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Trait-based approaches for understanding how biodiversity generates sustainable benefits in urban vegetated green infrastructure

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While it is appreciated that the biodiversity within vegetated green infrastructure generates ecosystem services that improve the well-being of urban residents, advances in urban sustainability are hindered because we lack a solid mechanistic understanding of how biodiversity provides these services. Here, we outline a trait-based urban ecology agenda for researching how species' traits provide ecosystem services (trait-service relationships) in tandem with how species with desired service-providing traits establish in vegetated green infrastructure (community assembly). Because trait-service relationships and community assembly processes can differ in urban versus natural environments, this agenda will fill major knowledge gaps of how biodiversity promotes urban sustainability. Results from our research agenda can be implemented by planners and managers to enhance service provisioning and ultimately improve urban sustainability.

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Introduction

Vegetated green infrastructure (VGI) is an essential ingredient for sustainable urban systems [1]. VGI encompasses the multitude of urban greenspace types within a city, both engineered and natural, including forest remnants, vacant lots, city parks, rain gardens, green roofs, and residential yards [2]. The vegetated component of VGI can provide benefits to humans (*sensu* [3]) through ecosystem services such as urban heat-island mediation [4], mitigating stormwater runoff [5], crime reduction [6], carbon sequestration [7], biodiversity conservation [8], esthetic improvements [9], and improvements to human mental and physical health [10,11], among others. VGI promotes urban sustainability in part by generating services directly where they are consumed to support the health and well-being of urban residents [12]. The benefits provided by ecosystem services enhance multiple dimensions of sustainability, including reducing resource consumption, efficiently removing waste, and improving human capital [12–15].

Across the urban landscape, the individual green elements that comprise the VGI network can be represented as ecosystem service providing units (SPUs) — the smallest physical unit that provides an ecosystem service and can be planned and managed [16,17]. While all SPUs, both natural and engineered, provide ecosystem services, some are explicitly designed with a specific ecosystem service in mind, such as mitigating stormwater runoff [18] or esthetics [19]. However, the presence of vegetation alone within an SPU does not guarantee the delivery of a particular service. Rather, the type of ecosystem service, as well as its quality and strength are determined by the biodiversity of the vegetation and other species present in the SPU [20]. This recognition of the importance of biodiversity for providing benefits rather than solely being a benefit itself is a recent paradigm shift that promises to accelerate sustainability science [21,22]. Despite this revelation, we lack sufficient mechanistic understanding of exactly how and when biodiversity generates the ecosystem services that support sustainable urban systems.

Investigating the mechanistic role of biodiversity in generating ecosystem processes, functions, and services has been a major focus of ecological research for the past three decades [23–26]. From these studies, several important revelations have emerged that are relevant to the planning of sustainable VGI. First, in general, *biodiversity* refers to the diversity of life forms in a given area and is often represented by the taxonomic dimension of biodiversity, that is, species diversity. However, it is more effective to consider the functional dimension of biodiversity when studying biodiversity–ecosystem service relationships by considering species in terms of their functional traits, that is, the physical, morphological, phenological, physiological, and so on, characteristics of a species' phenotype that determine species' responses to environmental conditions and/or effects on ecosystem functioning [27,28]. In particular, species' functional *effect* traits, such as size, color, growth rate, and so on, determine the degree to which a species contributes to an ecosystem service [29–31]. For example, floral color is an effect trait that contributes to the delivery of esthetic ecosystem services [9], whereas leaf shape, surface area, and surface characteristics influence a species' ability to provide air quality improvement services [32]. Second, the role of biodiversity, in the form of functional effect trait diversity, in supplying single ecosystem services, is inconsistent and might vary across services (e.g. [33]). However, functional effect trait diversity appears to be more consistently associated with the ability of SPUs to provide *multiple* services simultaneously, that is, multifunctionality [34,35]. Finally, while species' functional effect traits determine the degree to which they provide an ecosystem service, it is species' functional *response* traits that determine their tolerance to environmental conditions and disturbances. Biodiversity in the form of functional response trait diversity is needed for ecosystem service resilience in the face of disturbances created by global change [36,37].

