Urban Forestry & Urban Greening 49 (2020) 126635

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Green infrastructure space and traits (GIST) model: Integrating green infrastructure spatial placement and plant traits to maximize multifunctionality

Tyler J. Tran, Matthew R. Helmus, Jocelyn E. Behm*

Integrative Ecology Lab, Center for BioDiversity, Department of Biology, Temple University, 1925 N 12th Street, Philadelphia, PA 19122, USA

ARTICLE INFO

Handling Editor: Tenley Conway

Keywords:
Green infrastructure spatial placement GISP model
Green stormwater infrastructure
Philadelphia
Plant functional traits
Urban ecosystem services
Urban vegetation

ABSTRACT

Vegetated green infrastructure (GI) is used as a sustainable complement to traditional stormwater infrastructure in many cities and is reported to provide additional benefits such as heat island mediation, crime reduction, increased property values, improved air quality, improved human well-being, improved aesthetics, biodiversity conservation, and carbon sequestration. However, we hypothesize that the simultaneous provisioning of multiple benefits – multifunctionality – is not guaranteed yet may be achieved by planning two critical components of GI: the spatial placement of GI within a city and the traits of the plant species used to vegetate GI. We propose the Green Infrastructure Space and Traits (GIST) model, a new planning tool for evaluating and maximizing GI multifunctionality based on optimizing both site selection and plant traits in GI design to promote urban planning with higher sustainability and benefits to humans. GIST involves identifying priority areas for GI placement and using plant species with traits that maximize benefits and multifunctionality in priority areas. As a case study, we apply GIST to Philadelphia, USA, and identify new locations for GI and plant traits that would increase multifunctionally across the city. For the nine benefits we examined, GIST indicates high potential for multifunctionality for the Philadelphia GI system. An assessment of the GI planning in Philadelphia to date indicates that the actualization of this multifunctionality has not been fully realized and could be improved with strategic GI placement and plant species selection. Further, we identified a cluster of correlated benefits which may be a common pathway for multifunctionality across cities. Overall, our work supports the hypothesis that multifunctional GI is possible when proper planning tools that integrate spatial placement and plant traits are used.

1. Introduction

The sustainable management of stormwater is a major ecological and planning challenge for urban governments (Brabec et al., 2002; Seto et al., 2012). Many older cities, especially in the northeastern US, have combined sewer systems that use the same plumbing for both sewage and stormwater. During large rain events, the combined sewer infrastructure can be overloaded beyond capacity, resulting in raw sewage flowing into waterways, impacting ecosystems and human health (Fong et al., 2010; Vazquez-Prokopec et al., 2010). An emerging sustainable strategy is to update traditional stormwater infrastructure with green infrastructure (GI) that diverts stormwater from sewers and allows it to more slowly percolate into the water table and be transpired by vegetation (Madden, 2010).

GI installations used for controlling stormwater are often vegetated in the form of rain gardens, green roofs, bioswales, and street-tree trenches, and form a patchwork of greenspace throughout a city. While GI is often implemented to provide the benefit of stormwater diversion, the vegetated layer allows it to provide other benefits simultaneously, i.e. multifunctionality, including urban heat island mediation (Cameron et al., 2012), crime reduction (Kondo et al., 2015), increased property values (Voicu and Been, 2008), improved air quality (Nowak et al., 2006), improvements to human well-being (South et al., 2018), aesthetic improvements (Tzoulas et al., 2007), biodiversity conservation (Kazemi et al., 2011), and carbon sequestration (Nowak and Crane, 2002). However, multifunctionality is not guaranteed and trade-offs among benefits may occur if different benefits are contradictory due to the spatial placement of GI within the city or the traits of plants used to vegetate GI (Rodríguez et al., 2006; Bennett et al., 2009; Mouchet et al., 2014).

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* Corresponding author at: 1925 N 12th Street Philadelphia, PA 19122, USA.
E-mail addresses: tylerjtran@gmail.com (T.J. Tran), mrhelmus@temple.edu (M.R. Helmus), jebehm@temple.edu (J.E. Behm).

https://doi.org/10.1016/j.ufug.2020.126635
Received 12 April 2019; Received in revised form 6 February 2020; Accepted 10 February 2020
Available online 13 February 2020

Spatial trade-offs in GI benefits result from spatial variation in the capacity of areas within a city to provision single benefits; an area that provides one benefit well may not provide another benefit well. In contrast, some areas may provide multiple benefits simultaneously. If planners optimize spatial placement of GI, multifunctionality may be possible (Bodnaruk et al., 2017; Dagenais et al., 2017; Meerow and Newell, 2017). For example, Meerow and Newell (2017) created the Green Infrastructure Spatial Planning model (GISP) intended for planners to identify areas within a city that best provide single benefits and multifunctionality. Application of the GISP model to Detroit, USA, revealed spatial trade-offs between habitat connectivity for biodiversity and stormwater diversion, urban heat island mediation, and air quality improvements (Meerow and Newell, 2017). Using GISP, they assessed the planning of GI in Detroit and conclude that GI is neither spatially configured to maximize multifunctionality, nor does Detroit's GI configuration optimally provide any single benefit except greenspace access (Meerow and Newell, 2017).

In contrast to the spatial placement of GI, the benefits provided by the vegetated layer of GI are determined by the traits of the plant species used. Because plant species vary in their traits, species can exert differing influences on benefits assuming, of course, there is sufficient abundance of the species present at a GI site. Trade-offs in benefits can arise due to conflicts in how certain plant traits confer individual benefits. For example, maximizing the trait 'plant height' can maximize the benefit of stormwater diversion for GI (Lundholm et al., 2015), yet might minimize the benefit of crime reduction or perceived safety (Ahmad et al., 2014). Planners can optimize the traits of the plant species used to vegetate GI to ensure intended benefits are provided, yet models guiding planning decisions that incorporate plant traits are lacking. Our study provides a novel tool for incorporating plant traits with spatial planning to maximize multifunctionality.

Here, we hypothesize that multifunctionality can be achieved more readily when both spatial placement and plant traits are included in GI planning decisions. We present the Green Infrastructure Space and Traits model (GIST) to maximize multifunctionality in GI implementation to help planners and designers maximize multiple benefits and provide a construct on which future GI research can expand. The goal of the GIST model is to maximize GI multifunctionality through spatial placement and plant traits by i) arranging the spatial placement of GI to maximize multifunctionality; and ii) selecting plant species with traits that ensure maximal multifunctionality (Fig. 1). The GIST model leverages recent work on relating plant traits, rather than specific plant species, to multifunctional benefits of GI (Lundholm et al., 2015; Cameron and Blanuša, 2016) and uses methods from the field of functional ecology to estimate the magnitude of those benefits (e.g., Lavorel et al., 2011; Storkey et al., 2015). Most work on plant traits and GI has focused on biological benefits, but social benefits are also generated by plant traits. GIST emphasizes how different plant traits affect multifunctionality and allows for better GI planning.

