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Research Paper

Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit

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HIGHLIGHTS

- Green infrastructure in Detroit is not being sited to maximize ecosystem services.
- A Green Infrastructure Spatial Planning (GISP) model is developed and applied to Detroit.
- The GISP model provides an integrated, stakeholder-driven approach to maximize ecosystem services.
- The model reveals tradeoffs, synergies and hotspots for future green infrastructure.
- The model and planning approach can be readily deployed for other cities.

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ABSTRACT

Cities are expanding green infrastructure to enhance resilience and ecosystem services. Although green infrastructure is promoted for its multifunctionality, projects are typically sited based on a particular benefit, such as stormwater abatement, rather than a suite of socio-economic and environmental benefits. This stems in part from the lack of stakeholder-informed, city-scale approaches to systematically identify ecosystem service tradeoffs, synergies, and 'hotspots' associated with green infrastructure and its siting. To address this gap, we introduce the Green Infrastructure Spatial Planning (GISP) model, a GIS-based multi-criteria approach that integrates six benefits: 1) stormwater management; 2) social vulnerability; 3) green space; 4) air quality; 5) urban heat island amelioration; and 6) landscape connectivity. Stakeholders then weight priorities to identify hotspots where green infrastructure benefits are needed most. Applying the GISP model to Detroit, we compared the results with the locations of current green infrastructure projects. The analysis provides initial evidence that green infrastructure is not being sited in high priority areas for stormwater abatement, let alone for ameliorating urban heat island effects, improving air quality, or increasing habitat connectivity. However, as the Detroit GISP model reveals, it could be developed in locations that simultaneously abate stormwater, urban heat island, and air pollution. Tradeoffs exist between siting to maximize stormwater management versus landscape connectivity. The GISP model provides an inclusive, replicable approach for planning future green infrastructure so that it maximizes social and ecological resilience. More broadly, it represents a spatial planning approach for evaluating competing and complementary ecosystem service priorities for a particular landscape.

1. Introduction

For decades cities and communities have grappled with how to strategically balance often competing economic, environmental, and social justice goals (Campbell, 1996). Now there is increasing pressure to plan not just for sustainability but also for 'resilience', or the ability to cope with disturbances or changes (Ahern, 2011; Davoudi et al. 2012). As with sustainability, planning for resilience is contested and political (Chelleri, Waters, Olazabal, & Minucci, 2015).

A major strategy for enhancing the sustainability and resilience of cities and communities is the expansion of green infrastructure (Lennon & Scott, 2014). Green infrastructure refers to the development of urban green spaces, such as parks, rain gardens, and greenways, that provide a variety of social and ecological benefits, from improved public health to stormwater abatement (Jim, Yo, & Byrne, 2015; Young, 2011). These benefits are often classified using

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the ecosystem services framework, which includes four major categories of services: provisioning, regulating, supporting, and cultural (Ahern, 2007; Andersson et al., 2014; Elmqvist, Gomez-Baggethun, & Langemeyer, 2016). Researchers, government agencies, and organizations are actively promoting the expansion of green infrastructure. Cities such as Detroit, New York City, and London have ambitious policies to implement it on a large scale (Berkooz, 2011; Mell, 2016).

Despite its growing popularity, there are challenges associated with expanding green infrastructure, which are emblematic of the broader politics of resilience planning (Meerow & Newell, 2016). Although often promoted on the basis of its *multifunctionality*, green infrastructure is frequently researched and implemented from the perspective of a single benefit, usually stormwater abatement (Kremer et al., 2016; Newell et al., 2013). We lack integrated planning models that evaluate synergies and tradeoffs among the social and ecological benefits of green infrastructure. This is problematic because green infrastructure benefits are highly localized, thus siting decisions have significant implications for local environmental and social justice (Hansen & Pauleit, 2014).

To address this research gap, this paper introduces a spatial planning approach to identify tradeoffs and synergies associated with ecosystem services provided by green infrastructure, and to identify priority areas where green infrastructure can be strategically placed to leverage co-benefits. We introduce the Green Infrastructure Spatial Planning (GISP) model, which combines GIS-based multi-criteria evaluation of six benefit criteria (stormwater management, social vulnerability, access to green space, air quality, urban heat island, and landscape connectivity) and expert stakeholder-driven weighting. This model is designed to facilitate spatial planning at a citywide scale, which would then be followed by detailed suitability assessments at smaller spatial scales. Initially applied to Detroit, Michigan, the GISP model is designed to be generalizable and applicable for other cities and communities.

Detroit is a post-industrial city facing numerous resilience challenges including a weak economic base, high poverty and vacancy rates, and aging infrastructure (Gallagher, 2010; Schilling & Logan, 2008). Yet Detroit's extensive vacant land also presents an opportunity for urban transformation, and green infrastructure is a primary redevelopment strategy (Berkooz, 2011; Nassauer & Raskin, 2014). But are green infrastructure projects in Detroit being strategically planned and sited in areas where ecosystem service benefits are maximized and needed most? What are the spatial tradeoffs and synergies associated with these benefits? We use the GISP model to answer these questions, comparing the modeled 'hotspots' with the locations of green infrastructure projects across Detroit.

The structure of this paper is as follows: The next section provides background for the GISP model by summarizing the spatial planning approach, the ecosystem services provided by green infrastructure, the relationship between green infrastructure and resilience, and the planning challenges associated with green infrastructure, including in the Detroit context. Section 3 introduces the GISP model methodology and the data sources used to apply it to Detroit. Section 4 presents the results, including analysis of synergies, tradeoffs, hotspots, and the comparison between modeled priority areas and locations of current green infrastructure projects in Detroit. In Section 5, we reflect on the implications of these results and discuss strengths and limitations of the GISP modeling approach, and suggest ways to further improve it. The paper concludes by stressing the need for strategic and integrated green infrastructure planning in Detroit and beyond, and offers the GISP model as a promising spatial planning approach to evaluate often competing ecosystem service priorities and to identify strategic locations where co-benefits can be maximized for a particular landscape.

2. The spatial planning of green infrastructure for resilience

Cities can enhance their sustainability or resilience through spatial land-use planning. The European Commission (1997, p. 24) broadly defines spatial planning as approaches "used largely by the public sector to influence the future distribution of activities in space." Some spatial planning takes an "ecosystem approach," in which effective management of land and water provides a suite of *ecosystem services* for the benefit of humans and the natural environment (Wilson & Piper, 2010, p. 42). The expansion of green infrastructure in cities has emerged as a popular strategy to operationalize this ecosystem-based approach to spatial land-use planning (Lennon and Scott, 2014).

Commonly defined as the "interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations" (Benedict & McMahon, 2002, p. 12), green infrastructure has emerged as a complement to, and even a situational replacement of, more centralized 'gray infrastructure' (e.g. water pipes, pumps, and sewers) in large part because of its potential to enhance resilience for society and the natural environment. Scholars and practitioners argue that green infrastructure fosters urban resilience by increasing diversity, flexibility, redundancy, modularization, and decentralization (Ahern, 2011; Godschalk, 2003; Wardekker, de Jong, Knoop, & van der Sluijs, 2010; Wilkinson, 2011).

The relationship between green infrastructure and these resilience characteristics is often focused on stormwater management (Ahern, 2013). In particular, green infrastructure has the potential to reduce dependence on centralized stormwater infrastructure, based on the rationale that decentralized systems are more modular, provide functional redundancy, and are therefore less vulnerable to catastrophic failures (Ahern, 2011). Green infrastructure is also more flexible than massive buried pipes and pumps (Mell, 2016; Palmer, Liu, Matthews, & Mumba, 2015; Casal-Campos et al., 2015), which may be especially important given the changing and uncertain climate (Foster, Lowe, & Winkelman, 2011; Mell, 2016). During heavy precipitation events, green infrastructure can help alleviate flooding and pressure on aging or undersized sewer systems (Voskamp & Van de Ven, 2015). In cities with combined sewer systems, this can reduce the likelihood of combined sewer system overflows (CSOs), which in the United States alone purportedly cause 850 billion gallons of pollution annually (Carson, Marasco, Culligan, & McGillis, 2013). In this respect, green infrastructure can improve water quality by reducing harmful outflows. In coastal areas, wetland and mangrove green infrastructure can act as natural buffers against storm surges, thereby mitigating flooding (Danielsen et al., 2005). A meta-analysis found that green infrastructure reduced both overall stormwater runoff and water pollution levels (Jaffe, Zellner, Minor, Gonzalez-Meler et al., 2010, p. 8).