Given the complexity of biodiversity's role in generating ecosystem services, we recommend a focused ecological research agenda to better elucidate the linkages between biodiversity and sustainability. The ultimate goal of this research agenda is to generate actionable results that can be implemented by planners and managers to advance the sustainable delivery of ecosystem services and their benefits to citizens via biodiversity in VGI. We advocate focusing on relationships between functional effect trait diversity and single ecosystem services first, then layering on inquiries of resilience and multifunctionality. The crux of our research agenda to understand how functional traits provide ecosystem services in VGI is investigating trait-service relationships and community assembly in tandem. *Trait-service relationships*, also referred to as trait-benefit relationships (e.g. [38]), describe the mechanistic links between certain effect traits and the ecosystem services and downstream benefits they provide to citizens. Since many of these relationships still need to be studied, identifying them is crucial for planning and managing VGI to provide desired ecosystem services [34,38]. *Community assembly* is the collection of processes by which species arrive and establish in VGI [39–41], and in urban systems, these processes may be partially or completely controlled by humans. Once these processes are identified, managers may be able to modify them to attract and sustain species with particular effect traits needed to deliver desired benefits [42,43].

Despite their interrelatedness and clear relevance to urban VGI, trait-service relationships and community assembly are often studied independently, and usually in natural or rural ecosystems [39–41,44]. By considering them in tandem in urban VGI, we believe significant advances in urban sustainability science are possible that can then be implemented by planners and managers. In addition, once these relationships and processes have been identified, questions regarding ecosystem service resiliency and multifunctionality can be addressed. Below, we provide an overview on trait-service relationships and community assembly research in the context of acquiring species with desired service-providing traits into VGI. We describe how insights from this research can be implemented to generate targeted, resilient, and multifunctional VGI. Our focus is primarily on plant species since they are well-studied, provide numerous benefits, and form the foundation for VGI ecosystems, though avenues for incorporating higher trophic levels are discussed in the conclusion.

Trait-service relationships in vegetated green infrastructure

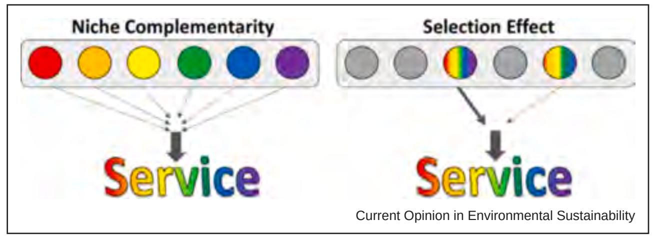
It is well-accepted that species' effect traits provide ecosystem services in general [34], and identifying exactly which traits provide specific services is an active research area (reviewed in [30]). For example, in an experiment to identify the effect traits associated with the ecosystem service of rainwaterinterception capacity, candidate plant traits such as height, leaf inclination angle, leaf area index, diameter, biomass, and so on, were manipulated and plants were subjected to simulated rainfall [45]. Measurements of waterstorage capacity following the rainfall simulation in this experiment indicated that plant biomass was the trait that best indicated rainwater interception capacity [45]. Similar approaches have examined how effect traits such as plant size, morphology, vegetation structure, flowering, and color influence human visual preferences in the provisioning of cultural ecosystem services (summarized in [24]). While numerous trait-service relationships have been studied [23,24], many linkages have yet to be unraveled and more studies are needed that directly assess relationships between several candidate effect traits and a focal service to determine which trait(s) is associated with the service. Future studies can employ methods of testing several candidate traits, keeping in mind that desired services may be provided by multiple traits. At the minimum, studies should identify the direction of correlations between effect traits and the services they provide. However, studies should ideally quantify the magnitude of a service provided by particular trait values to facilitate the parameterization of trait-service models for planning purposes. When enough studies have been conducted in varying contexts, consistent trait-service relationships will emerge that can be compiled (e.g. [23,24]) and applied to urban systems (e.g. [38]).

Given the naturally dynamic nature of traits, experimental identifications of plant effect traits related to ecosystem services should be coupled with explorations of trait variation across space and time in urban systems [46]. Spatiotemporal trait variation within a species may generate drastically different trait values that influence the supply of an ecosystem service. For example, seasonal changes in foliage color can affect residents' perception of the esthetics of urban greenspace vegetation [47,48]. In addition, the potentially strong selective pressures in urban environments may result in evolution of functional effect traits as species adapt to urban conditions over time, yet examples of this are scarce and more work is needed to uncover the prevalence of evolutionary processes in urban areas [49,50]. Finally, it is important to consider that even in the absence of trait variation, there is context dependency in the links between traits and ecosystem services, such that in some contexts, effect traits may contribute to a service, whereas in other contexts, they do not [16]. Understanding how the spatiotemporal components of trait variation across an urban landscape and how traits are related to services in various contexts affect the generation of ecosystem services is needed for the design and management of SPUs.