As a case study, we focus on Philadelphia, USA, a leader in using GI to mitigate stormwater runoff into its combined sewer infrastructure (Madden, 2010). Though the primary reason for the GI program is stormwater diversion, GI in Philadelphia yields multiple benefits (Brears, 2018); we consider urban heat island mediation, crime reduction, increased property values, improved air quality, improvements to human well-being, aesthetic improvements, biodiversity conservation, and carbon sequestration. We first develop the GIST model and apply it to Philadelphia to identify the potential for multifunctionality: areas where spatial placement of GI and combinations of plant traits would maximize single benefits and multifunctionality. We then assess the planning of existing GI for single benefits and multifunctionality in Philadelphia. Because Philadelphia's GI initiative was created to address stormwater issues, we test whether there was an active selection process in GI placement and plant traits oriented toward stormwater diversion. Finally, to determine how multifunctionality in Philadelphia GI can be improved, we examine the underlying structure of the multifunctionality as to whether it is dominated by single benefits or a more even representation of multiple benefits.

2. Methods

2.1. The Philadelphia GI system

Philadelphia, the sixth most populous city in the United States, is situated in the center of the northeast megalopolis, and is dealing with aging infrastructure amidst modern development (PWD, 2019). Its combined sewer system serves a municipality that is predominantly impervious surface (54 % of the land area) (PWD, 2019). In fiscal year 2018, nearly 12.5 billion gallons of stormwater and raw sewage overflow discharge entered the region's main rivers, the Delaware and the

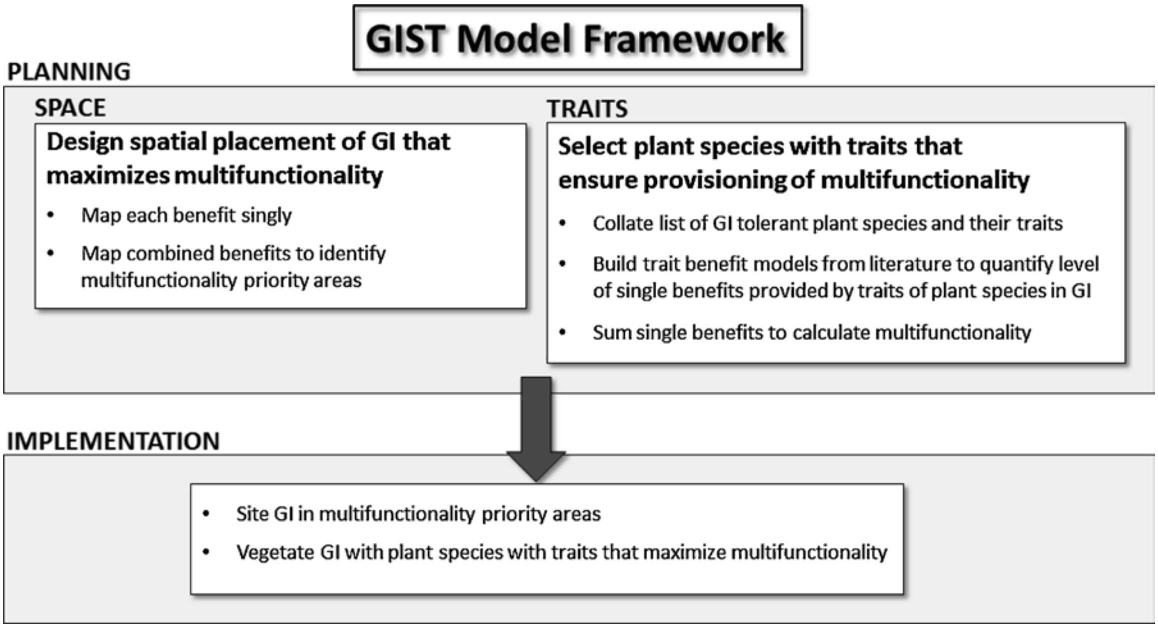

Fig. 1. Green infrastructure space and traits (GIST) model framework for urban planning that considers spatial placement and plant traits of GI to maximize multifunctionality.

Schuylkill, that provide drinking water to residents (PWD, 2018). In 2011, the Philadelphia Water Department (PWD) launched the Green City, Clean Waters initiative to reduce runoff by 85 % in 25 years in large part by increasing GI (PWD, 2019).

From the PWD, we obtained a spatial dataset of the size and location of GI in Philadelphia comprising both vegetated and non-vegetated GI, specifically, stormwater basins, curbside bumpouts, green roofs, stormwater planters, rain gardens, bioswales, tree trenches, wetlands, stormwater trees, cisterns, and pervious pavement. For our spatial GIST analyses (Fig. 1), we excluded non-vegetated GI because the benefits we assessed depend on vegetation, yielding a total of 1129 GI sites. For a subset of these sites (n = 137), PWD provided additional data in the form of recent vegetation surveys from 2015 to 2017 that reported species identification and the percent cover of each plant species. For the full dataset (1129 GI sites), we know the sites are vegetated, but not with what species or plant traits, therefore we use this full dataset in only the spatial component of GIST (Fig. 1). Because the vegetation survey data (137 GI sites) provides species information for which traits can be identified, we used this smaller vegetation survey dataset for the analyses in the trait component of GIST (Fig. 1).

2.2. GIST model: spatial placement of GI to maximize multifunctionality

The spatial component of the GIST model is similar to the GISP model created by Meerow and Newell (2017) that quantifies and maps the relative magnitudes of benefits across a city in order to identify where GI should be located. To be clear, the goal of the model is not to quantify the contribution of existing GI to the levels of any particular benefit. Although these assessments of the efficacy of GI are important, they are conducted after the planning stage. We describe the main components of GISP here, but please refer to Meerow and Newell (2017) for exact details. Because areas of cities vary in how well they provision certain benefits, planning for the spatial placement of GI to maximize single benefits and *multifunctionality* (see Table 1 for definitions of italicized GIST terms) can be guided by using a *placement model* that indicates where GI should be sited. For single benefits, *equity-based placement models* guide GI site selection to maximize single benefits by placing GI in areas where the benefits are in deficit (Table 2) (Locke et al., 2010; Heckert and Rosan, 2016; Meerow and Newell, 2017). For example, locations with the highest runoff coefficient, most impervious surface, or that drain to sewer overflow outputs constitute areas where stormwater diversion is in deficit and an equity-based placement model would select these areas for GI (Locke et al., 2010; Meerow and Newell, 2017). Note that for our implementation of GIST we use ‘equity’ in a purely spatial sense assuming an equal distribution of benefits among locations is the ideal goal (Truelove, 1993). However, other factors, including value-driven components of equity, can be included into equity-based placement models if not all benefits are deemed beneficial to all residents (Heckert and Rosan, 2016). Equity-based placement models are appropriate for many single benefits and are applied to maximize all single benefits in our study (Table 2).

In contrast to equity-based models, *complementation-based placement models* maximize a single benefit by adding GI to areas where the benefit is already abundant under the assumption that ‘bigger is better.’ For biodiversity conservation, there is support for both equity-based and complementation-based approaches to maximize the benefit (Taylor et al., 1993; Colding, 2007). There is an ongoing debate termed the single-large-or-several-small debate (e.g., Burkey, 1989), over whether biodiversity is enhanced more by creating fewer large habitat patches or more smaller patches. Smaller patches enhance habitat connectivity and increase the biodiversity in that particular location however, biodiversity is typically highest in large habitat patches, because larger patches often contain higher quality habitat that supports sensitive species (Fahrig, 2013). Indeed, habitat connectivity and patch size are strong predictors of biodiversity in human-dominated urban areas (Goddard et al., 2010; Beninde et al., 2015), including novel habitat types that urban green spaces like GI may provide (Sandström et al., 2006; Uno et al., 2010; Wang et al., 2017). For GI planning, we term these two contrasting placement models biodiversity-complementation (i.e., adding GI to make existing GI larger, increasing patch size) vs. biodiversity-equity (i.e., placing GI in areas without existing GI, increasing connectivity).

