 2 and 3), and a collection of complementary data. The following subchapters reflect on the research methods, preliminary results, and future research needs identified thus far.

9.6.1 Literature review methods and results

Besides its original purpose of laying the groundwork for paper 1, the narrative review (pre-study, chapter 815) raises a number of new questions on the development of ecologically inspired planting design practices, and the ways natural and cultural forces have been interpreted and juxtaposed in landscape historically. The review is currently largely reliant on a few previous historical overviews on naturalistic and ecological planting and refers often to secondary or even tertiary sources, which highlights the need to analyze a broader range of garden history and landscape design literature. Further research into the history of DPC and the relationship between ecology and cultural considerations would also require a deeper and preferably multilingual analysis of original sources with precise research questions and possibly more refined discourse analysis methods.

While systematic reviews are preferred for their transparency and active attempts to minimize bias and enable replicability, they are not especially suitable for emerging, loosely defined or interdisciplinary topics, or exploratory studies as was the case for both the pre-study and paper 1 (Snyder 2019; Fan et al. 2022). The choice of narrative and scoping reviews over systematic review methods was thus also made partially out of necessity: literature on and relevant to the DPC-framework is very difficult to find through simple keywords (see the list of DPC synonyms in Table 1 and Table 2 and the literature search process for paper 1). The difficulties in literature selection for paper 1 is not unique: the more recent planting design and URG vegetation reviews by Oliveira Fernandez et al. (2025) and Corduan & Kühn (2024), despite having broader research topics, also had to exclude several records and/ or add material from complementary searches to arrive at a sufficient and relevant body of literature for analysis. This indicates in general that research on urban vegetation and planting design is poorly organized when it comes to common terminology and key words.

9.6.2 Interview study methods and results

The chosen interview format of semi-structured group interviews worked well for attaining desired information: the interviewees spurred each other on, and provided insights into questions that were not a part of the interview framework. The number of example projects and informants was also suitable to reach a decent data saturation point. Additionally, site inventories of the example projects were very useful for discussing them with the informants, and for relating their answers to the researcher's observations of the site. Two weaknesses with this study design could be identified, however: It was difficult to gather the whole group of informants with different roles at once, and it was also sometimes difficult to get the complementary material or information from the interviewees as it was often unclear who would send over drawings or other design documents. It is also probable that the project organizations and people that were willing to be interviewed had formed strong positive professional relationships, whereas parties with strong disagreements on the projects or with the other organizations might be more difficult to involve in group interviews.

9.6.3 Case study methods and results

How much of the designed case studies is "research on design" and how much is "research through design" is somewhat debatable. On one hand, the process and results of the case study design are equally analyzed in this study, leaning more towards "research on design", or a post-positivist application of research through design; on the other, the design process and the follow-up procedures of the designed case studies have produced valuable information on the context-sensitivity of the design process and how these actions could, should, and cannot be conducted in a scientifically sound manner (Lenzholzer et al. 2013; Lenzholzer & Brown 2016).

Regardless of the methodology nomenclature, the case studies have provided data both on design and through it. For example, as a professional landscape architect with around five years of work experience at the time of composing the planting mixes, it was surprisingly difficult not to use tacit knowledge and anecdotal evidence in the design process. The mechanical, filter-based design process was also slower than a process that allows for an interplay between intuitive choices and looking for evidence. This indicates that there might be a tradeoff between design method objectivity and efficiency. Considering that even "objective" design methods are not currently based on accurate data on plants or site conditions, it is also unclear to which extent "objective" methods improve the effectiveness of the resulting designs in attaining ecological, technical or socio-cultural design objectives. Despite these shortcomings, transparency about design methods is important for planting design research, as it enables studies on the effectiveness of different design strategies and methods.