Although a necessary starting point, simply identifying traits related to ecosystem services is not sufficient to facilitate sustainable management and design of SPUs. Once traits are identified, the next challenge is to determine how the traits of individual species scale up to provide ecosystem services at the level of the biological community within an SPU [34,44]. In general, two main mechanistic relationships, derived from biodiversity and ecosystem- functioning literature, underlie most ecosystem services at the community level: niche complementarity and the selection effect (Figure 1) [51]. Under *niche complementarity*, the level of ecosystem service provided scales with trait diversity, meaning the more diversity of a trait that is present, the more service is provided. For example, gardens with a diverse array of plant growth form and floral colors are associated with a higher delivery of esthetic ecosystem services compared with gardens with single-growth forms and colors [9]. In comparison, for the selection effect, trait diversity is not needed to provide the ecosystem service, rather, a service can be provided by a single, optimal version of a trait. For example, plants in urban greenspaces provide the ecosystem service of crime reduction when they are present but do not obscure human-sight lines [52,53]. Therefore, crime-reduction services are provided by a single trait of short plant heights.

In urban areas especially, the associations between niche complementarity or the selection effect and a particular

Figure 1



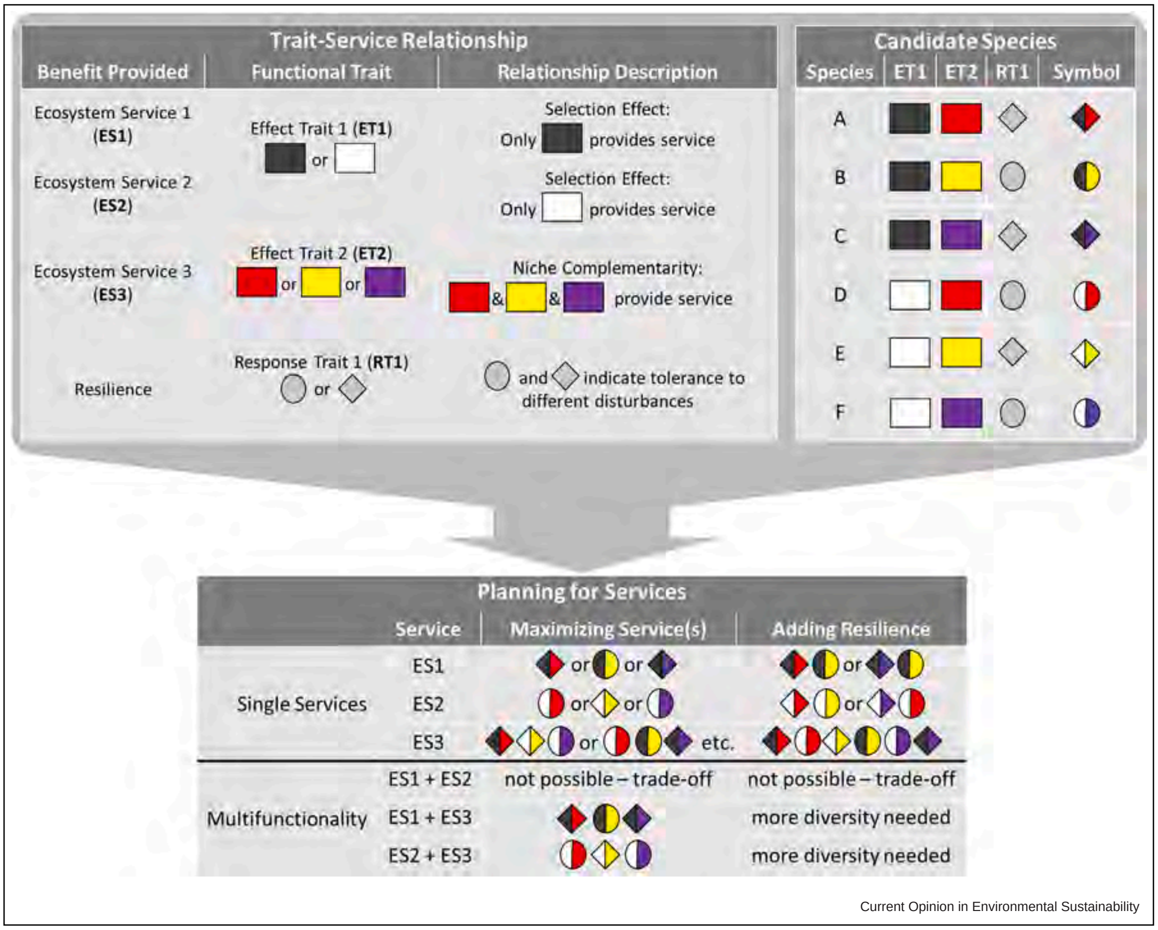
Two main mechanisms that underlie trait-service relationships: niche complementarity and the selection effect. Under niche complementarity, species (circles) have different traits (colors) and all traits are needed to supply the full ecosystem service. Without the suite of species and their diverse set of traits, the service is not supplied in its full capacity. For the selection effect, a single species can supply the entire service; species still vary in their trait values that contribute to the service (large arrow vs. small arrow) and may lack traits related to the service entirely (gray circles).