For each benefit, GIST uses a placement model to first map *priority areas* for single benefits, and then determines priority areas for

Table 1
GIST Model metrics and their definitions.

	GIST Metric	Formula/ Definition
	Multifunctionality	When GI sites provide multiple benefits due to spatial overlap in priority areas for single benefits and/or single traits providing multiple benefits.
	Trade-off	Opposite of multifunctionality; when different benefits cannot be satisfied with the same solution. Can arise due to a lack of spatial overlap in priority areas for single benefits and/or when different benefits are maximized by different values of the same trait.
Space		
	Placement model	Model indicating priority of GI placement based on amount of benefit in an area unit (i.e., census tract in our study of Philadelphia). Placement models are used to calculate priority scores from condition scores.
	Equity-based placement model	Placing GI in areas where benefits are in deficit.
	Complementation-based placement model	Placing GI in areas where benefits are already abundant.
	Priority area	Location identified through placement model where a single benefit or multifunctionality would be increased from GI installation.
	Priority score	Score for each area unit calculated as a function of the condition score and placement model. Areas with high priority scores are high priority for GI installation under GIST.
	Multifunctionality priority score	Sum of all priority scores within an area unit, scaled between zero and 1.
	Condition score	Score for each area unit indicating magnitude of benefit. Can be calculated as a relative value from factors that affect benefits from publicly available datasets, or a more exact value from detailed datasets of the benefit. Higher scores indicate higher benefit potential.
	Spatial-benefit score	Score for each GI site calculated as the product of the area unit priority score and the log-transformed area of GI site.
	Spatial-benefit multifunctionality score	Score for each GI site calculated as the sum of all spatial-benefit scores within that GI.
Traits		
	Trait-benefit model	Models derived from relationships between plant traits and benefits reported in the literature developed in GIST and used to estimate the strength of the benefits derived from plant trait values.
	Trait-benefit score	Score for each GI site calculated using trait-benefit model applied to traits of plant species present in GI weighted by the percent cover of that species and the total area of the GI. Higher trait-benefit scores indicate higher benefits provided.
	Trait-benefit multifunctionality score	Score for each GI site calculated as the sum of all trait-benefit scores within that GI.

Table 2
Spatial placement and plant trait considerations to maximize single benefits.

Benefit	Spatial placement to maximize benefit	Documented trait-benefit relationships
Stormwater diversion	Areas with high impervious area[1] Areas with high runoff coefficient[1, 2] Areas draining to high volume of combined sewer overflows[2]	Plant height (+)[3] Leaf size traits (+)[4–6] Canopy density (+)[7] Stomatal conductance (+)[7] Phenology: summer active (+)[7] Species richness (+)[8–10]
Heat island mediation	Areas with high land surface temperature[1, 2]	Plant height (+)[3] Leaf size traits (+)[3, 11] Species richness (+)[9–10]
Crime reduction	High crime areas[1]	Plant height (+/-)[12–16] Naturalness (-)[16] Understory density (-)[16] Canopy density (+)[16] Species richness (-)[12]
Increased property values	Low property value areas[1]	Plant size (+)[17, 18] Height range (+)[17, 18]
Improved air quality	Areas of poor air quality[1]	Plant size (mostly +)[19] Leaf size traits (+)[19–21] Plant VOC emissions (-)[22] Species richness (+)[9–10]
Improved human well-being	Areas with poor health ratings[1]	Colorfulness (+)[23] Growth form (categorical)[24, 25] Species richness (+)[26]
Aesthetic improvements	Aesthetically-lacking areas	Colorfulness (+)[24] Growth form (categorical)[24, 25] Flower size (+)[24, 27] Leaf size traits (+)[24] Leaf N (+)[7] Leaf toughness (+)[7] Bloom time length (+)[17]
Biodiversity conservation	Areas with large habitat[1] *or* Areas lacking habitat to increase connectivity[2]	Colorfulness (+)[28] Flower size (+)[29] Floral reward (+)[29] Flower abundance (+)[29] Bloom time length (+)[29] Height range (+)[30] Species richness (+)[30]
Carbon sequestration	N/A	Plant height (+)[31] Leaf size traits (+)[31] Late flowering (-)[7] Bloom time length (+)[7, 31] Canopy density (+)[7] Species richness (+)[9, 32]

See Appendix A for references.

multifunctionality using the overlapping priority areas from the mapped single benefits. Priority areas are those area units (e.g., census tracts) with the highest *priority scores* for a benefit across a city, and *multifunctionality priority scores* are the sum of priority scores for all benefits in an area unit. To calculate priority scores, GIST applies a placement model to *condition scores*. Condition scores are the magnitude of a benefit present in an area unit; lower condition scores indicate a worse condition in an area unit for a benefit. Condition scores are often based on proxies, like impervious surface area, that influence the magnitude of each benefit and can often be calculated using publicly available data sources as many studies have done (Locke et al., 2010; Meerow and Newell, 2017) (see below). As such, the condition scores we calculate in GIST are estimates of the relative magnitude of a benefit for comparing across benefits for general planning purposes and should not be interpreted as exact measures of a particular benefit. In circumstances where planners have access to more comprehensive data sources, exact measures of benefits can be calculated and used in GIST. Under an equity-based placement model, area units with lower condition scores will have a higher priority score. For instance, a census tract with high proportion of impervious area (benefit proxy) would have a low condition score for stormwater diversion (benefit); the census tract's current condition is poor and should be prioritized for GI under an equity-based placement model (high priority score). For Philadelphia, we calculated condition scores at the census tract unit ($n = 384$), which was the finest spatial resolution across the available public data sets for each benefit.

We calculated condition and priority scores for seven benefits across Philadelphia (Table 2). For stormwater diversion, condition scores were calculated from the proportional area of impervious surface in census tracts as a proxy using high resolution ($1\ m^2$) land cover data (O'Neil-Dunne et al., 2013). Although areas draining to high-volume overflows and areas with high runoff coefficients have been used in other studies to evaluate conditions for stormwater diversion (Table 2), we used impervious surface area because it is a simple, but relatively accurate and common proxy (Keeley, 2007; Locke et al., 2010) and of the three proxies, these data are most readily available across other cities where GIST can be applied. Heat island mediation condition scores were calculated using the mean of three Landsat 8 thermal images from June, July, and August 2016 during summer when heat island effects would be strongest, as done by Meerow and Newell (2017). We used the mean of multiple images from low-cloud dates to avoid potentially anomalous temperatures on a single date. To estimate land surface temperatures, we converted digital numbers from raw images to top-of-atmosphere reflectance values, then converted to at-satellite brightness temperatures. Crime prevalence (per-capita) condition scores were estimated as the total number of violent, property, and narcotic crimes in 2016 as collated by the Philadelphia Police Department (City of Philadelphia, 2016a) divided by census tract total population in 2016. Single and multi-family property values (USD/ft^2) were acquired from the City of Philadelphia (City of Philadelphia, 2016b); we exclude property values of businesses because our focus is on the residential populations that live within the census tracts. The air quality improvement condition score was based on estimated levels of fine particulate matter ($PM_{2.5}$) from a downscaled version of the Community Multiscale Air Quality Modeling System (Berrocal et al., 2010). As a proxy for human well-being, we used the proportion of adult residents who answered yes to CDC 500 Cities Project survey questions asking if respondents have had poor mental or physical health during at least 14 of the past 30 days (Center for Disease Control, 2016). For both biodiversity scenarios (biodiversity-complementation and biodiversity-equity) we determined condition scores based on potential habitat, quantified as the vegetated proportion of a census tract from land cover classification data.