2.1. Green infrastructure and ecosystem services

Green infrastructure's utility as a resilience strategy goes beyond its ability to abate stormwater, for fundamental to green infrastructure's appeal is its *multifunctionality* (Kabisch et al., 2016; Madureira & Andresen, 2013; Sandström, 2002). The literature has extensively catalogued these multiple benefits as provisioning, regulating, supporting, and cultural *ecosystem services* (Ahern, 2007; Andersson et al., 2014; Elmqvist et al., 2016; Tzoulas et al., 2007). Besides stormwater abatement, this literature commonly cites five additional ecosystem service benefits: 1) improved air quality; 2) urban heat island mitigation; 3) improved communities and reduced social vulnerability; 4) greater access to green space; and 5) increased landscape connectivity (Table 1). These ecosystem

Table 1
Green Infrastructure Spatial Planning (GISP) model criteria and data sources.

Resilience planning priority	Ecosystem service category	Criterion	Spatial attributes (Indicator)	Data sources for Detroit
Managing stormwater	Regulating; provisioning	Stormwater hazard	Average runoff coefficients based on Rational Method and CSO outfall location data	SEMCOG parcel-level land use layer (2008); Motor City Mapping (no structure) parcel layer (2015); Detroit Water & Sewerage waste water discharge event location data (2008–2014) (Data Driven Detroit, 2015)
Reducing social vulnerability	Cultural	Social Vulnerability Index (SoVI)	Combination of indicators shown to correlate with social vulnerability to natural hazards	SoVI data for 2010 created by the Hazards and Vulnerability Research Institute, University of South Carolina (Hazards and Vulnerability Research Institute, 2015)
Increasing access to green space	Cultural	Lack of access to parks	Estimate of tract population without access to parks	Parcels within a 10-minute walk of a park (SEMCOG 2016); City of Detroit parcels (2015)
Reducing the urban heat island effect	Regulating	Land surface temperature	Average land surface temperature	Estimate of average daytime surface temperatures per census tract from MODIS for June, July, & August 2010 (Burillo et al., 2015)
Improving air quality	Regulating	Severity of air pollution	Particulate matter ($PM_{2.5}$) emissions	High-resolution traffic-related air pollution estimates (Batterman & Ganguly 2013)
Increasing landscape connectivity	Supporting	Patch Cohesion Index	Physical connectedness of wildlife habitat (forest cover) within spatial unit	Southeast Michigan Council of Governments (SEMCOG) land cover layer (2010)

service benefits serve as the criterion indicators for the GISP model and so are briefly summarized here.

Ambient air pollution annually leads to an estimated 3.7 million premature deaths and is especially acute in urban areas (World Health Organization, 2014). Green infrastructure and vegetation improves air quality by reducing nitrogen dioxide, particulate matter (Pugh, Mackenzie, Whyatt, & Hewitt, 2012), and ozone levels (Taha, 1996). Street trees are also positively correlated with lower child asthma rates (Lovasi, Quinn, Neckerman, Perzanowski, & Rundle, 2008).

By cooling the immediate surrounding through the shading of buildings and other surfaces, vegetation can ameliorate the urban heat island (UHI) effect (Tzoulas et al., 2007). Impervious surfaces in urban areas are 2 °C warmer on average in the summer (Bounoua et al., 2015) and increasing urban tree canopy can reduce air temperatures by 1–3 °C (O'Neill et al., 2009). Health impacts due to UHI are also projected to become more severe with climate change (Stone, 2012).

Green infrastructure can build community resilience by reducing social vulnerability, the incapacity of residents to deal with environmental hazards (Cutter, 1996). The factors that shape vulnerability are complex and difficult to quantify. Studies have, however, linked increased vegetation to a variety of social benefits that would likely influence or interact with social vulnerability including: lower crime rates (Kuo & Sullivan, 2001); increased feelings of social safety (Maas, Spreeuwenberg et al., 2009) better health (Kardan et al., 2015), especially for women and the elderly (Takano, Nakamura, & Watanabe, 2002; Vries, Verheij, Groenewegen, & Spreeuwenberg, 2003) better mental health (Alcock, White, Wheeler, Fleming, & Depledge, 2014) and reduced stress (Ward et al., 2012); and increased social capital (Maas, Dillen, Verheij, & Groenewegen, 2009; Rung, Broyles, Mowen, Gustat, & Sothern, 2011).

It is especially problematic, therefore, that low-income and minority communities have less green space per capita, both in terms of access and total area (Heynen, 2006; Wolch, Wilson, & Fehrenbach, 2005). This relative park poverty is an environmental injustice (Jennings, Gaither, & Gragg, 2012; Wolch, Byrne, & Newell, 2014). Strategically siting future green infrastructure could reduce these inequities (Dunn, 2010), provided such efforts do not lead to 'green' gentrification and negatively impact the very communities these efforts were designed to assist (Wolch et al., 2014).

Finally, some forms of green infrastructure can benefit the ecological matrix of urban areas. Due to urbanization processes and sprawl, the urban landscape is often highly fragmented, or composed of a series of isolated patches (Ahern, 2011). Reduced habitat connectivity (i.e., fragmentation) usually results in fewer ecosystem services (Mitchell, Bennett, & Gonzalez, 2013). By connecting fragmented patches, green infrastructure can be sited to form contiguous ribbons of urban green space. This connectivity has positive implications, especially for biological diversity (Kong, Yin, Nakagoshi, & Zong, 2010). Landscape ecology focuses on two types of connectivity: 1) structural, or the spatial configuration of habitat patches; and 2) functional, which takes into account the behaviors of various species (Tischendorf & Fahrig, 2000). With regard to planning for structural connectivity, Colding (2007, p. 46) argues for "ecological land-use complementation," or the clustering of urban green space "to increase available habitats for species, to promote landscape complementation/supplementation functions, and to nurture key ecosystem processes essential for the support of biodiversity." But different actors govern green space differently, which makes landscape-scale planning challenging, both politically and institutionally (Ernstson, Barthel, & Andersson, 2010).