Due to time limitations the designed case studies (study 3) are only represented briefly in this thesis. The case study setup was conceived as a four-year study in total, where the licentiate phase focuses on the planting design process, vegetation establishment and maintenance during the 2-year warranty period. The future paper presenting the study will further detail discuss the results, hypothesize possible explanations for the observations, and predict future performance. The eventual continuation of the study into the PhD-phase was thought to allow further insight into the development of socio-cultural values of the assemblages, as well as their value as insect habitat. Socio-cultural values in very simplistic terms could be derived from the growth, health and flowering data collection that has been started during the licentiate phase, but the suitability of such proxy values for determining cultural ESS delivery in any generalizable capacity can be put into question. Thus, instead of adding a specific study on the cultural ESS delivery of the tested planting strategies, potential future studies on the designed case study plantings will probably continue to focus on URG vegetation development in biophysical terms, and possibly be complemented with a study on the suitability of biophysical proxy values for evaluating specific ESS delivery potential of urban vegetation.

Case study methodologies proved to be flexible and useful for all three applications: the designed case studies, example project inventories, and complementary URG inventories. Using real-life cases in their complex contexts was rewarding, and helped to anchor the studies in the practical issues that urban NbS and urban vegetation faces. However, all three applications would have benefited from a deeper understanding of the possibilities and limits of case study methods, especially when it comes to formulating research questions or hypotheses that can be answered with a case study setup. When it comes to the site inventories for study 2 and the complementary inventories, the number of sites is high enough that the data could be analyzed with more sophisticated methods and findings presented in a manner similar to Beryani et al. (2021) or Winfrey et al. (2018). While it is possible to answer the hypothesis posed in study 3 and thus contribute to the overall aims and objectives of this thesis, the findings overall are not generalizable in a statistical sense (Yin 2018:20–21). There might also have been questions and hypotheses that could have been answered in an analytically generalizable manner (ibid.) if there had been fewer variables in the planting designs and between sites, or if data collection from sites had been more comprehensive and precise. Still, it is also apparent that while field or laboratory experiments would have enabled the extraction of generalizable results, a change in methods would also have changed the questions and distanced the studies from everyday planting design practice. Combining case studies, designed or otherwise, with controlled quantitative experiments and qualitative research thus seems a reasonable strategy for learning more about the design and performance of urban vegetated NbS.

While a decent body of URG vegetation research is available (Corduan & Kühn 2024), many questions remain unanswered. Comparisons of vegetation establishment and long-term development between different URG substrates is an obvious area of interest, especially combined with studies on URG:s capacity to improve the quality and decrease the quantity of stormwater outflow and/ or other ecosystem services. The influence of substrate on vegetation development in combination with the influence of the timing of establishment (spring, summer, autumn) and plant species would also be interesting, and would help to understand which of these three factors (substrate, timing of planting, plant identity) makes the biggest difference for the outcome. The influence of site condition variables (e.g. light, moisture, salt, temperature, oxygenation) on plant performance in URG:s would further be helpful for the development of URG:s as NbS.

More generally, the planting design research areas identified by Hitchmough & Dunnett (2014) are still relevant. One example of a research design that might help in understanding the influence of site conditions and competitive relationships on ornamental vegetation establishment and performance might be to compare plantings composed according to DPC tools and in alignment with the DPC-framework's goals and objectives with completely randomized plant selections. The comparison could be done theoretically, on a trait-level (with inspiration from e.g. Van Mechelen et al. 2015) and in practice, under different kinds of site conditions. This study design might also help to identify possible "all-round perennials" and see if and which traits they have in common.

10. Conclusions

The DPC-framework is seemingly compatible with urban NbS, as both approaches are based on utilizing the power of nature, specifically plants, to improve not only human well-being but also to support broader ecosystem values. It relates to three of the four criteria for nature-based solutions, with the exception of "*answer to societal challenges*" where DPC literature has thus far mostly been concerned with improving human well-being by enhancing the quality of urban green spaces. The case study, interview and inventory results do not show that DPC consisting of herbaceous perennials and subshrubs is inherently more successful as a planting design strategy than any other observed ones.