ecosystem service are not fixed and may be context-dependent. For example, in nonurban forests in Brazil, carbon sequestration was the result of niche complementarity, but in urban forests, it was due to the selection effect [54]. While in both forest types, wood density was the effect trait linked to carbon sequestration, there was a positive relationship between tree diversity and carbon sequestration in nonurban forests, but in urban forests, there was no relationship with diversity. Instead, carbon sequestration was provided by only a few dominant species with high wood densities [54]. In general, niche complementarity is thought to arise due to coexisting species partitioning resources [55]. As such, niche complementarity may be more prevalent in communities of species with a shared evolutionary history compared with the novel ecosystems more frequently found in urban areas [56], but this idea has not been thoroughly explored.

Understanding trait-service relationships will allow ecologists and planners to assess ecosystem services provided by existing SPUs and design future SPUs to deliver desired services. For planning purposes, it is possible to estimate the level of ecosystem services provided by the biodiversity within SPUs, so that species and traits can be augmented if needed to attain a desired level of a service (e.g. [57]). Services can be quantified using metrics on trait values such as the Shannon–Weiner diversity metric (niche complementarity) and community-weighted means of the trait values providing the service (selection effect) [38]. In cases where services are provided by multiple traits, weighting traits by their relative contribution to the service or selecting the most influential trait may be needed to effectively parameterize trait-service relationship models.

Quantifying the amount of a single service provided can allow planners to maximize the provisioning of that

Figure 2



Using species functional traits and trait-service relationships to plan for benefits from SPUs within vegetated green infrastructure. In this example, three ecosystem services (ES1–ES3) are provided by two effect traits (ET1&2) through specified trait-service relationships. ET1 contributes to ES1 and ES2, but in opposing directions, so that there is a trade-off between the two services. ET2 contributes to ES3 only. For example, ET1 could represent plant height that contributes positively to stormwater diversion (ES1) and negatively to crime reduction (ES2); ET2 could represent floral color that contributes to visual esthetics (ES3). Resilience is provided by the response trait (RT1) and the different shapes indicate tolerance to different disturbances such as drought or herbivory. Note, in other contexts, trait-service relationships may differ from the ones we present here. The two effect traits (represented as colors) and one response trait (represented as shapes) are found in varying combinations in 6 candidate species (A–F). Knowing the trait-service relationships and candidate species makes it possible to plan for each service. Planners can aim to maximize each service singly through species/trait selection, and add resilience to that single service by adding supplementary species with the same effect trait but different response traits. In addition, planners can maximize multiple services at the same time to plan for SPUs that provide multifunctionality. While adding supplemental species to enhance resilience of multifunctional SPUs is possible, in this example, the limited number of candidate species makes it impossible to add resilience, underscoring the role of functional trait biodiversity in supporting resilience and multifunctionality in SPUs.