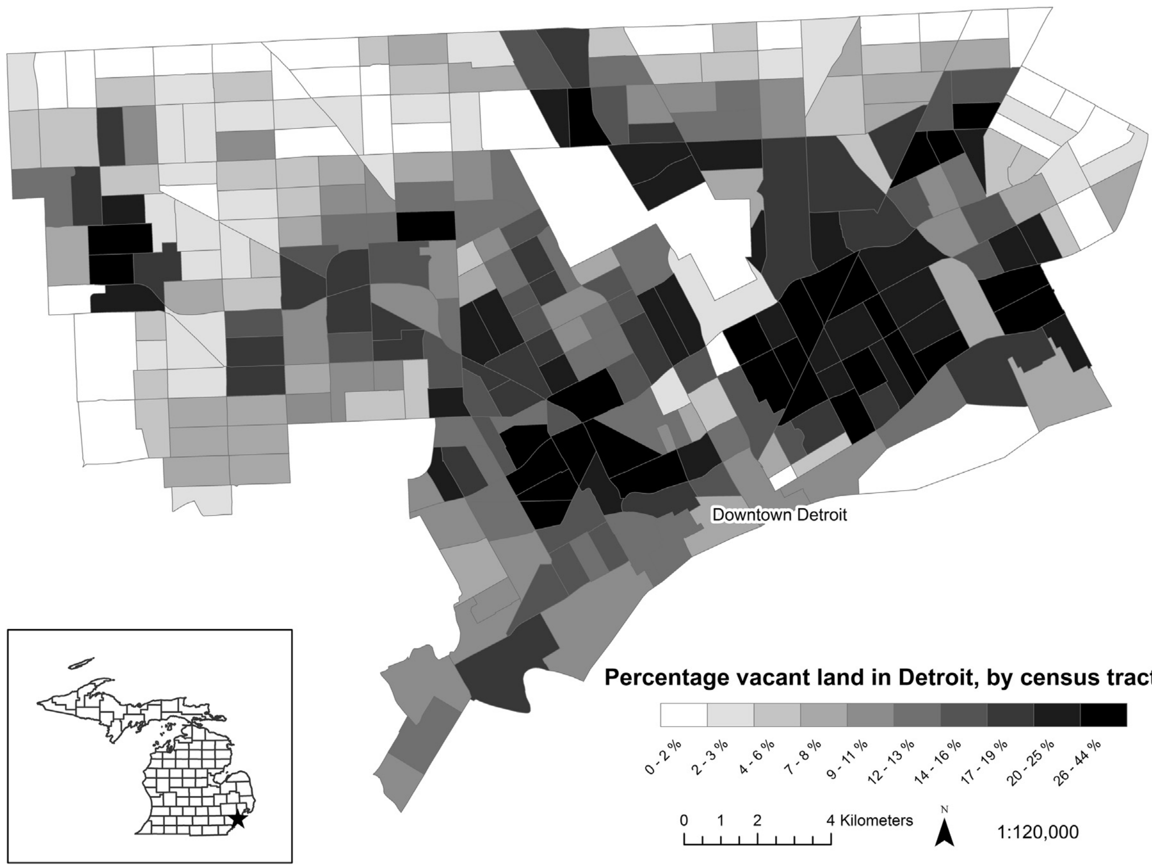

Fig. 1. Vacant land in Detroit neighborhoods, as a percent of total census tract area.
Note: The map shows the percent of the total area of each 2010 census tract made up of vacant parcels with no structure (Motor City Mapping, 2014).

2.2. The challenges of green infrastructure planning and Detroit

Evidence suggests that from a stormwater abatement perspective green infrastructure can be comparable, and in some instances superior, to gray infrastructure in terms of performance and cost (Jaffe et al., 2010; Casal-Campos et al., 2015). But it is the other co-benefits that really "tip the scale" in its favor (Palmer et al., 2015). To date, however, cities and their respective government agencies have not fully accounted for the multiple ecosystem services that green infrastructure provides, including tradeoffs and synergies between these services (Elmqvist et al., 2016; Hansen & Pauleit, 2014; Lovell & Taylor, 2013; Madureira & Andresen, 2013; Snäll, Lehtomäki, Arponen, Elith, & Moilanen, 2015). Part of this is due to the planning silos that persist in cities, making it difficult to bring together different departments and groups (Kambites & Owen, 2006; Thorne et al., 2015). For this reason, Larsen (2015, p. 488) has called for a new "green infrastructure utility" focused on providing multiple ecosystem services. Transcending these barriers is critical as green infrastructure functions are highly local, with a limited "service benefit area" (Hansen & Pauleit, 2014). Where green infrastructure gets sited, therefore, determines who and what reaps these benefits (Meerow & Newell, 2016). Despite the obvious implications for environmental and social justice and the acknowledgement that spatial planning decisions – particularly those related to sustainability– are invariably based on conflicting criteria and priorities (Campbell, 1996), we lack fundamental knowledge of whether green infrastructure developments are equitably distributed *across* cities (Brink et al., 2016).

Detroit is one city where green infrastructure has emerged as a planning priority, making it an interesting, timely, and appropriate case study city to examine and improve these processes (Schilling & Logan, 2008). For decades, the loss of manufacturing, population decline, weak tax revenue base, and social strife have plagued the city. It has one of the nation's highest rates of property vacancy, with over 40 square miles of vacant residential, commercial, and industrial land (Fig. 1). This represents almost one in four of Detroit's properties and totals approximately 100,000 properties—nearly 20% of the city's total land area (Dewar, 2006). The city is also grappling with increasingly intense and frequent precipitation events due to climate change (Karl, Melillo, & Peterson, 2009).

The abundant underutilized land in Detroit presents opportunities for transformation and urban redevelopment, if appropriate strategies and policies can be put in place (Herrmann et al., 2016). In the late 1990s, green infrastructure emerged as a revitalization strategy for the city, beginning with the transformation of abandoned rail infrastructure into greenways (Gallagher, 2010). Green infrastructure projects are being planned and implemented by city and regional agencies, non-profit organizations (NGO), and private entities. The most significant player thus far is the Detroit Water and Sewerage Department (DWSD), a public utility that provides services to the city and administers a sprawling water-sewage infrastructure to communities across seven counties. Facing increasingly strict EPA water regulations and the need to reduce flows into its combined sewer system, DWSD has invested in bioretention, green streets, and tree planting projects (DWSD, 2015). For similar reasons, the NGO Greening of Detroit is planting trees in many parts of the city, often in partnership with DWSD. To catalyze community redevelopment in particularly hard-hit areas of the city, green infrastructure projects are also being implemented in the Lower East Side of Detroit through the EPA-funded Great Lakes Restoration Initiative (GLRI). Fig. 2 presents the locations of these major green infrastructure initiatives. Additionally,