We did not quantify condition scores for two benefits, carbon sequestration and aesthetic improvements (Table 2), due to insufficient data. Even though carbon dioxide levels may vary spatially across a city, the magnitude of carbon sequestration is not felt at the neighborhood or census-tract level, so placement decisions for carbon sequestration are not appropriate at such a fine scale. Additionally, we were unable to evaluate aesthetic improvements in a spatial context because of limited aesthetics data. Note, both carbon sequestration and aesthetic improvements were included in the trait analyses component of GIST (see below).

From these condition scores, we used the appropriate placement model to calculate priority scores for each benefit, and scaled priority scores between zero and one to facilitate comparisons among benefits in subsequent analyses. We used biodiversity-equity, not biodiversity-complementation, priority scores to calculate multifunctionality priority scores to avoid the two biodiversity scenarios neutralizing each other, and because increasing habitat in deficient areas is likely a more appropriate placement model for biodiversity in Philadelphia given the already large size of its three biggest urban parks, Fairmount Park, Wissahickon Valley Park, and Pennypack Park.

The potential for multifunctionality is strongest when many benefits are positively correlated and few *trade-offs* (i.e., negative correlations) exist. We evaluated the potential for multifunctionality for Philadelphia GI by calculating pairwise Pearson correlations of priority scores between benefits within the 384 census tracts.

2.3. GIST model: plant trait selection to maximize multifunctionality

The trait component of GIST involves selecting plant species with traits that ensure maximal provisioning of multiple benefits (Fig. 1). Because GI can present harsh growing environments, it is necessary to first make a list of candidate plant species and their associated traits that can tolerate local GI conditions. Such lists already exist for many cities and regions.

Using plant functional traits to examine the provisioning of multiple benefits to an ecosystem is an increasingly popular assessment framework, because plant traits are of great importance to ecosystem processes and functioning (Table 2) (Lavorel et al., 2011). These relationships between plant traits and the benefits they provide can be formalized in *trait-benefit models* which estimate the relative magnitude of benefits provided by traits. While biologically-focused benefits of GI are often intuitively associated with specific plant traits (e.g., maximizing stormwater diversion by plants with higher leaf area index; Liu et al., 2014), plant traits also impact socioeconomic benefits of GI (e.g., relationships between plant size and property values; Behe et al., 2005). In addition, some benefits are maximized through variation in trait values rather than maximizing single traits. For example, variation in plant color and flower size are associated with greater aesthetic improvements (Kendal et al., 2012) and variation in plant size is associated with higher biodiversity (Evans et al., 2009). See Appendix B for an overview of consistently observed relationships between plant traits and benefits that were used for building trait-benefit models.

For Philadelphia, PWD collated a list of plant species that tolerate the environments in Philadelphia's GI. We used this list which includes plant traits for each species such as typical height, width, branching density, bloom time, foliage texture, bloom color, light requirements, and inundation, drought, and salinity tolerance (PWD, 2014). Then for each of our nine benefits (Table 2) we derived unique trait-benefit models from the directionality of trait-benefit relationships reported in the literature (Table B1, see Appendix B for methods). These trait-benefit models rely heavily on the directionality of the relationship between a trait and benefit to quantify *relative* differences in the levels of community-weighted trait means associated with particular benefits among GI (e.g., Lavorel et al., 2011; Storkey et al., 2015). Future research into the mechanistic relationships between individual traits and benefits will allow models like these to be further refined so that estimating the *actual* amount of the benefit provided is possible. However, for the purposes of GIST, quantifying relative differences in benefits among GI is sufficient for assessing the potential for single benefit provisioning and multifunctionality.

Like we did for GI spatial placement, we estimated the potential for multifunctionality of Philadelphia GI based on correlations among traits for the plant species from the PWD plant list by simulating GI plantings. To do this, we extracted the number of plant species from each of the 137 GI in Philadelphia for which we had vegetation data and created 137 new species assemblages by randomly selecting plant species from the PWD approved plant list keeping the number of species per site constant. Then, for each simulated GI site, we used the trait-benefit models to calculate the relative magnitude of each single benefit for each assemblage. We repeated these simulations 1000 times and then calculated pair-wise Pearson correlations among benefits. This procedure allows us to calculate the potential for multifunctionality specifically for Philadelphia's GI system based on its plant list and number of species observed per GI.

2.4. Assessment of Philadelphia's GI planning

Ideally, GI in Philadelphia is sited in areas with high priority scores and vegetated with plant species with the traits that provide needed benefits. However, because PWD's Green City, Clean Waters initiative is aimed at mitigating stormwater runoff, GI may consistently be placed in stormwater priority areas. If PWD selects plant species with traits aimed at mitigating stormwater runoff, then plant traits for stormwater diversion should also be maximized across Philadelphia. To test these hypotheses, we first calculated spatial- and trait-benefit scores (see below) for each GI installation, and then asked if the mean spatial- and trait-benefit scores across Philadelphia for stormwater diversion and each of the other benefits differed from GI placed randomly and vegetated with species selected randomly. Observed mean spatial- and trait-benefit scores that are significantly different from random GI support the hypothesis of an active selection process for that benefit by planners.

For each of the 1129 GI sites in our spatial dataset, we calculated a *spatial-benefit score* by multiplying the log-transformed area of the GI site by the priority score of the census tract in which it is situated. To calculate *trait-benefit scores* for each of the 137 GI sites in our trait analysis, we applied our trait-benefit models to vegetation survey data of plant species composition and percent cover within GI provided by PWD. For each trait, we used community-weighted means calculated as means of species-level trait values weighted by percent cover (Violle et al., 2007). We then compared the spatial- and trait-benefit scores of GI sites (hereafter 'observed GI') to randomly simulated plant communities and spatial arrangements (hereafter 'simulated GI'). Random simulations (or permutation tests) are common methods for generating null model distributions of the variable of interest (in this case spatial- and trait-benefit scores) to compare to the observed value for significance testing (Gotelli and Graves, 1996). For our simulated spatial arrangements, we randomly projected polygons of the same size as the observed GI sites across our map of priority scores for Philadelphia's census tracts 1000 times and calculated spatial-benefit scores in the same manner as we did for observed GI. When simulating GI, we preserved the areas of observed GI in projecting polygons to minimize a potentially confounding effect of differing areas. Keeping area values constant allowed for a more controlled comparison of observed GI and randomly simulated GI. For simulated plant species assemblages, we used the same simulated plant assemblages described above (with the same numbers of species as observed GI) and calculated trait-benefit scores in the same manner we did for observed GI. For comparability between benefits, we scaled all simulated scores for each benefit between zero and one. We used two-tailed tests to determine if observed GI in Philadelphia had significantly different spatial- and trait-benefit scores than the null model distribution generated from randomly simulated GI. The use of two-tailed tests allowed us to determine if spatial- and trait-benefit scores were higher or lower for observed GI versus simulated GI.