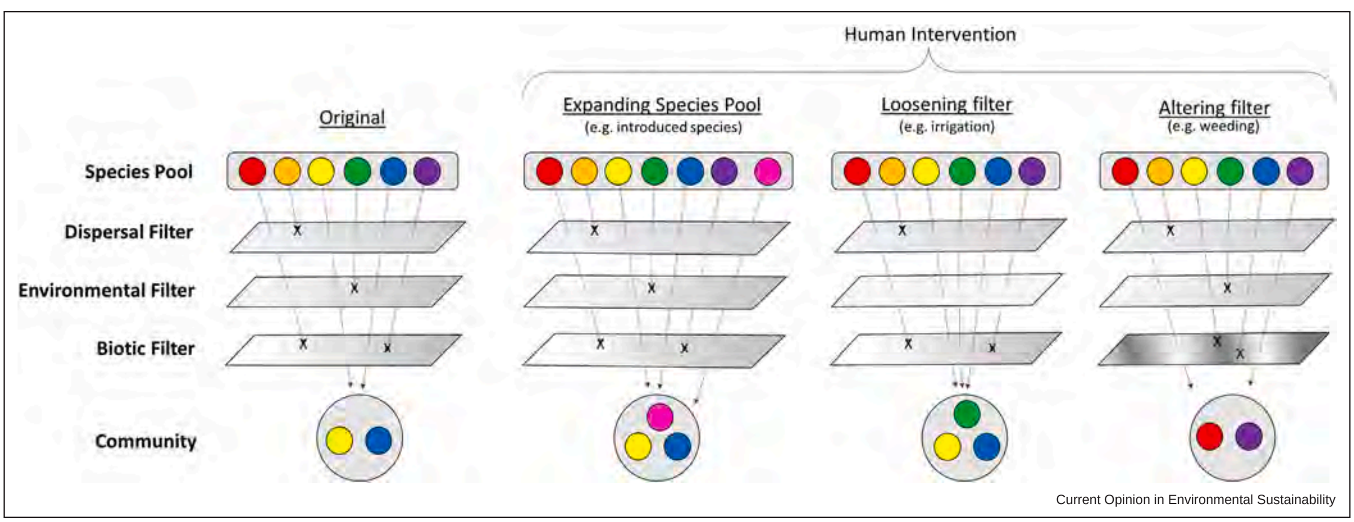
single service, plan for resilience in that service, and explore additional services, specifically multi-functionality provided by SPUs (Figure 2). Managing SPUs to be resilient and provide a continued supply of an ecosystem service in the face of disturbance and/or global change drivers is a major goal for urban VGI [58]. Since species' response traits determine their tolerance to disturbance, to have resilient SPUs that provide high levels of a single service, species with similar effect traits should have a diversity of response traits (Figure 2). Beyond single services, many SPUs provide multiple services simultaneously, and multifunctional SPUs may be critical for increasing the sustainability of VGI [59,60]. Multifunctionality is most easily obtained when the same trait value provides different ecosystem services. For example, the effect trait 'plant height' is positively associated with both stormwater diversion and heat-island mediation services [61], which facilitates the ability of SPUs to provide both services. Multi-functionality can also be obtained when species have different effect traits that contribute to different services such as tall plants with colorful flowers that provide both stormwater diversion and visual esthetic services (Figure 2). However, trade-offs among services can emerge when different values of the same trait are needed to provide individual services. While the traitplant height is positively associated with stormwater diversion, it is negatively associated with crime-reduction services [52,53,61], meaning both services cannot be delivered well by a single SPU (Figure 2). When trade-offs exist, managers need to prioritize ecosystem services based on stakeholder needs.

Elucidating trait-service relationships for a range of services across geographically disparate urban areas will greatly accelerate our understanding of the role of biodiversity in generating sustainable VGI. Understanding how consistently services are delivered by the selection effect versus niche complementarity will be invaluable for informing VGI planning and management. Once trait-service relationships have been identified, the next challenge is understanding how species with desired traits establish and survive in SPUs. By pairing trait-service relationship studies with explorations of community assembly, researchers can provide a holistic assessment of services provided by SPUs to inform the design and management of sustainable VGI.