Herbaceous plantings composed according to the DPC-framework generally showed acceptable establishment success in the case studies, although at a lower overall rating than the other 3 planting design strategies tested. With the exception of the DPC1b-mix at Torgny Segerstedts allé, all of the DPC-mixes of the designed case studies showed good to great establishment results in terms of coverage development, which made them equally successful to the other two planting design strategies incorporating herbaceous perennials, and more successful than the shrub monoculture. The shrub monoculture had the highest survival rate at all sites. The DPC-mixes had the lowest survival rates, DPC1b and DPC1c being below the cutoff rate (75%) for acceptable survival. Height development was well below expectations for all of the strategies except for the meadow mix. Four of the five subsites showed good vegetation development, whereas Torgny Segerstedts allé North just barely reached acceptable development. The standard deviation in overall performance in 2024 was similar between subsites, between the four vegetation strategies, and the eight plant mixes, indicating that none of these basic variables alone explained performance variation.

The interview results indicate widespread tendencies in urban development projects to deprioritize plant needs at the cost of functional NbS. Many of the interviewees stated that planting design is among the last phases of the design process, and it is only done after city planners and road and stormwater engineers have given the prerequisites for planting design. At the same time, the interviewees regularly report on issues that the engineered solutions and deleterious maintenance practices like the use of road salt cause for URG vegetation. The harm to plants caused by hostile growing conditions was neither diminished with increased, DPC-aligned considerations for plant selection, nor by leaning heavily towards “safe” or “robust” plant choices. Rather, the example projects with good vegetation development were characterized by the application of design solutions to ameliorate growing conditions for plants, but also by less stressful growing conditions like smaller roads or park settings. The case studies, however, do also indicate that plant selection does matter, as the performance of non-hardy and otherwise unfit plants varied more between sites and site conditions than the performance of fitter plants.

The studies conducted in this thesis suggest that the weaknesses of the DPC evidence base and design methodologies for herbaceous DPC prevent it from improving the performance or reliability of vegetated NbS. The scientific literature on DPC neither provides principles and methods for planting design, nor does it support the design tools provided by gray DPC literature. The designed case study also serves as an example of the difficulties for applying the DPC tools, partially due to a lack of suggested methods for site analysis, a lack of common, measurable definitions for site conditions, and lack of available information on many of the plant traits that should be included in the analysis phase of plant selection, but also due to the internal discrepancies of the DPC design tools.

The studies in this thesis also suggest that well-developed DPC do have the potential to provide multiple ESS and support biodiversity through their species-richness, flowering performance, structural complexity, and biomass production without increased maintenance needs. Additionally, the DPC-framework seems to be effective at highlighting the complexity of planting design and the environmental factors that influence urban vegetation development, and thus the ecosystem services that plantings can deliver. The most critical problems of DPC are also not “DPC-problems”, but rather apply to all planting design and vegetation management: There is a lack of practically applicable scientific evidence for optimizing ornamental vegetation development and performance through plant selection, plant arrangement, or vegetation management. The results of this thesis indicate that the prerequisites for reliably creating and managing vegetated urban NbS are not met.

This thesis identifies considerable knowledge gaps pertaining to planting design variables like plant selection and planting patterns, urban vegetation establishment, and ESS delivery by urban vegetation, which means that vegetated NbS performance cannot currently be predicted or optimized through the means of planting design and vegetation management. The literature review in particular shows that research on DPC is fragmented, largely inconsiderate of supra-urban NbS like urban rain gardens, and only weakly connected to societal challenges and ecosystem service delivery. The case study further demonstrates that the use of the DPC-framework's design tools presupposes access to an evidence base on plant traits that simply does not exist today. Evidence-based planting design is a key requirement for landscape architects' capacity to contribute to solving the environmental crises our planet is facing right now (Brown & Corry 2011). The necessity of evidence-based design is especially clear in the context of NbS, as the concept requires effective and efficient functionality and discourages "random actions" (Albert et al. 2021; Sowińska-Świerkosz & García 2022).