2.5. How is multifunctionality structured in Philadelphia's GI?

Optimally, GI sites should have high multifunctionality scores with low spread among single benefit scores, meaning that single benefit scores are high and contribute equally to the overall multifunctionality score (Bennett et al., 2009). To explore the structuring of multifunctionality scores, we quantified the observed multifunctionality across Philadelphia's GI by summing all single-benefit scores within each GI site to yield *spatial-benefit multifunctionality* and *trait-benefit multifunctionality scores*. For Philadelphia, we weighted all benefits equally, however, weights such as those based on stakeholder input could be used when available (Meerow and Newell, 2017). To quantify the evenness across benefit scores, we calculated the Gini coefficient, a statistical dispersion index of the level of inequality among benefits in their contribution to multifunctionality, using the DescTools R package (Signorell, 2019). We used 1 – Gini so that higher values indicated a more even distribution (equal contribution among benefits) and lower values indicated a more dispersed distribution (unequal contribution) among benefit scores. We compared the magnitude and dispersion of spatial- and trait-benefit multifunctionality scores between observed and simulated GI sites, allowing us to visualize areas for improvement in current and future GI multifunctionality. All analyses and simulations were conducted in R; code and data for analyses are provided at https://github.com/ieco-lab/GIST (R Core Team, 2017).

3. Results

3.1. GIST model assessment of Philadelphia

Application of the GIST model to Philadelphia revealed variation in priority scores across single benefits and clear priority areas for multifunctionality (Fig. 2). These areas with high potential multifunctionality are driven by low property values, high crime, and high impervious surface area.

For the spatial placement of GI, there was high correlation among census tract priority scores for most benefits (Fig. 3). An exception is biodiversity-complementation, which was negatively correlated with most other benefits, signifying a trade-off. Additionally, increased property values and improved air quality were also significantly negatively correlated with each other.

Most trait-benefit scores of simulated GI sites in Philadelphia were positively correlated (Fig. 3), with crime reduction being the only benefit negatively correlated with others. There is high potential for multifunctionality in Philadelphia with respect to both spatial placement of GI and the traits of plant species that can tolerate GI conditions. Given that most priority areas and trait-benefit scores are positively correlated across pairs of benefits, it is possible to vegetate and site GI in a way that incurs few trade-offs and maximizes multifunctionality in Philadelphia.

3.2. Assessment of Philadelphia's GI planning

Overall, we found support for an active selection process in siting Philadelphia's GI, as five of the eight benefits analyzed had higher observed scores than simulated GI placed randomly across the city (Fig. 4). Our hypothesis that GI is sited to provide stormwater diversion was supported; however, improved air quality had the highest deviation from the random distribution across all benefits. In contrast to the spatial placement of GI, observed trait-benefit scores did not differ from simulated GI for any benefit (Fig. 4); there is no evidence for consistent selection of plant species traits for GI for any benefit, including stormwater diversion. Effective GI that is installed to prioritize benefits with respect to spatial location and plant traits should be greater than the mean spatial- and trait-benefit scores from simulated GI (Fig. 4, upper-right quadrant) for each of its targeted benefits. However, no benefit scores fall within this quadrant.

3.3. How is multifunctionality structured in Philadelphia's GI?

Ideally, multifunctional infrastructure provides multiple benefits equally rather than prioritizing one benefit over others. In our analyses, this idealized scenario of high multifunctionality scores resulting from equal contributions among benefits is represented by points above the 50th percentile for multifunctionality scores and evenness (Fig. 5, upper right quadrants). For the spatial placement of GI, the median across spatial-benefit multifunctionality scores is slightly above the 50th percentile, and the median evenness score is slightly lower than the 50th percentile. Comparatively, the median trait-benefit multifunctionality score is in the lower-left quadrant (Fig. 5), indicating low multifunctionality and low evenness compared to simulated scores for both spatial placement and traits. These results indicate that the multifunctionality scores for both spatial placement and plant traits are on average due to low equality across single benefit scores.

4. Discussion

On the path to sustainability, urban planners require the tools and knowledge necessary to shift GI in the direction of maximum effectiveness and multifunctionality. We proposed that multifunctionality is achieved when GI provides multiple benefits simultaneously through positive correlations among benefits in their spatial placement and provisioning by plant traits. Here, we provide the GIST model to assist planners in the design of multifunctional GI in urban areas. By applying GIST to Philadelphia, we demonstrate that there is a high potential for multifunctionality in GI with respect to both spatial placement and plant traits, yet only a fraction of this potential has been fully realized.

4.1. Insights from spatial component of GIST model for multifunctionality

Multifunctionality can be attained in a purely spatial context when spatial correlations among priority areas for single benefits exist due either to spatial overlap in different factors that contribute to different benefits or if the same underlying factors influence multiple benefits. Application of the GIST model revealed a high potential for multifunctionality in Philadelphia through strategic spatial placement of GI because most benefits were positively correlated spatially. The cluster of benefits with the highest positive correlations comprises stormwater diversion, heat island mediation, crime reduction, improved air quality, and biodiversity-equity. Although we used different datasets to quantify the condition scores of each benefit in this cluster, these correlations are not surprising as similar factors such as the amount of impervious surface or lack of green space are associated with the provisioning of each benefit spatially in our analyses (Cameron et al., 2012; Grote et al., 2016; Kondo et al., 2017). Accordingly, biodiversity-complementation