Community assembly in vegetated green infrastructure

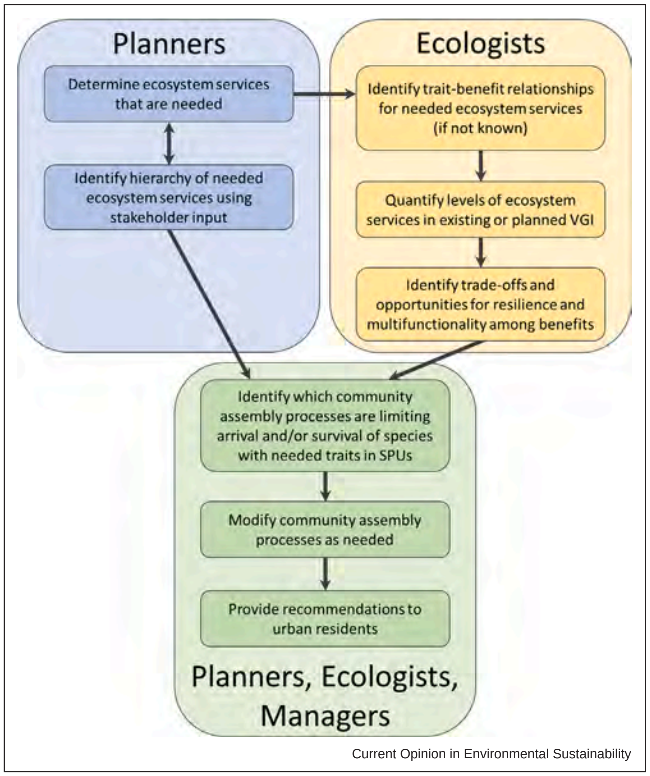
Community assembly is the collection of processes that determine which species arrive and establish in an SPU [41,62]. Specifically, according to community assembly theory, the species within an ecological community are the subset of a larger species pool that successfully passes through dispersal, environmental, and biotic filters (Figure 3) [63]. While community assembly is often not considered in the context of ecosystem services, communityassembly processes that act on species response traits determine how species arrive and persist in SPUs to provide services through their effect traits. Therefore, understanding community assembly processes is critical for planning ecosystemservice provisioning. Most community assembly research is from natural systems, which may have limited applicability to community assembly in VGI due to differences in species pool size, filter strength, and selectivity (Figure 3). As such, several frameworks have been developed recently to understand community assembly processes in urban systems and how humans are influencing them [39–41,64]. Humans influence urban community assembly directly by controlling what species are in VGI by planting species, and indirectly through activities that influence community assembly components in the urban environment, such as irrigation and mowing [65–67]. For SPUs where humans do not directly control what species are present and biodiversity arises spontaneously, such as forest remnants and vacant lots, modifying community assembly processes may be the only way managers can influence what species are present and in turn what ecosystem services are provided. Ideally, to achieve VGI that provides useful benefits and enhances urban sustainability, human activities should influence community assembly components to increase the likelihood of

Figure 3



Components of community assembly in urban vegetated green infrastructure. In the original context, the species (circles) and their traits (colors) in the final community are a subset of the regional species pool that successfully passes through dispersal, environmental, and biotic filters. An X indicates the failure of a species to pass through a filter, thus never reaching the community. Humans intervene in community assembly processes in a number of ways. Humans often expand the species pool by introducing species, which can add novel traits to a community beyond those possessed by the resident species (pink circle). Other human activities (e.g. irrigation) serve to loosen filters, which allows for more species to pass through the filter (lightened environmental filter), or alter the filter (e.g. weeding), which changes which species can and cannot pass through the filter (mottled biotic filter).

Figure 4



Flowchart showing roles of planners (blue) and ecologists (yellow) alone and together with managers (green), in planning, managing, and designing sustainable VGI to incorporate the role of biodiversity in providing desired benefits to humans in urban systems through ecosystem services.

certain species with desired traits to be in VGI [42,43]. Below, we describe how the four community assembly components — species pool, dispersal filter, environmental filter, and biotic interaction filter — affect the presence of species in VGI with effect traits that provide ecosystem services and how these components could be modified to enhance the presence of beneficial species in VGI.