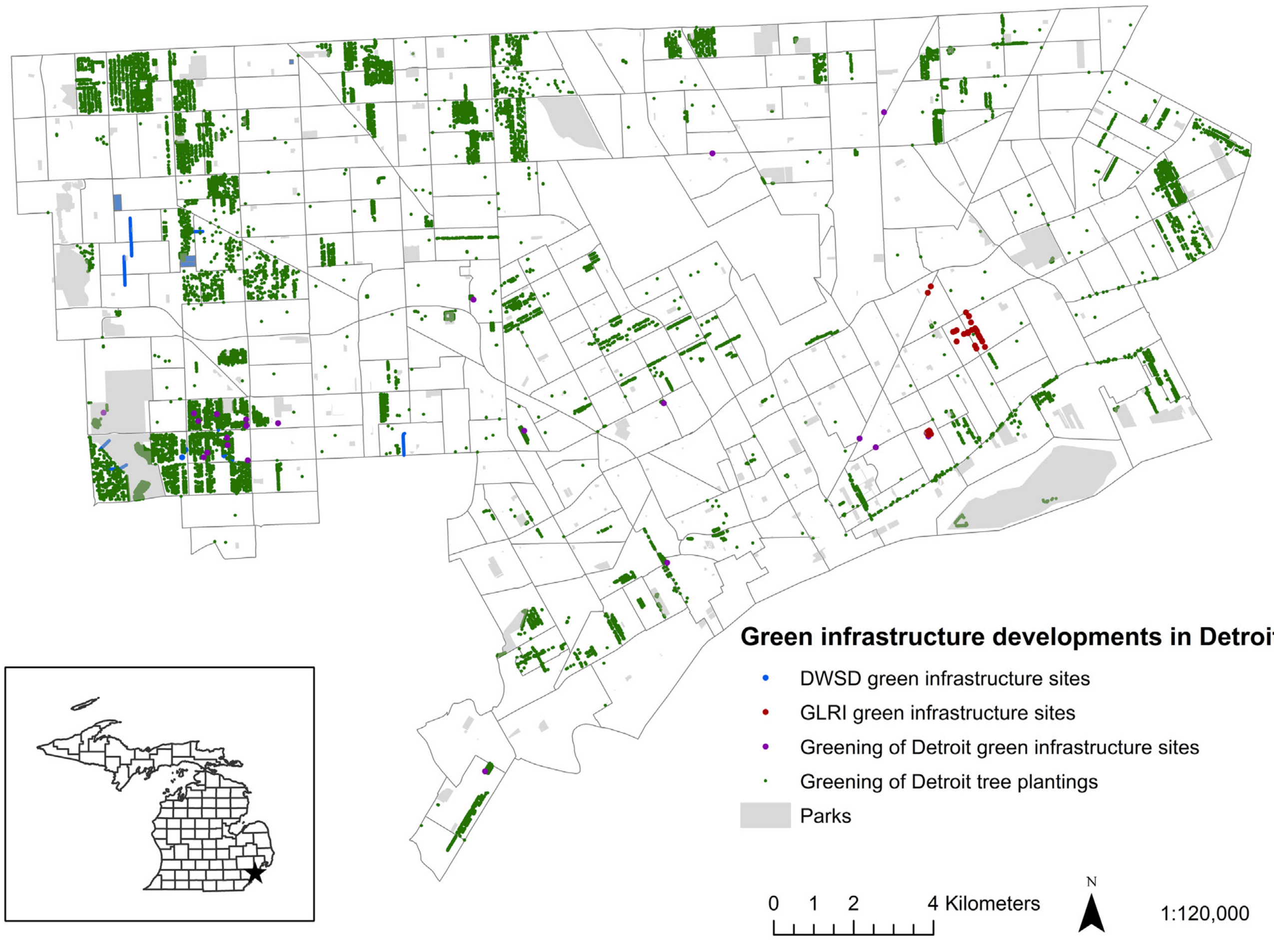

Fig. 2. Locations of major green infrastructure projects across the city of Detroit. (Please see the web version of this article for a color version of this figure.)
Note: Data on Detroit Water and Sewerage Department (DWSD) sites from Tetra Tech (2016); Great Lakes Restoration Initiative (GLRI) sites from Detroit Future City (2016); and greening and tree planting data from Greening of Detroit (2016a, 2016b).

private actors are also engaged in greening initiatives. For example, Hantz Woodlands, to the alarm of community groups, purchased a large block of consolidated land parcels in the lower eastside from the city and planted trees ostensibly for future harvest (Safransky, 2014).

But are these projects being planned and sited in locations that enhance multiple aspects of urban sustainability and resilience? Or are they being sited haphazardly, opportunistically, and for the purpose of one benefit, such as stormwater, rather than a suite of potential ecosystem service benefits (e.g., improved air quality, access to green space, habitat connectivity)?

To answer these questions and to identify spatial tradeoffs, synergies, and areas in Detroit where green infrastructure could be strategically sited to maximize *multifunctionality*, we developed an integrated stakeholder-driven modeling approach called the Green Infrastructure Spatial Planning (GISP) model.

3. Methods: Green Infrastructure Spatial Planning (GISP) model

The GISP model is GIS-based and uses a spatial multi-criteria evaluation (MCE) framework that incorporates stakeholder priorities so the results serve as collaborative decision-support tools (Jankowski and Nyerges, 2001). GIS-based or spatial MCE models allow stakeholders – defined broadly as "the individuals who affect or are affected by certain decisions and actions" (Freeman 1984 in Prell, Hubacek, & Reed, 2009, p. 515) – to visualize the implications of their preferences and identify tradeoffs in policy goals (Malczewski, 2006). For this reason, MCE has been referred to as an "institution in action" to build support for sustainable and resilient solutions (De Brucker, MacHaris, & Verbeke, 2013, p. 122).

Although multifunctional green infrastructure planning needs to consider stakeholder preferences (Hansen and Pauleit, 2014), relatively few studies use a GIS-based MCE approach to do so. Kremer et al. (2016) apply spatial MCE to evaluate the distribution of ecosystem services across New York City as a means to identify priority areas for green infrastructure. They demonstrate the potential impact of different weighting schemes, but do not use stakeholder-derived weights. Madureira and Andreson (2013) identify "spatial priority areas" for green infrastructure in Porto, Portugal, but based on just two criteria: 1) access to green space and 2) potential to reduce the UHI effect. They also do not incorporate stakeholder input to weight these criteria. Similarly, Norton et al. (2015) identify priority areas within the City of Port Phillip in Melbourne, Australia on the basis of the cooling benefits of green infrastructure. Conine, Xiang, Young, and Whitley (2004) do use stakeholder-derived weights in their GIS analysis to identify potential greenway sites in Concord, North Carolina, but do not consider tradeoffs of this green infrastructure. Recent work by Hoang et al. (2016) introduces a helpful methodology and tool to examine spatial benefit tradeoffs and synergies of specific green infrastructure interventions designed to manage urban flooding. However, they do not integrate stakeholder weights or use the model to identify priority areas across the entire city. Therefore, the GISP

Table 2
Detroit stakeholder survey results.

Method	1-Stormwater	2-SoVI	3-Green space	4-UHI	5-Air quality	6-Connectivity
Rating						
Order	**1**	**2**	**3**	**6**	**4**	**5**
Mean rating	4.61	4.39	4.18	3.70	4.17	3.78
Standard deviation	0.66	0.71	0.83	0.91	0.87	1.02
Ranking						
Order	**1**	**2**	**4**	**6**	**3**	**5**
Mean ranking	1.79	3.11	3.53	5.00	3.42	4.16
Standard deviation	1.18	1.20	1.50	1.20	1.64	1.77
Pair-wise comparisons						
Order	**1**	**3**	**4**	**6**	**2**	**5**

approach advances spatial MCE modeling for green infrastructure by integrating an array of ecosystem services and local stakeholder priorities and by assessing tradeoffs and synergies to facilitate equitable distribution and leverage co-benefits.

3.1. Six ecosystem benefit criteria

The six benefit criteria, or ecosystem services, described in Section 2.1 serve as the foundation of the GISP model (Table 1). The scale of analysis is the 2010 U.S. census tract, the smallest spatial unit for which data were readily available for all criteria. To make the GISP model generalizable for other cities, we used publicly available pre-processed data, or that readily obtainable from stakeholders. We applied a linear scale transformation ("score range") to measurement scales so all criterion scores ranged from zero to one (Malczewski, 1999). To assess synergy and tradeoff patterns, we used Pearson's bivariate correlations for all census tracts in Detroit (N = 296) to test relationships between the criteria scores. Results were cross-checked with Spearman's rank correlations and tradeoff patterns were consistent. Using ESRI's ArcGIS Online and Story Maps applications, we then integrated the individual and combined criteria maps into a web-based interface. The selection rationale, data sources, limitations, and processing steps for the six benefit criteria are as follows:

3.1.1. Stormwater

To identify areas prioritized based on stormwater management concerns, we combined two indicators: 1) an estimated runoff coefficient using the Rational Method, originally proposed by Mulvany in 1850 (O'Loughlin, Huber, & Chocat, 1996); and 2) CSO waste water discharges (location and volume). The runoff coefficient was calculated using a modified land use layer based on high-resolution parcel-level land use data (SEMCOG, 2008) and data on vacant (no structure) parcels (Motor City Mapping, 2014). Using the rational method, we estimated a relative runoff coefficient for each census tract by first assigning each land-use category in the land use layer a runoff coefficient (Table A1), and then multiplied these coefficients by the area of that land-use classification within each tract. Obtaining coefficients from the literature (Strom, Nathan, & Woland, 2009), we validated them by consulting a Detroit-based stormwater expert (personal communication, February 5, 2016). For each census tract, we summed the results of each land-use category and then divided it by the total tract area (Table 2).

For the CSO indicator, we summed the total diluted raw sewage released at all discharge locations (2008–2014) within each census tract. This indicator was then standardized (0–1). Census tracts with no discharge locations received a score of 0. We then added the standardized scores for both the runoff coefficient and the CSO indicator and rescaled the combined score from 0 to 1.

3.1.2. Social vulnerability

Social vulnerability is challenging to measure, with various methods of assessing and mapping it (Cutter & Finch, 2008; Dunning & Durden, 2013). We used the Social Vulnerability Index (SoVI) created by the Hazards and Vulnerability Research Institute (Cutter, Boruff, & Shirley, 2003; Cutter and Finch, 2008). Freely available to many states through NOAA and other sources, SoVI is arguably the most well-established and widely -used methodology (Dunning & Durden, 2013). SoVI is a composite index of socio-economic and demographic variables that research has shown relate to susceptibility to natural hazards, but 11 of the variables (including wealth, age, density of the built environment, housing, and race) account for more than 75 percent of variance between U.S. counties. The SoVI version used in the GISP model compares census tract scores for the 27-variable index across Detroit (Hazards and Vulnerability Research Institute, 2015).