Based on the literature review, further challenges for finding viable planting design methods that help fulfil the four NbS criteria (Sowińska-Świerkosz & García 2022) can be summarized into five points:

1. Poorly formulated methodologies for NbS-relevant planting design, above all pertaining to multifunctionality but also to the social and ecological aspects of local adaptation, is a threat to the capacity of urban vegetation to effectively and efficiently function as factual solutions for societal challenges. The DPC-framework and DPC research can assist with the latter aspects to an extent, if they are used in tandem with explicit design goals and -methods. Thus, planting design for NbS should start by identifying the most relevant societal challenges (IUCN 2020a; e.g. European Commission 2021) to address on the site.
2. Poor understanding of the linkages between vegetation attributes and vegetation performance in NbS (e.g. relevant plant species and composite vegetation attributes for ESS delivery) hinders vegetated NbS from contributing with effective and efficient ecosystem service delivery. While the relevant evidence base is still insufficient, planting design for NbS should early on identify the ecosystem services that can contribute the most to meeting the identified local challenges. ESS catalogues like TEEB (2011) or CICES (2023) can be used to support this phase. Early considerations for suitable evaluation methods for different ESS would also be useful for setting measurable goals for the

planting (European Commission 2021; Sowińska-Świerkosz & García 2021).

3. Poor evidence base on which vegetation attributes are relevant for their overall performance (e.g. quantification of site tolerances, defining "robustness" and identifying corresponding traits, finding the limits for vegetation adaptability to different site conditions, the influence of vegetation phenology on maintenance needs) limits the capacity of vegetated NbS from being "powered by nature". Yet, identifying the biological and ecological prerequisites for ESS delivery through vegetation is necessary for creating and managing vegetated NbS. Thus, project priorities, engineered solutions or site conditions may need to be changed to either match the ambition levels to the realities of the project, or the conditions for vegetation may need to be improved to meet NbS criteria.
4. Lack of widely accepted and easily available monitoring and evaluation methods for urban vegetation hinder learning from existing solutions, and thus from improving the effectiveness and efficiency of vegetated NbS. Additionally, monitoring and evaluation only provide applicable information if the observation data can be analyzed in the context of design, construction and maintenance parameters.
5. "Designed plant communities" as a concept is poorly defined, and literature on the DPC-framework is difficult to find due to inconsistent naming of ecological and naturalistic planting design approaches. On the other hand, there are currently no alternative, better defined planting design frameworks for urban ornamental vegetation, nor do the alternative planting design approaches (horticultural, robustness, ecological engineering, urban greening and nature conservation) have as holistic a view on both the biophysical and sociocultural dimensions of urban vegetation as DPC. Additionally, the same knowledge gaps that plague the DPC-framework are just as limiting for evidence-based applications of the alternative planting design approaches. Thus, while the DPC-framework cannot promise improved planting design outcomes, it can contribute to a more reflexive planting design process that encourages designers to consider a broad range of design variables and possible developmental paths for designed vegetation.

This thesis would thus like to argue for developing the DPC-framework into an evidence-based planting design and vegetation management practice that can, when needed, contribute to NbS by engaging explicitly with solving societal challenges like climate resilience, water management, and urban place regeneration. Not all urban vegetation needs to be NbS (Randrup et al. 2020), but where vegetated NbS are employed, their planting design and vegetation management need to reliably contribute to all four NbS criteria. The creation and management of vegetated urban NbS, like URG:s, requires not only the development of urban vegetation knowledge, planting design methodologies and vegetation maintenance practices, but also rethinking the priorities of urban planning and urban infrastructure engineering. Indeed, the effective and efficient application of urban nature-based solutions seems to require the development of **nature-based cities,** where thriving vegetation is understood as an integral part of livable urban environments for people.

11. Afterword

> "People who want to create a perfect garden should have a quadruplet personality. - - -. Earth, air, fire and water: The down-to-earth farmer, the ultimate philosopher, the most compelling storyteller, and the most realistic cynic." (Henk Gerritsen: Essay on Gardening, (2008:381))