Species pool

The species pool is a metaphorical concept, rather than a specific location, that encompasses all species that could plausibly be found in the focal community within an SPU and likely extends far beyond the urban political boundaries [41,63]. For example, for an SPU at the scale of a residential yard, the species pool includes the species in the surrounding SPUs that can disperse to the yard, as well as species available for homeowners to add to their yard from garden-supply centers or other sources [68,69]. For urban SPUs especially, humans expand species pools beyond the native species in the region to include non-native and ornamental species (Figure 3). Humans expand species pools with species that are often selected in a nonrandom manner with respect to their traits, which may be the traits that provide a desired ecosystem service, or traits unrelated to the service such as traits that influence cost, availability, and/or tolerance of conditions within the SPU [24,68]. When humans populate species pools based on traits unrelated to the desired services, it could result in weaker services being provided in the VGI than intended. For example, the species in the species pool compiled for stormwater VGI in Philadelphia, Pennsylvania, USA, were chosen based on their response trait of tolerating wet hydrological conditions, rather than effect traits that allow them to intercept rainwater and provide the benefit of stormwater mitigation [70]. As a result, the primary purpose of VGI to mitigate stormwater was not realized at full capacity, thus lowering the contribution of these areas to urban sustainability [38]. While it is clearly imperative to choose species with response traits that allow them to tolerate urban conditions within VGI, neglecting effect traits in planning can limit attaining sustainability goals. Understanding the factors that influence human decisions on species pools can identify possible barriers to increased sustainability.

Dispersal filter

As communities assemble, species must successfully disperse from the species pool to the focal community.

Barriers to dispersal — either natural or anthropogenic — can limit dispersal success and 'filter' out species from the species pool that may otherwise contribute to ecosystem services in joining the focal community [63]. Plant species arrive at urban SPUs through two main dispersal pathways: dispersal from the surrounding landscape and direct plantings by humans (i.e. a human-mediated form of dispersal). For species directly planted by humans, dispersal filters are circumvented, which can allow for the presence of service-producing species that are eliminated by strong dispersal filters such as geographic barriers or loss of animal dispersers. Circumventing dispersal filters can be an effective strategy for enhancing the resilience of SPUs and longevity of plantings when planners select species with response traits that tolerate predicted environmental changes, such as selecting and planting tree species predicted to withstand climate change [71]. Compared with directly planted species, for species that naturally disperse, dispersal to SPUs such as remnant forest patches may have occurred long before the region was developed into an urban landscape. Dispersal filters may be changed by the urban landscape and human actions often create tighter dispersal filters that eliminate service-providing species [72,73]. In particular, patches in urban landscapes may be too distantly spaced and unreachable for wind-dispersed species to successfully disperse [74] and the urban environment may disrupt animal dispersers [75]. Alternatively, some species such as *Ailanthus altissima*, a globally invasive tree species, have wind-dispersed seeds that disperse better on smooth concrete relative to other substrates [76]. For service-providing species that are excluded by dispersal filters, strategies are being devised to improve patch connectivity, restore animal dispersers, or circumvent dispersal altogether to maintain these species across VGI and enhance urban sustainability [73].

Environmental filter

The environmental filter encompasses the abiotic conditions that species must survive following dispersal to the SPU and may include broad-scale factors such as climatic conditions, or finer-scale SPU-specific conditions, such as soil nutrient concentrations [41]. Urban ecosystems are often regarded as having strict environmental filters due to conditions such as the heat-island effect, contamination, and altered hydrology [64,77]. However, management interventions such as fertilization and irrigation can also loosen environmental filters (Figure 3) [69,78]. For example, in the Sonoran Desert ecosystem in Phoenix, Arizona, USA, irrigation loosens the strong abiotic filter of water availability, resulting in higher plant diversity in irrigated greenspaces [78]. Whereas in residential yards in the Minneapolis–St. Paul Metropolitan area, Minnesota, USA, fertilizer addition was associated with an increased diversity of cultivated species but decreased diversity of spontaneous species [69]. Since management interventions such as fertilization and irrigation are often unsustainable and costly, identifying how plant communities and associated ecosystem services change in their absence is necessary for planning sustainable VGI. In urban SPUs, environmental filters, and thus plant community composition and effect traits, may vary substantially between managed and unmanaged VGI even at a small spatial scale [77,79]. More sustainable modifications of the environmental filter to enhance total biodiversity to help support resilience and multifunctionality may include increasing habitat heterogeneity within SPUs through nutrient patchiness [80,81], or disturbances such as mowing [67].

Biotic interaction filter

Finally, species must also survive the biotic conditions to persist within SPUs. Biotic interactions such as competition, seed predation, pollination, and herbivory, among others, may serve as biotic filters for species within SPU communities. There are countless examples of humans modifying biotic filters in a way that eliminates beneficial species through the facilitation of competitors and herbivores or elimination of pollinators (reviewed in [82]). However, facilitating species interactions aimed at allowing particular beneficial species to persist or biodiversity to flourish is a promising avenue [83], especially if it reduces the need for human intervention, making SPUs more sustainable. For example, plantings of *Sedum album* on a green roof facilitated the growth of other species during drought conditions [84]. Recent evidence suggests that in addition to planted species on green roofs, facilitation also occurs among spontaneous vegetation in urban-vacant lots [85]. More work is needed to determine the extent to which facilitation among spontaneous vegetation species promotes the presence of service-providing species rather than invasive species that provide ecosystem disservices.