3.1.3. Access to green space

For access to green space, the available indicator was relative 'park poverty.' Spatial data on all city parcels within a 10-min walk of a park (SEMCOG, 2016) served as the basis of the analysis. To generate this dataset, which entailed calculating all parcels within a half mile of park entry points along the walkable road network (excluding non-walkable features such as highways, highway ramps), SEMCOG used the Pandas for Network Analysis (Pandana) extension in UrbanSim (Waddell, 2002). To calculate the percentage of the total area in each census tract falling outside of the 10-min walking distance, we compared this SEMCOG dataset with a city-wide parcel layer (City of Detroit, 2015) and census tract information. We then multiplied this percentage by the total tract population (2010 Census), resulting in an estimate of the population without park access for each tract. It does not account for variations in park size or quality, however, which is a limitation. This methodology is similar to that used by Wolch et al. (2005), but differs in that rather than a simple buffer distances along the walkable road network are used.

3.1.4. Urban heat island

To map the UHI, the mean daytime land surface temperatures for three summer months (June–August 2010) were calculated for each census tract. Burillo, Chester, Chang, and Thau et al. (2015) derived temperatures using Moderate Resolution Imaging Spectrometer (MODIS) sensor data and the Google Earth Engine API. For validation, we compared census tract scores with percent impervious surface in each tract, a proven indicator of the UHI effect (Yuan & Bauer, 2007). They were significantly positively correlated (.53, $p < 0.00$).

3.1.5. Air quality

A high-resolution spatial air pollution model based on traffic-related emissions, developed by Batterman and Ganguly (2013a), was the data source for air quality. We used the model's simulated annual average emissions of particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$) for 2010. We focused on $PM_{2.5}$ because the World Health Organization (2013) has concluded that long-term exposure to $PM_{2.5}$ has a higher mortality risk than PM_{10} (World Health Organization, 2013). As the air quality model uses a 150 square meter grid, for those instances where the grid did not align with census tract boundaries, we used the mean of all intersecting grid cells.

3.1.6. Landscape connectivity

The GISP model uses metrics related to the structural connectivity of the landscape, which relates to the impact of habitat structure on biodiversity (Itkonen, Viinikka, Heikinheimo, & Kopperoinen, 2015). We used the Patch Cohesion Index metric in Fragstats, a free software used to measure physical connectedness of habitat patches (McGarigal, Cushman, & Ene, 2012).

Areas classified as 'forest' in the land cover dataset (2010) served as representative patches based on the assumption that this land cover type would provide habitat for the largest number of species in the Detroit region. Even if green infrastructure development does not all focus on reforestation, Colding's (2007) theory of "ecological land-use complementation" suggests that it would still be beneficial to cluster new vegetation near existing forest patches.

We used Geospatial Modeling Environment (Beyer, 2014) software to convert the forest polygons from vector to raster cells so Fragstats could analyze them individually. This does make the results subject to edge effects, since each tract is analyzed in isolation. Tracts were then analyzed as a batch to generate a Patch Cohesion Index score for each tract, and those with higher connectivity scores were prioritized.

3.2. Local stakeholder priorities

After constructing maps for the six indicators, we held a meeting in Detroit with 23 expert stakeholders representing government agencies, local and national nonprofits, and community development organizations (Table A2). Stakeholders were selected in consultation with local contacts on the basis of their expertise and leadership in green infrastructure and urban development issues in Detroit. At the meeting, these stakeholders weighted the model criteria based on which green infrastructure benefits they valued most by completing a survey asking them to compare the importance of the six benefit criteria using three methods: rating, ranking, and pair-wise comparisons. Stakeholders also provided feedback on the data sources and criteria used in the model and its broader utility as part of an open discussion at the meeting. We audio recorded the meeting for subsequent review. Stakeholders were also asked via email to provide anonymous feedback on both the model and meeting. They were also given the opportunity to review a draft of this paper prior to publication.

We used the ESRI Story Maps application to present the individual criteria and aggregated results based on different weights from the stakeholders' ranking and pair-wise comparison survey results. For the latter, we used an Excel-based AHP calculator (Goepel, 2013). We then used weighted linear combination to develop combined maps from the two sets of weights to identify 'hotspots' or priority neighborhoods for green infrastructure expansion. As distribution of scores differed significantly across the criteria, individual criterion scores were first divided into 10 quantiles before applying weights and combining them.

3.3. Mapping existing projects in Detroit

To generate a map of major public green infrastructure projects underway or planned in Detroit (Fig. 2), we included current projects to be implemented by 2016 by the DWSD, Greening of Detroit, and the Great Lakes Restoration Initiative (Greening of Detroit, 2016a; Detroit Future City, 2016; Tetra Tech, 2016). Although no comprehensive map of all green infrastructure projects for the city exists yet, these projects were identified by city stakeholders as the major public ones. We then calculated the total number of individual locations that intersected with each census tract in the City of Detroit. Some projects are more spatially extensive than others (e.g. parks vs. tree planting), but as we only had data on the locations, we counted them all equally. We then compared these sites with those identified as priority areas for green infrastructure by the GISP model by running Pearson's correlations

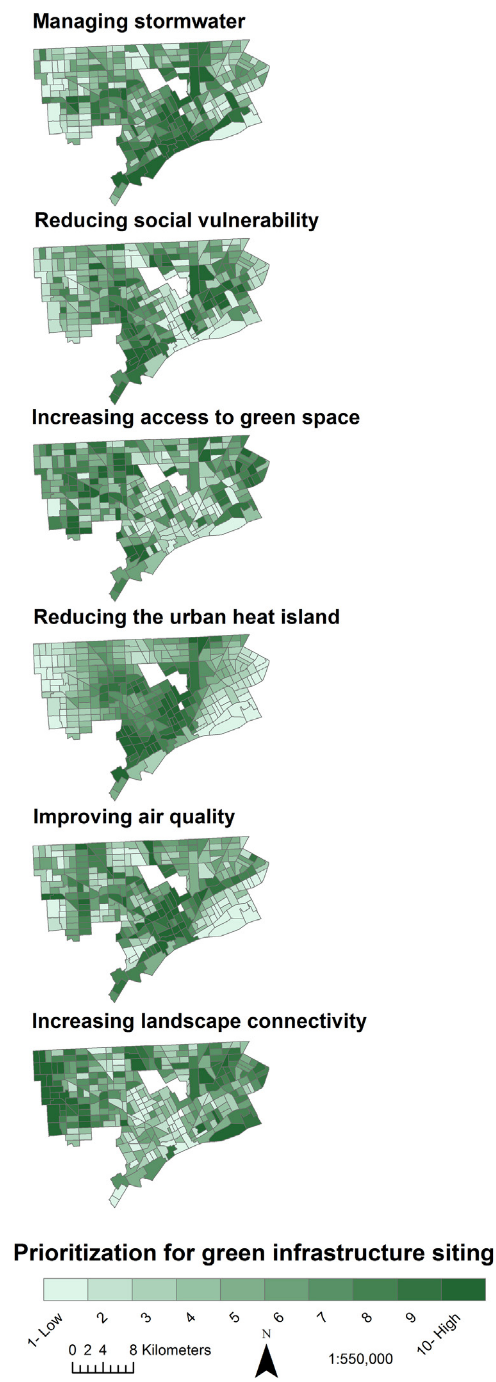

Fig. 3. Six Green Infrastructure Spatial Planning (GISP) model criteria: Each map shows the relative prioritization of census tracts in Detroit for green infrastructure based on a commonly cited green infrastructure benefit. (Please see the web version of this article for a color version of this figure.)

between the number of sites in each census tract and the GISP model scores (individual criteria and combined and stakeholder-weighted results). We also ran correlations at the census tract level between vacant land and the green infrastructure sites, based on the rationale that vacancy and blight in some neighborhoods may provide an added incentive and opportunity for green infrastructure development.