Henk Gerritsen's Priona Garden, as it appears in his book *"Essay on Gardening"* (2008), as it fell due to multiple years of unintended neglect, and its relatively recent resurrection, is in my mind the most powerful case study of the practical application of designed plant communities. In *"Essay on Gardening"* Gerritsen describes in his often humorous and self-reflective style how his lifelong love of plants and natural ecosystems transformed as he discovered the experiential and artistic potential of designed vegetation in Mien Ruys' garden. He then set out to introduce his favorite native and exotic plants and recreate his ideal natural plant communities in his garden by using every piece of ecological knowledge he had accumulated thus far. His efforts bore both the fruits of success, and failures after bitter fights. The successes were spurred on by his network of peers, his hard work, and serendipity. Gerritsen thought carefully about the site conditions and suitable plant combinations for different parts of his garden, but the rich clay soil of the garden made it difficult to prevent highly competitive, weedy plants from taking over from valuable introduced species that were adapted to poor soils. Gerritsen and his partner Anton Schlepers had also different views about what a garden is and how they should be managed, which led to compromises for them both. Yet, it was precisely the tug-of-war between art and plant ecology, the attachment to specific plant compositions, the wish for a garden to "sort itself out", the craft of gardening, and the pleasure of letting the garden unfold spontaneously that made Priona Garden so rich in detail, innovation and variety.

These juxtapositions are reflected in the way urban nature and nature-based solutions are discussed as well, as urban dwellers, politicians, and urban design professionals negotiate how shared spaces are used, and which interests get priority in which parts of built areas. As Priona Garden's history shows, the neglect of designed and semi-natural vegetation leads to the impoverishment of green spaces, both in terms of species richness, but also in the clarity and useability of more formal design elements like walls, hedges, art and recreational spaces. Yet, letting go of some of the control is not only a way to cut down on maintenance, but also a necessity – indeed, the idea of complete control of outdoor spaces is only an illusion. The balance between strategic actions and deliberate inaction is what long-term vegetation management is all about, whether it be in a garden, in an urban rain garden, or in recreational woodlands. The key is to understand how both human and non-human stakeholders are affected by these vegetation management choices, and how they affect the further development of vegetation. After all, both DPC and NbS live and die according to their capacity to support living ecosystems, and the desirability of these ecosystems to people. And both can be invigorated again with some care and attention from the right people, as has been the case with Priona Gardens.

I have come to think that not only gardeners, but researchers on planting design need to embody the qualities Gerritsen describes above: There needs to be a solid practical understanding of the biophysical world at multiple scales; an ability to rise above clichés and appraise previous work critically; and the courage and imagination to dream aloud of a better world without losing sight of the obstacles and unpredictability of the world where the research is (or isn't) put into practice. I hope to have demonstrated at least some of the four qualities in my work, but can't help but worry that cynicism or even pessimism might take hold in people (including myself) as they become aware of the shaky scientific foundations of planting design and vegetation management, and thus a large part of the premises for both DPC and NbS. To that worry, I say: What are the alternatives? Continuing with current solutions is demonstrably inadequate in the face of current societal challenges; High-input, low-return solutions will never be realistic on a large scale; and fully embracing spontaneous vegetation establishment and development does not come without tradeoffs, even though there is absolutely room to move towards wilder urban vegetation. No, at the time of writing I can't see any better use of my time than to continue building on the thoughts, ideals and dreams of other DPC practitioners to design and develop vegetation that meets the needs of people and non-human organisms alike, by working with nature more often than working against it. To do that, I hope to cultivate not only the four traits described by Gerritsen above, but also critical thinking and sense of humor, which seem to be the prerequisites for learning from not only your successes, but also from your failures.

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All photos have been taken by the author.

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I

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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