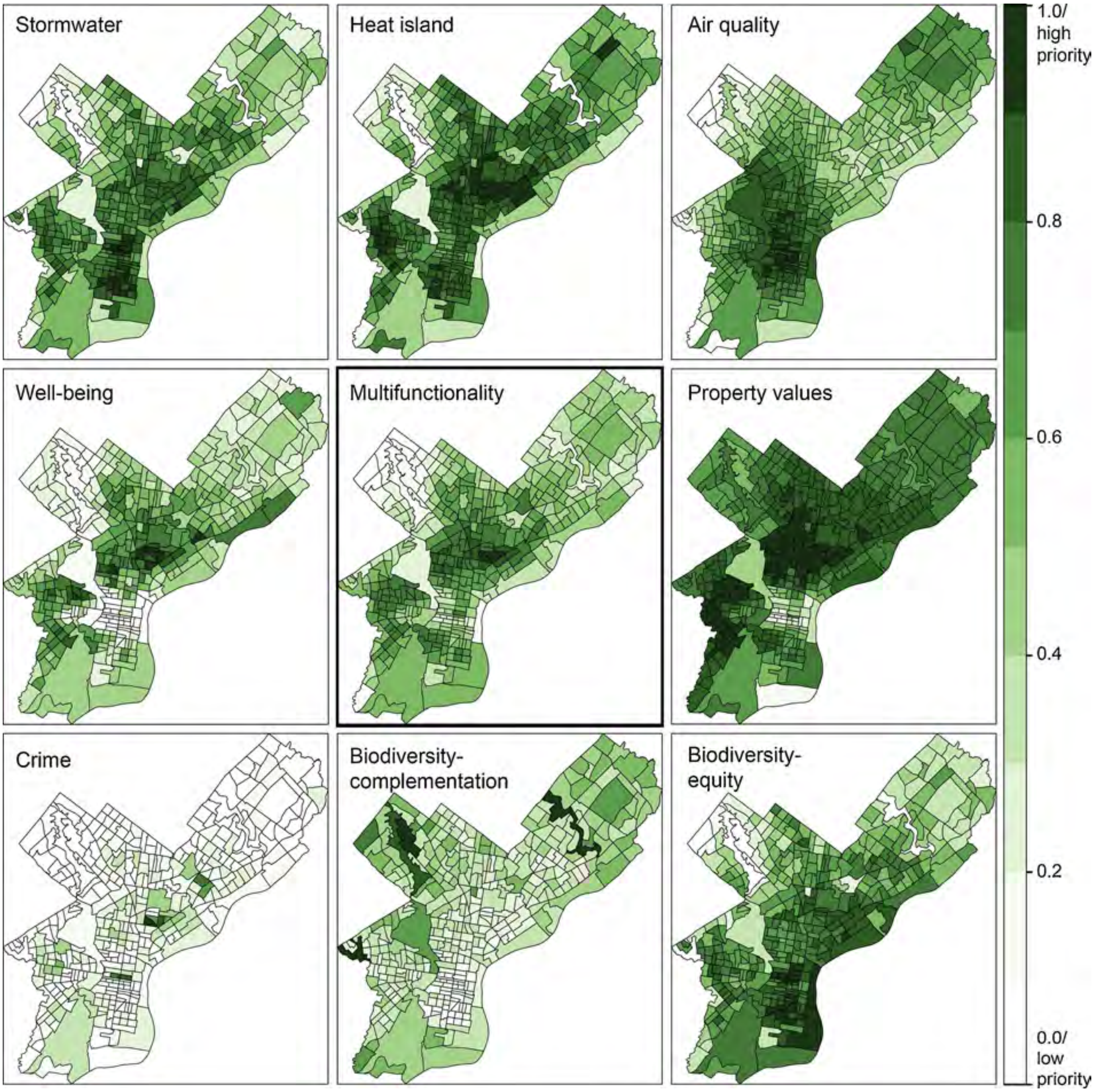

Fig. 2. Priority scores of 384 census tracts for single benefits and multifunctionality (center) for green infrastructure (GI) placement in Philadelphia. The benefits are: stormwater diversion, heat island mediation, improved air quality, improved well-being, increased property values, reduced crime, increased biodiversity-complementation, increased biodiversity-equity, and multifunctionality, i.e. summed priority scores across all benefits (including only biodiversity-equity, not biodiversity-complementation). Darker green areas are higher priority areas for GI placement to maximize each benefit (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

was negatively correlated to this cluster of benefits as its priority scores were calculated using a complementation-based placement model which prioritized placing GI in areas with existing green space. Application of the GISP model developed by Meerow and Newell (2017) in Detroit revealed a similar cluster of positively correlated benefits comprising managing stormwater, reducing urban heat island, and improving air quality, which as a group was negatively correlated to habitat cohesion, a metric comparable to our biodiversity-complementation benefit (Meerow and Newell, 2017). Given that similar clusters of benefits driven by the same underlying factors emerged in two cities, this benefit cluster may be common in many cities and provide a path for multifunctionality across ecological and social benefits.

Comparatively, the negative correlation between improved air quality and increased property values in Philadelphia may be less universal across cities. Indeed, there is a consistently reported positive relationship between socioeconomic status and air quality in many regions as lower income residents often live in areas with lower air quality and more pollution sources (Clark et al., 2014; Di et al., 2017; Graça et al., 2017a). In Philadelphia, we observed the opposite pattern; the negative relationship between property values and air quality is likely due to poor air quality from vehicular traffic in the dense, high property-value central business district. Much of the heavy industry in Philadelphia is situated along the Schuylkill and Delaware Rivers, somewhat separated from residential areas. Additionally, the Philadelphia Energy Solutions oil refinery, which recently ceased operation, was a large source of air pollution, closest to neighborhoods that are not those experiencing deepest poverty. In contrast to Philadelphia, in Porto, Portugal, the worst air quality is in low income areas because their greenspaces are predominantly vacant lots which have the lowest capacity for removing airborne pollutants relative to greenspaces dominated by trees like parks and woodlands found in higher income

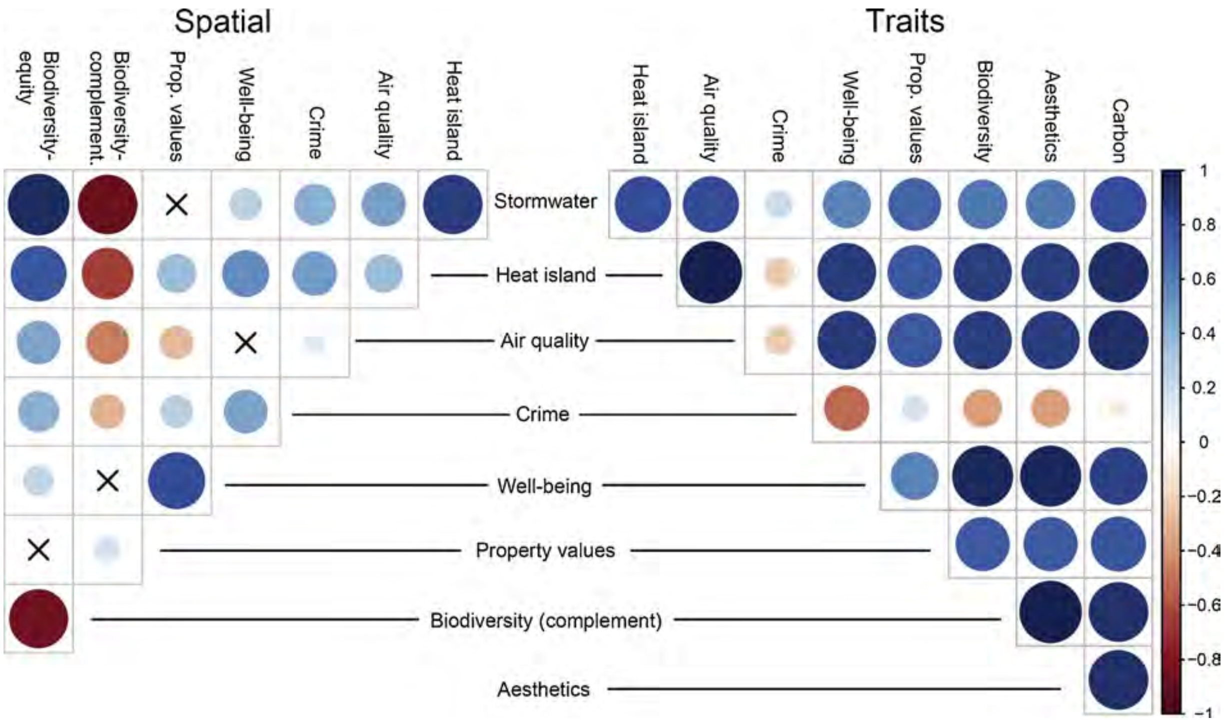

Fig. 3. Correlations between census tract level spatial priority scores (left) and trait-benefit scores predicted from plant traits in simulated GI (right) for pairs of benefits indicates high potential for multifunctionality in Philadelphia. Size and color of circle indicates magnitude of correlation coefficient; shading indicates direction of correlation (see scale at right). A black "X" indicates that the correlation was not significant at $\alpha = 0.05$.