4. Results: green infrastructure tradeoffs, synergies, and hotspots

Applying the GISP model to the city of Detroit reveals that some areas have a greater need for green infrastructure interventions than other parts of the city, and that these locations differ by ecosystem service. Areas that would be high priority for stormwater abatement, for example, are generally not best suited for maximizing landscape connectivity. Priority locations for other resilience benefits, including addressing stormwater, urban heat island, and air quality problems, appear more synergistic, but a strategic planning process is still needed in order to capitalize on these synergies and manage trade-offs. Unfortunately, such a process seems to be lacking in Detroit, as the locations of current green infrastructure projects across the city do not align with most of the priority areas identified with the GISP model. For example, Detroit stakeholders claimed that reducing social vulnerability was an important benefit of green infrastructure (second only to stormwater abatement), yet projects have not been sited in areas where residents are most vulnerable according to the SoVI. By combining different planning criteria and weighting them according to local stakeholders' priorities, the GISP model could enable planners to identify 'hotspots' where green infrastructure has the greatest potential to foster social and ecological resilience.

Tradeoffs between the six resilience benefits considered in the GISP model are evident spatially (Fig. 3) and through negative correlations. We see a statistically significant negative relationship between stormwater and landscape connectivity criteria (Fig. 4). Thus, restoring the urban ecological fabric by siting green infrastructure near more interconnected forest habitat patches would not place it in ideal locations to abate stormwater, and vice versa. Landscape connectivity is also negatively correlated with UHI and air quality, which is not surprising given that vegetation is thought to contribute to cooler local temperatures and less air pollution (Larsen, 2015). These spatial tradeoffs reveal that *multifunctionality* across all benefits can be an elusive goal and underscores the fact that planning for green infrastructure is a contested and political process, in which tradeoffs have to be understood and negotiated. This is reflective of sustainability and resilience planning more broadly.

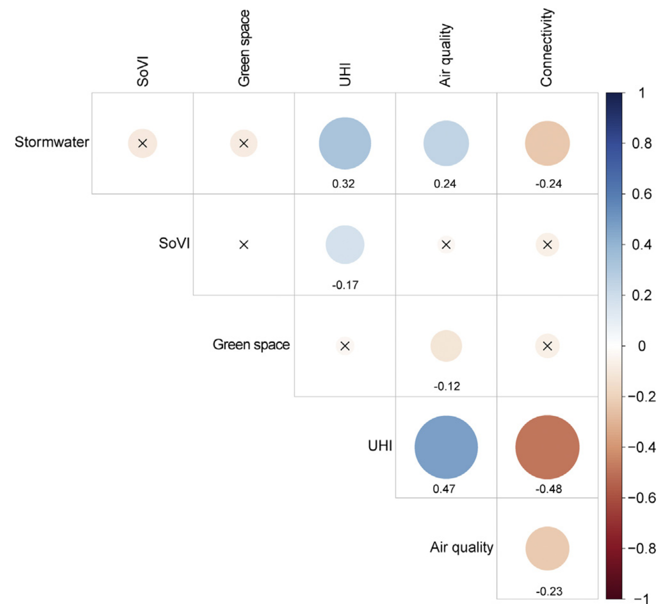

Fig. 4. Spatial trade-offs and synergies between GISP model criteria.
Note: The diameter size and shading of circles depict the Pearson's correlation coefficient for GISP model criteria. A larger circle indicates a stronger negative (red) or positive (blue) relationship. Circles marked with an "X" are not statistically significant. (Please see the web version of this article for a color version of this figure.)

The GISP model also reveals potential spatial synergies across the Detroit landscape where green infrastructure can enhance resilience. Positive correlations are statistically significant for stormwater, UHI, and air quality. Thus, even if stormwater concerns drive siting decisions, green infrastructure will also be located in areas that suffer from urban heat island and air quality impacts. Areas of high social vulnerability are also areas that suffer from heat island impacts, which is concerning since vulnerable communities are less able to cope with extreme heat events (O'Neill et al., 2009). Given that UHI and air quality criteria are also positively correlated, public health concerns seem to be co-located, at least in Detroit. Prior research has also shown a negative interaction between poor air quality and mortality due to extreme heat

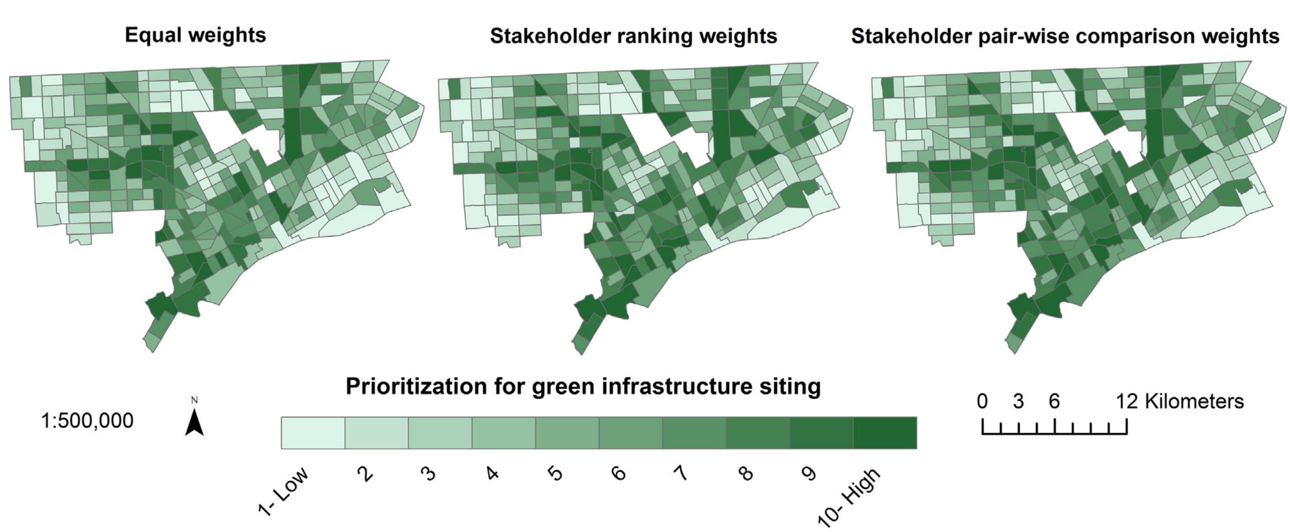

Fig. 5. Combined criteria using different weighting methods. (Please see the web version of this article for a color version of this figure.)

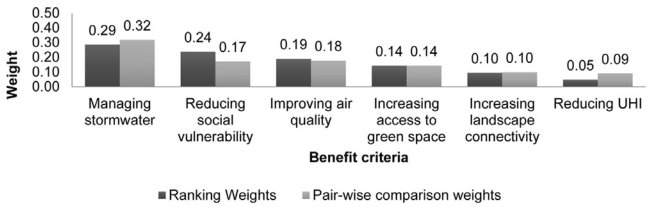

Fig. 6. Stakeholder priorities for green infrastructure in Detroit, by benefit category.

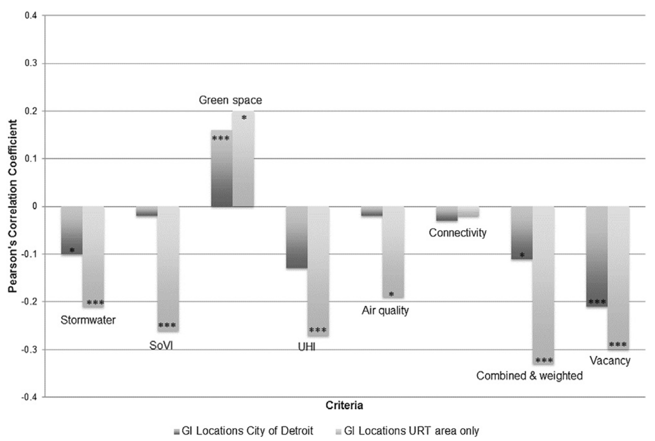

Fig. 7. Pearson's correlation coefficients for Detroit green infrastructure locations and GISP model criteria and vacancy rates *Note:* "*" indicates correlations are statistically significant at $p < 0.1$; "***" indicates significant at $p < 0.05$.

(Harlan & Ruddell, 2011). This may provide an added incentive to locate green infrastructure in these areas, especially with rising global temperatures.