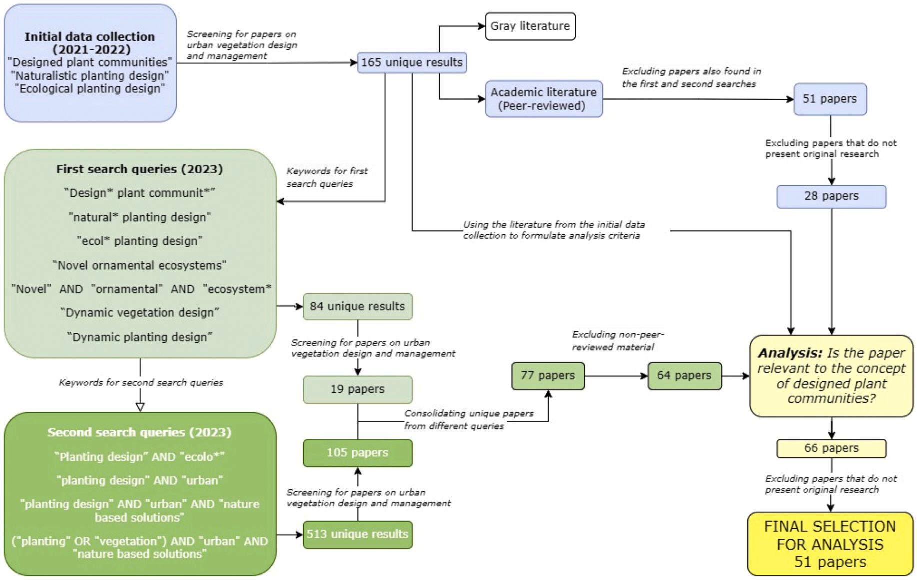

Fig. 2. Flow chart of the data collection and literature selection process for reviewing the potential of designed plant communities for urban nature-based solutions.

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

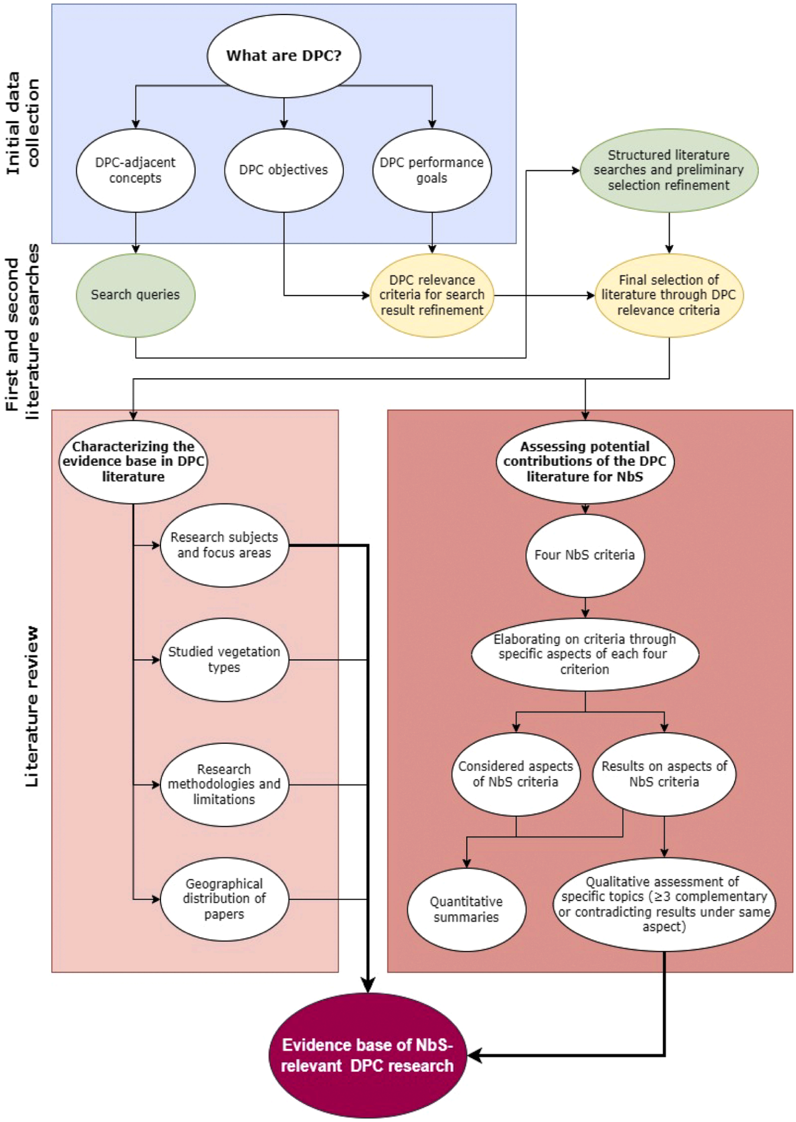

Fig. 3. The process of reviewing the potential of designed plant communities (DPC) for urban nature-based solutions (NbS).