Integration and implementation

Designing VGI that fully leverages the capacity of biodiversity to provide sustainable benefits to humans will be a multidisciplinary undertaking that requires collaborations between ecologists, planners, and managers (Figure 4) [86,87]. To implement the agenda we have outlined here, we recommend integrating trait-service relationship and community assembly research within a planning context. First, we suggest planners identify the hierarchy of benefits needed in an urban area. In addition, planners should seek resident feedback on benefit rankings to ensure equitable representation and distribution of benefits [88]. Second, ecologists can identify trait-service relationships for the prioritized benefits and quantify the relative magnitude of services provided in existing or planned SPUs. While it is possible for VGI to provide multifunctionality, trade-offs may prevent this for certain combinations of services [44,60]. During this step, ecologists can determine the extent that multi-functionality is possible, if desired, based on trait correlations [38,44]. Third, ecologists can work with planners and managers to determine which components of community assembly are limiting the establishment and survival of species needed within VGI based on the trait-service relationship assessments. Finally, ecologists, planners, and managers can collaborate to modify community assembly components as needed to acquire the necessary species in VGI. Since the species pool, dispersal filter, and some environmental filters often operate at scales greater than a single SPU, a regional management approach will likely be needed to modify these components. Whereas for smaller-scale environmental and biotic filters operating at the scale of the SPU, local modifications within the SPU rather than regional-scale changes should be sufficient for securing the establishment of desired species.

While this agenda was devised for an audience of researchers, planners, and managers to advance the science behind urban ecosystem services, future results regarding validated trait-service relationships and community assembly approaches should be shared with urban residents and the general public so that they, too, can make informed decisions on their own SPUs to contribute to urban sustainability. This is especially important, given that in some cities, residential yards comprise a significant proportion of the total urban greenspace [89]. We suggest maintaining a dialog with residents and policymakers to understand the needs, preferences, and limitations of stakeholders, as well as providing useful information to inform policy. Programs that educate and recruit residents to plant and facilitate the establishment of service-providing species may be particularly effective for regional-scale management of urban VGI [90–92].

Although we focus on plants, the biodiversity in higher trophic levels also supplies benefits such as seed dispersal [75], disease dilution [93], and esthetic improvements [94], among others. Since humans have less capacity to manage mobile and undomesticated species in these higher trophic levels, understanding community-assembly processes becomes even more important to attain desired species in VGI Swartz et al. *unpublished data*. While some SPUs, such as pollinator gardens, are created with these higher trophic levels in mind, trait-based approaches to understanding the benefits animals provide at the community scale are scarce [23].

Finally, trait-based approaches to planning will ensure that the species with the needed traits are present to deliver desired benefits. Yet, because VGI comprises a dynamic complex ecosystem with traits that shift and evolve and with interconnections that extend well-beyond urban political boundaries, adaptive and iterative planning and management strategies are needed to maintain benefits as conditions naturally change. Of course, the full scope of benefits provided by VGI within an urban area is dependent on many factors, not the least of which is cost. As some management strategies may be cost-prohibitive, alternative management approaches may be useful, such as urban rewilding, an approach to increase urban biodiversity that minimizes human interventions [96], or reframing benefits to use the species that are already present [97]. To that end, finding the least intensive and economical management practices that result in desired benefits may help increase urban sustainability. As urban centers employ creative interdisciplinary solutions unique to their conditions, significant advances in urban sustainability through VGI can be made.

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CRediT authorship contribution statement
Jocelyn E. Behm: Conceptualization; Writing – original draft preparation; Writing – review and editing. **Nadège Bélouard**: Conceptualization; Writing – review and editing. **Jason M. Gleditsch**: Conceptualization; Writing – review and editing. **Payton M. Phillips**: Conceptualization; Writing – review and editing. **Timothy M. Swartz**: Conceptualization; Writing – review and editing.

Declaration of Competing Interest

The authors 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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- • of special interest
- •• of outstanding interest.

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