In light of citywide tradeoff and synergy patterns, it is helpful to identify specific high priority 'hotspots' (through the spatial overlay of all six criteria using linear combination) where green infrastructure is most needed in Detroit. As illustrated in Fig. 5, these hotspots shift slightly based on whether criteria are weighted equally or stakeholders' priorities are taken into account. However some areas, such as the southwest part of Detroit, do consistently appear as high priority for multifunctional green infrastructure. The Detroit expert stakeholders identified stormwater as the most important priority, based on survey results (Table 2) and the weights derived from them (Fig. 6). Reducing social vulnerability, increasing access to green space, and improving air quality were regarded as the next most important criteria. The ranking among these criteria shifted based on weighting method. The mean rating and ranking values suggest that social vulnerability was slightly higher priority than the other two, but all three are close. The landscape connectivity criterion came out fifth out of the six criteria in terms of importance. UHI amelioration was the lowest priority (ranked 6th in all three survey questions). Although beyond the scope of this study, examining how expert stakeholder priorities compare with Detroit residents' at large would be interesting.

4.1. *Assessment of green infrastructure project siting in Detroit*

So how do current and planned green infrastructure projects in Detroit align with the siting hotspots identified by the GISP modeling? Fig. 2 shows green infrastructure sites across the city, with projects by DWSD, Greening of Detroit, and the Great Lakes Restoration Initiative represented. Statistical analysis (Fig. 7) reveals that across the city, at a census tract scale, these sites are reducing park poverty (significant positive correlation), but not being sited in geographic areas that would be high priority for stormwater, UHI, social vulnerability, air quality, or habitat connectivity (all negatively correlated, stormwater and UHI significantly so). Even when Detroit stakeholders' priorities are used to weight and combine criteria, the results are still significantly negatively correlated with current green infrastructure sites (Fig. 8).

Large areas of vacant land in Detroit make it hypothetically easier to implement new green infrastructure and blight removal provides an added incentive. Therefore, one would expect these green infrastructure sites to be situated in areas of the city with especially high vacancy rates (Fig. 1), but analysis, at least at the census tract scale, indicates that this is not the case. In fact, there is a negative correlation between vacant land area percentages and green infrastructure locations (Fig. 7). Why this is so remains unclear and is an area for future research. DWSD's green infrastructure program is specifically designed to reduce runoff to the combined sewer system in the Upper Rouge River Tributary area, so it is logical that projects are clustered in that area. To account for this focus, we also ran correlations for just the census tracts in this region. The directions of the relationships do not change, and in most cases they actually have a stronger statistical significance (Fig. 7). This suggests that even within this priority stormwater area, there is a missed opportunity for city planners to leverage green infrastructure co-benefits.

5. Discussion

The results of the GISP model suggest that current green infrastructure projects in Detroit are not being strategically planned to maximize multiple ecosystem service benefits. As this study has illustrated, there will be spatial tradeoffs and synergies among and between these benefits. To make the green infrastructure planning process more effective, these tradeoffs and synergies need to be understood, contested, and negotiated, especially since siting it has significant implications for resource use, equity, and health across time and space. Indeed, if it were being planned more holistically to support social-ecological resilience in Detroit, the locations of the projects would be quite different. A more strategic and integrated process could help to ensure that multiple ecosystem services are provided to areas of the city that need them most.

The GISP model provides a flexible tool to facilitate this process by operationalizing a green infrastructure approach that "seeks to steer spatial planning towards integrated land use governance, wherein multifunctional ecosystem services potential are realized through enhancing positive synergies between abiotic, biotic and social systems." (Lennon & Scott, 2014, p. 574) This is not an entirely new or radical goal. Indeed, the underlying principles of multifunctional landscapes and the societal benefits of green space can be traced back to the 19th century, with the work of Frederick Law Olmsted and Ebenezer Howard (Eisenman, 2013; Mell, 2008). Over the last decade, however, a broader consensus on the meaning and value of multifunctional green infrastructure has emerged (Mell, 2016). Lennon and Scott (2014, p. 570) argue that the recent popularity of green infrastructure is part of a larger shift from planning for "sustainable development" and city competitiveness to planning to create "resilient places" and ecosystem services. This shift is driven in part by a growing concern with climate change impacts. Green infrastructure has "positioned itself as a 'go-to' approach in contemporary landscape planning, as it holistically addresses climate change, social development, and economic valuation simultaneously." (Mell, 2016, p. 5) Planning for multiple benefits requires breaking down traditional silos in cities, and this may be challenging, but a shared interest in promoting 'resilience' may be one way to get stakeholders from different departments or agencies into the same room. Resilience can serve a valuable

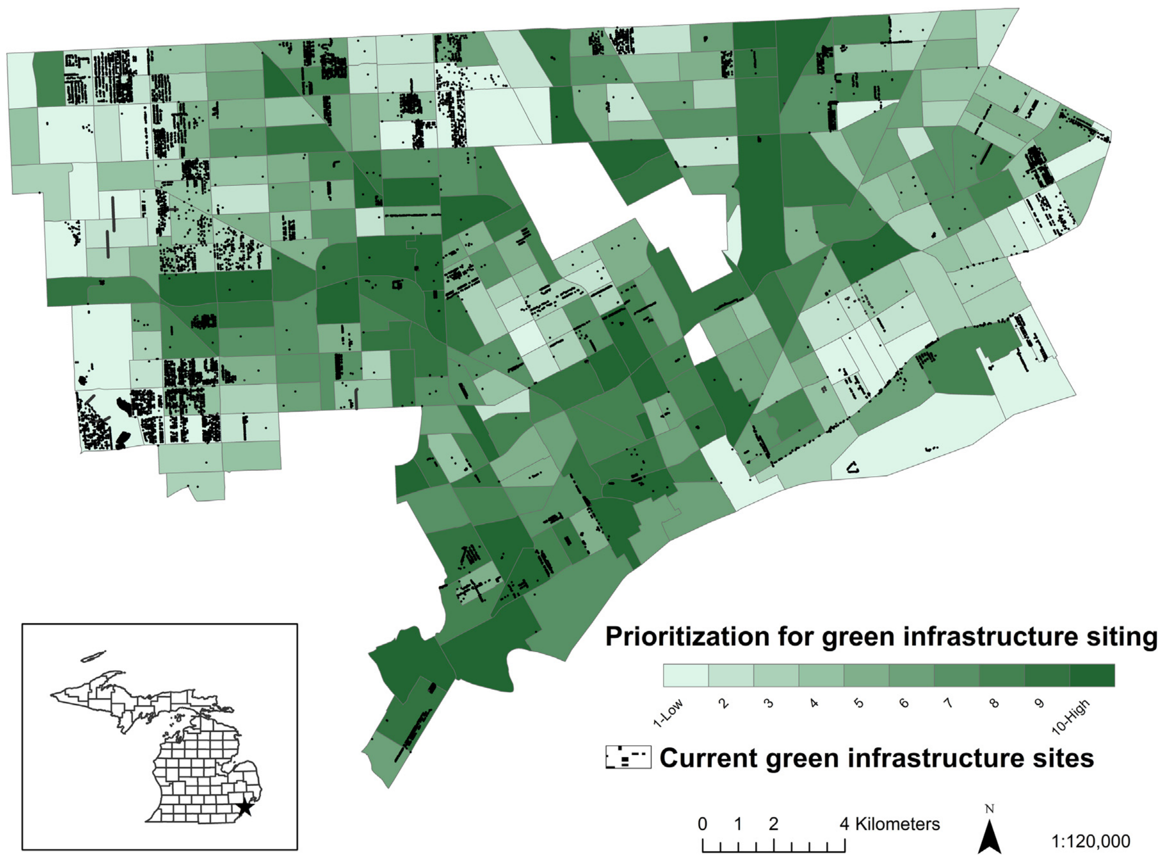

Fig. 8. Overlay of current green infrastructure project locations and GISP model combined criteria scores using stakeholder pairwise comparison weights. (Please see the web version of this article for a color version of this figure.)

function in this way, as a uniting concept or so-called "boundary object" (Brand & Jax, 2007; Meerow et al., 2016).