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), subshrubs (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

Table 3 (*continued*)

Article	Place, methodology, and short description/ aim of research
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

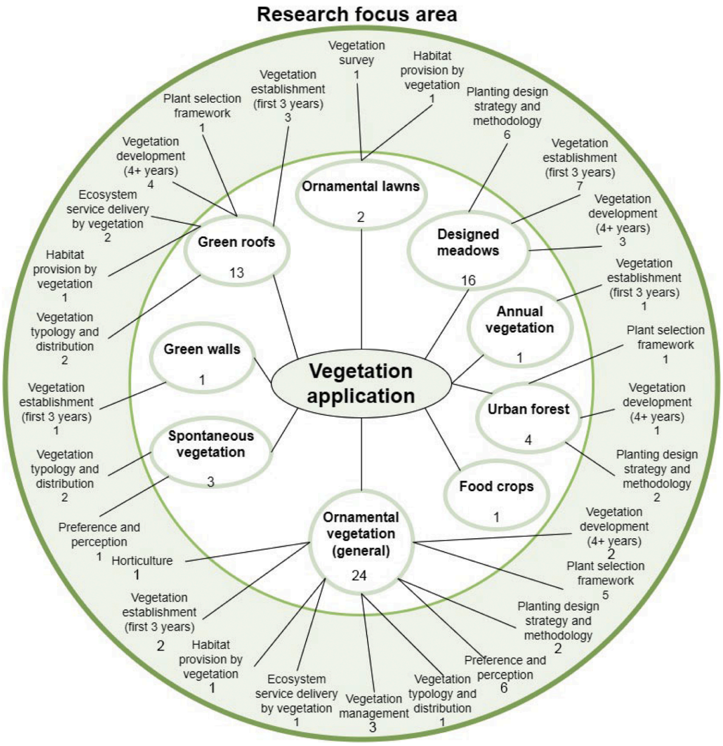

Fig. 4. Vegetation applications and research focus areas in the analyzed papers on designed plant communities.

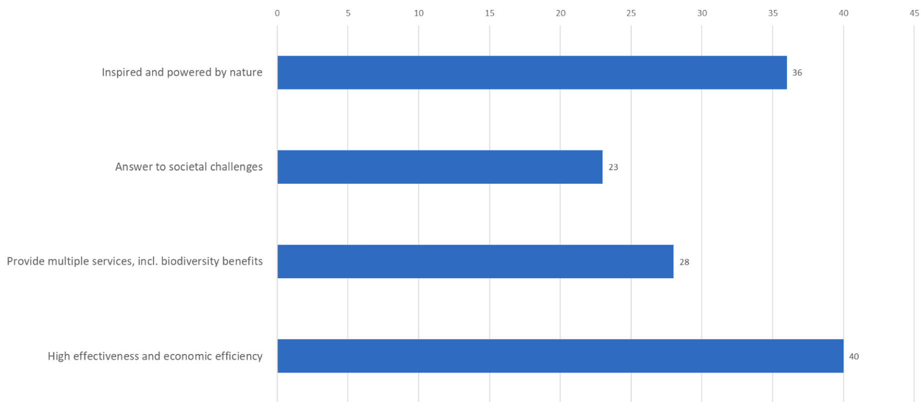

Fig. 5. Number of analyzed papers on designed plant communities (DPC) with results pertaining to the four criteria for nature-based solutions (NbS) (Sowińska-Świerkosz & García, 2022).

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:

Ella Uppala reports financial support was provided by Ramboll Foundation. Ella Uppala reports financial support was provided by Ramboll Sweden AB. Ella Uppala reports financial support was provided by Maiju ja Yrjö Rikalan puutarhasäätiö. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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Vegetation is the prerequisite for nature-based solutions such as urban rain gardens. This thesis investigates the relevance of designed plant communities as a framework for designing and managing rain garden vegetation. As realized performance is more important for NbS than adherence to specific design methods, the DPC-framework needs to be developed into an evidence-based planting design practice to improve design outcomes and thus the framework's relevance for NbS.

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SLU generates knowledge for the sustainable use of biological natural resources. Research, education, extension, as well as environmental monitoring and assessment are used to achieve this goal.

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