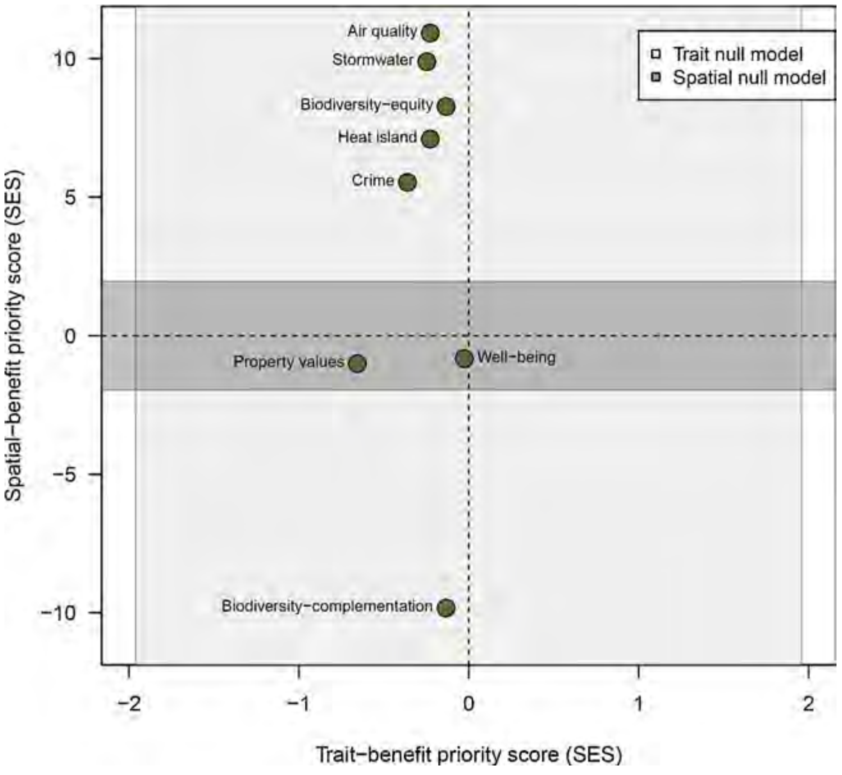

Fig. 4. Comparison of observed spatial- and trait-benefit priority scores to randomly simulated GI using standard effect sizes (SES). Points are the observed SES of each benefit relative to null distributions (shaded regions) generated by 1000 simulations of spatial site placement and trait assemblages. Six of the benefits significantly fall outside the spatial null distribution (darker gray region, all $P < 0.001$) while none fall outside the trait null distribution (lighter gray region). Note aesthetic improvements and carbon sequestration were not plotted in the figure because they were not included in the spatial analyses.

areas (Graça et al., 2017a). These city-specific results underscore the value of applying the GIST model to location-specific data.

The multifunctionality priority areas we identified in Philadelphia have relatively high stormwater diversion priority scores, but they are not the *highest* priority areas for the single benefit of stormwater diversion. This indicates that urban planners in Philadelphia may need to choose between ideal sites for stormwater management and sites that provide a wider range of social benefits. However, our multifunctionality scores were calculated through unweighted addition of benefit scores; incorporating stakeholder weights for particular benefits in the calculation multifunctionality scores (Meerow and Newell, 2017) may shift the selection of multifunctionality priority areas and

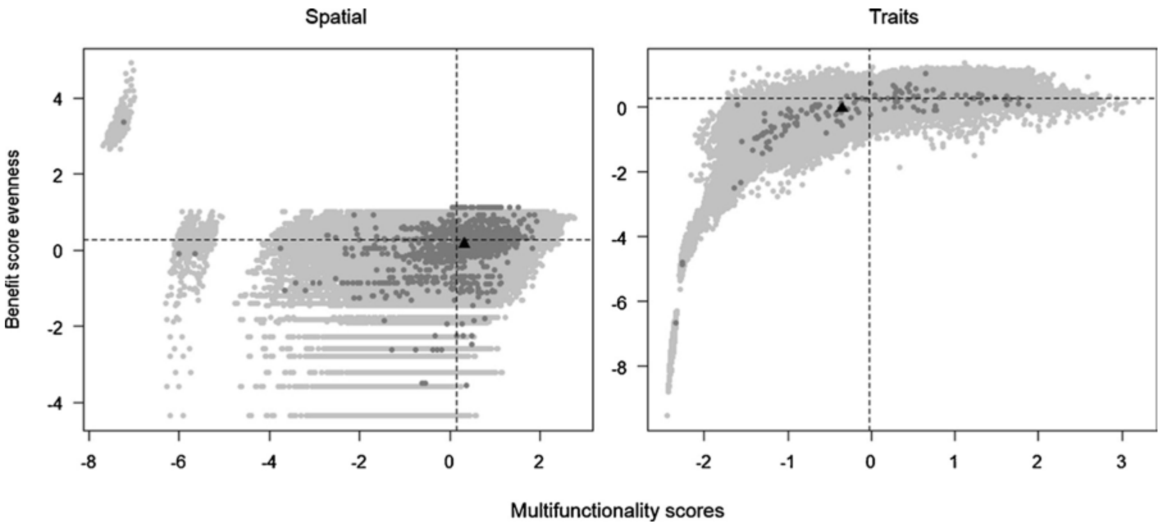

Fig. 5. Spatial- and trait-benefit multifunctionality scores (log-transformed) versus a measure of evenness across benefit scores (1 – Gini coefficient; larger values indicate more equality across scores). Light gray points represent 1000 simulations in the null model, and dark gray points represent scores for observed GI sites in Philadelphia. The black triangles represent the medians of observed multifunctionality scores, and dotted lines represent 50th percentiles for the null models. Axes are scaled to standard effect sizes for ease of interpretation.

ameliorate the need to choose among scenarios.

Spatial overlap in benefits leading to multifunctionality has been demonstrated in multiple cities, yet it is not a consistent outcome across studies. Research in Detroit, New York, Los Angeles, USA, and Manila, Philippines found that benefits influenced by the spatial distribution of impervious surface like stormwater diversion, improved air quality, and heat island mediation are positively spatially correlated (Meerow and Newell, 2017; Meerow, 2019). Across Europe, there is high potential for spatial GI multifunctionality; 23 % of the continent was designated as high priority area for GI placement, indicating that there is high incidence of single benefit priority area overlap (Liquete et al., 2015). Comparatively, in the Beauport borough of Quebec City, Canada, GI spatial multifunctionality is elusive; only two locations in the borough were deemed suitable for meeting the social, aesthetic, and environmental benefits assessed (Dagenais et al., 2017). Future work should identify which clusters of spatially correlated benefits can be identified consistently across cities, and which clusters are city-specific due to factors such as neighborhood distance to highways and waterways, historical urban planning practices, and the demographic and political history of cities (Madureira and Andresen, 2014).

For the spatial component of GIST, we took a broad-scale approach using the proxy that has the strongest influence on each benefit as reported in the literature. However, each benefit may be affected by a multitude of factors, and future applications of GIST may incorporate more complex calculations of condition scores from multiple proxies for each benefit if warranted. For example, more specific biodiversity metrics can be developed for species groups of interest as habitat quality, ideal habitat size, and habitat connectivity likely differ between mobile species like birds and less mobile groups like invertebrates (McKinney, 2008; Dallimer et al., 2012b; Braaker et al., 2014). Furthermore, for some species, persistence in the urban core may be contingent upon connectivity with larger green spaces within or beyond the urban boundaries (Delaney et al., 2010; Munshi-South, 2012), therefore including specific connectivity patterns rather than connectivity in general may be pertinent.

4.2. Insights from traits component of GIST model for multifunctionality

Application of the GIST model to the species from the PWD plant list also revealed high potential for multifunctionality due to positive correlations among all benefit scores calculated from plant traits except for crime reduction. The negative correlation between crime reduction and other benefits is due to the nuanced relationship between plant height and perceived safety, as well as the negative relationship between crime reduction and traits such as species richness and vegetation density for certain types of crime (Table B1; Donovan and Prestemon, 2012; Wolfe and Mennis, 2012; Ahmad et al., 2014). Interestingly, stormwater diversion and crime reduction were positively correlated, therefore planners installing GI in crime reduction priority areas could vegetate those GI with plant traits associated with crime reduction (e.g. plant height, canopy density) and use traits associated with other benefits for GI outside of crime reduction priority areas to achieve multifunctionality.

Although recent work indicates some consistent correlations among plant traits globally (Díaz et al., 2016), given the early stages of research into trait-benefit models, it is not apparent which benefit correlations we observed may be universal, or unique to the group of plants on the PWD plant list. Few studies have examined how different plant traits, and the diversity of such traits, contribute to GI multifunctionality (Lundholm et al., 2015), especially in an explicitly spatial context. In addition, due to the high correlations among benefits, planning for multifunctionality in the context of plant traits should be theoretically straightforward, however in practice, finding suitable plant species that can survive in GI is an ongoing process, and the PWD approved plant list is an evolving document. When selecting plant species by desired traits for GI multifunctionality, choosing species with a diversity of traits may lead to greater benefit provisioning and will increase urban resilience for global change (Oliver et al., 2015). It is encouraging for GI planning that four of the five benefits from the correlated cluster identified in the spatial analysis are also correlated for traits (Bello et al. 2010). This indicates designing GI that are multifunctional based on both spatial placement and plant traits is possible.

An area of active and ongoing ecological research is identifying which plant traits are associated with particular ecosystem functions that generate ecosystem services and benefits (Lavorel and Garnier, 2002; Funk et al., 2017). As such, selecting traits for parameterizing models is key and may influence the outcome of our results (Butterfield and Suding, 2013). In our approach for GIST, we provide a general framework for incorporating plant traits into planning decisions and used the range of traits with reported associations to each benefit in the literature. Going forward, trait-benefit models will be updated as more studies identify the directionality of relationships between traits and benefits and reveal the variation in these relationships across climate zones and ecoregions. At this point, true mechanistic models between traits and benefits have not yet been developed, particularly concerning relationships between plant traits and socioeconomic benefits. Future research will help elucidate and quantify these relationships so that magnitude of benefits can be studied beyond our initial focus on the direction of benefit.

4.3. GIST model recommendations to enhance multifunctionality in Philadelphia's GI

Ideally, GI are installed in priority areas so that they deliver maximum benefit, however having permission to modify enough land in priority areas may be a challenge in many cities. As a result, GI may not be installed in the highest priority areas of a city. In Philadelphia, we found that GI is sited in priority areas for most of the benefits we studied. In fact, the five benefits that were sited better than random are the same five that comprised the cluster of spatially correlated benefits in the GIST model. We suspect that GI installation sites were selected with the goal of optimizing stormwater diversion which also contributed to the other benefits due to their spatial correlations. In contrast, GI was not consistently sited in priority areas for increased property values and increased human well-being. The dataset of GI provided by PWD includes both public and private projects, and it is possible that more GI is installed in neighborhoods heavy in private development, which likely do not coincide spatially with low-property value and low human well-being areas. By installing GI in the multifunctionality priority areas indicated by GIST, these two benefits could also be addressed.

Compared to the spatial results, our finding that the plant species composition of GI was not consistently selected with traits to optimize any benefits likely stems from i) the emphasis of planners on selecting plant species to tolerate GI conditions, which is an important consideration; and ii) a lack of consideration of the relationship between plant traits and benefit provisioning when selecting species for GI (Cameron and Blanuša, 2016). In addition, we had far fewer GI sites with plant species composition data for our trait analyses compared to our spatial analyses, so these results may have in part been influenced by small sample size. Nonetheless, our results indicate that by actively selecting plant species with the traits that provide a needed benefit, planners can ensure that GI installations are fulfilling their desired role.

The multifunctionality and evenness scores across Philadelphia's GI are close to the 50th percentile of simulated spatial and trait-based scores indicating ample room for improvement (Fig. 5). We advocate for increasing multifunctionality scores by increasing evenness across benefits: site GI in multifunctionality priority areas and actively select plant species with traits to maximize multiple benefits. Though we idealize high evenness across benefits, some planners might not desire benefit evenness if certain benefits are of greater importance than others. Regardless of stakeholder priorities, our research shows that even with a primary focus on one benefit (e.g., stormwater diversion), multifunctionality can be achieved with few trade-offs between benefits, giving a high potential for multifunctionality from both spatial and plant trait fronts.

4.4. Conclusions and future directions

Win-win scenarios with multifunctional GI are possible because GI benefits are not isolated; many benefits directly influence the provision of others such as aesthetic improvements, increased property values, and improved well-being. Lower-income urban areas tend to be more disadvantaged by overall ecosystem service inequity (e.g., Graça et al., 2017b), so strategically placing GI and using plant traits to maximize benefits in those locations could create more equitable cities with respect to benefit distributions. However, the relative importance of GI benefits is dependent on the stakeholders involved, and opinions of benefit importance are sometimes contradictory (Hung et al., 2016). Certain benefits may in fact be disservices to some citizens; increased property values, while likely yielding more property tax revenue for municipalities may lead to gentrification and further marginalization and displacement of disadvantaged communities. Future projects should consider the incorporation of equity indexes to guide planning in an equitable direction (Heckert and Rosan, 2016).

While considering all GI as a collective group is necessary for developing a framework to maximize multifunctionality as we have done, GI types (e.g., bioswales, green roofs, etc.) can vary in benefit delivery (Graça et al., 2017a). Future work could explore the unique contributions of each GI type through field surveys that identify temporal and spatial variation in benefits provisioned. This would allow more detailed parameterization of the modeled relationships between plant traits and GI benefits and provide better understanding of how GI design can benefit urban areas.

Though most of our recommendations are more technical in nature, a cultural shift might be necessary to maximize GI multifunctionality. In most municipal governments, different staff members likely implement different portions of GI planning. Communication between teams planning spatial and vegetation aspects is imperative.

Philadelphia is still in the early years of its Green City, Clean Waters initiative, and future evaluations could document the evolution of GI multifunctionality in the city in both spatial and trait-based contexts. Our work provides knowledge for interdisciplinary best practices in planning, and we hope that this research will lead to maximally multifunctional green infrastructure.

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.

Acknowledgements

We thank two anonymous reviewers who provided comments that greatly improved the quality of this manuscript. We would like to thank the Philadelphia Water Department for providing invaluable data from plant surveys of green infrastructure in Philadelphia and data on green infrastructure locations. We thank the members of the Integrative Ecology Lab at Temple University for their helpful input throughout the process of this study. This study was supported by funds from Temple University.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2020.126635.

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