While the GISP model is useful as a way to operationalize a multifunctional resilience-based approach to spatial planning, it should not be considered a land suitability analysis, since it does not look at specific parcels nor does it consider land use, cost, or other constraints on green infrastructure development. In addition, the GISP model is not decision support for choosing specific green infrastructure technologies, since numerous additional factors would need to be considered. For example, filtration technologies would only be appropriate for areas where groundwater is not contaminated.

Rather, the model is best suited for identifying areas to focus on for green infrastructure development as part of a city's master or vision plan, to be followed up with finer-scale analysis. The GISP model, especially when presented in an easy-to-use web-based Story Map format (Fig. 9 and at www.gispmodel.com), is valuable as a planning tool for considering tradeoffs and benefits. As a representative of the Detroit City Planning Commission noted in the meeting, "As a planner for the city I think this would be very useful both from a macro level as we are looking at a master plan and from a neighborhood redevelopment and planning level."

We considered six ecosystem services criteria, but the modeling approach allows for additional criteria. For future iterations of the model, stakeholders suggested, for example, including data on flooding, asthma deaths (air quality indicator), soil type and historical hydrological network (stormwater indicator), and additional land cover types such as open space, wetlands, etc., and data on canopy quality (landscape connectivity indicator). Incorporating additional criteria hinges in part on data availability, which also poses a challenge with respect to the scale of analysis considered. Our unit of analysis was the census tract, for which there is a wealth of socio-economic and demographic data. However, each tract represents an average of 4000 residents, so there can be significant variability within them that is not captured in the model. Additionally, they are unrelated to the scales at which governance or planning occurs. Research is currently underway that quantifies both the services and potential 'disservices' (e.g. water use in arid climates and increased pests and allergens (Lo & Balbus, 2015; Pataki et al., 2011)) associated with green infrastructure. As the results from these studies emerge they can be incorporated into the GISP model and the benefit criteria adjusted accordingly.

Finally, the GISP model can be applied as a spatial planning approach for a broad swath of cities. Comparing modeling results and stakeholder priorities across different cities will build generalizable knowledge about ecosystem service tradeoff and synergy patterns, how green infrastructure is sited, and how stakeholders perceive the importance of its various benefits.

6. Conclusion

A growing number of scholars, organizations, and cities like Detroit are promoting green infrastructure as an alternative to traditional gray stormwater infrastructure, as a way to provide multiple ecosystem services to residents, and as a strategy for enhancing urban sustainability and resilience. A primary rationale for expanding green infrastructure is *multifunctionality*, yet most studies and green infrastructure plans to-date, including those in Detroit, focus only on one or a few of the benefits and do not examine tradeoffs or synergies. This represents a missed opportunity to enhance social-ecological resilience and equity.

This paper has introduced a generalizable spatial planning approach that integrates six commonly cited benefits of green

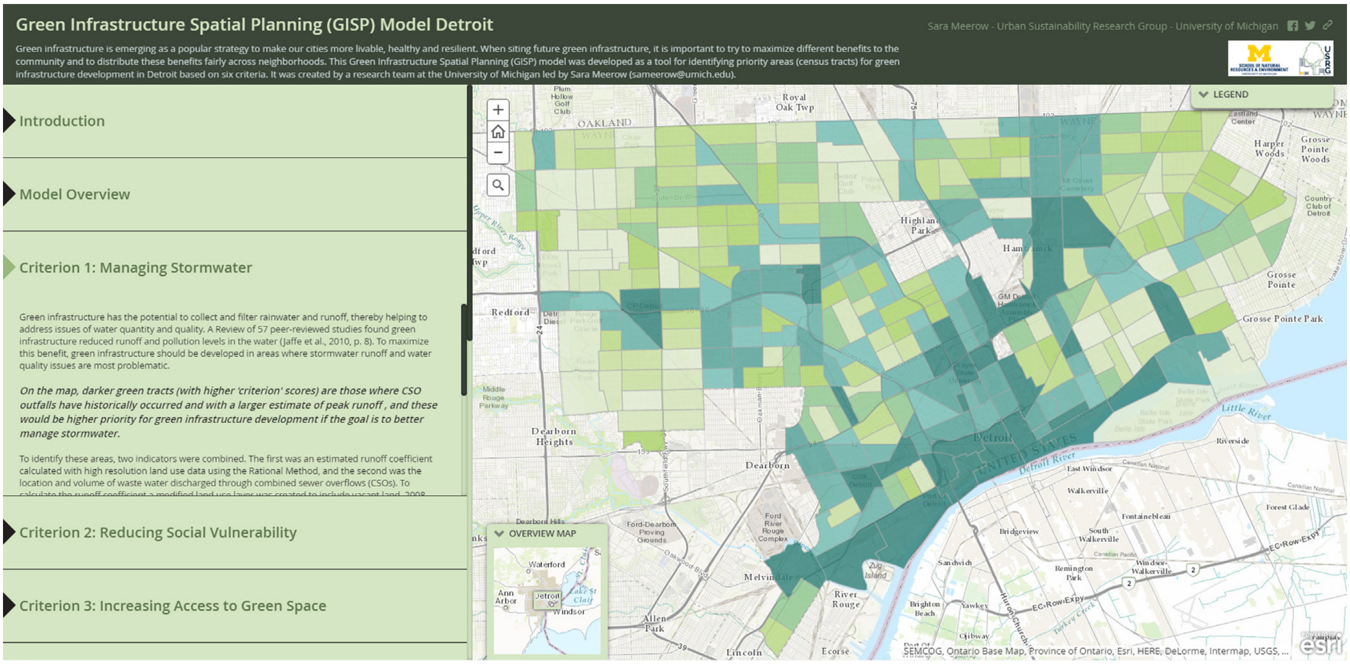

Fig. 9. Screenshot of the stormwater GISP model criterion in the web-based Story Map (www.gispmodel.com). (Please see the web version of this article for a color version of this figure).

infrastructure (addressing stormwater, social vulnerability, park poverty, UHI, air pollution, and landscape connectivity problems) into a GIS-based MCE model. Priority areas for the six criteria are individually mapped, and then combined, taking into account local stakeholders' planning priorities. This approach can assist local communities, planners, and agencies in identifying 'hotspots', assessing potential spatial tradeoffs, and ultimately enabling these decision-makers to create green infrastructure plans that incorporate a wider range of socio-economic and environmental benefits and local resilience priorities.

We used the GISP model to examine ongoing green infrastructure developments in the City of Detroit. The results revealed important tradeoffs (e.g. between stormwater and connectivity criteria) and synergies (e.g. stormwater, UHI, and air quality) in priority areas, illustrating why a strategic spatial planning process is needed in order to maximize ecosystem service benefits. Our findings suggest that this process could be improved in Detroit. The locations of current green infrastructure projects do not match the modeled priority areas. Detroit stakeholders identified reducing social vulnerability as an important benefit, but our analysis suggests that projects are not being sited in areas with the most vulnerable populations or even the highest vacancy rates.

The GISP modeling approach shows promise both as an aid to facilitate more strategic siting decisions in applied settings and as a research instrument to examine synergies and tradeoffs in green infrastructure benefits. Initially developed using six criteria for Detroit, the modeling approach can be adopted for the spatial planning of other ecosystem services in a wide range of cities.

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Appendix A.

Table A1
Rational method coefficients[a].

Land use classification	Coefficient
Commercial	0.6
Governmental	0.6
Industrial	0.8
Multi Family Residential	0.65
Single Family Residential	0.4
Parks and Open Space	0.2
Transportation, Communication, and Utilities	0.85
Airport	0.85
Water	0
Vacant, No Structure	0.3

[a] Adapted from Strom et al. (2009).

Table A2
Detroit expert stakeholder meeting participants, January 2016.

Name of organization	Type
1. Alliance for the Great Lakes	Local Nonprofit
2. Brightmoor Alliance	Community development organization
3. City of Detroit General Services Department	Municipal government
4. Detroit City Planning Commission	Municipal government
5. Detroit Economic Growth Corporation	Local nonprofit
6. Detroit Economic Growth Corporation	Local nonprofit
7. Detroit River Conservancy	Local nonprofit
8. Detroit Water and Sewerage Department	Municipal government
9. Detroit Water and Sewerage Department	Municipal government
10. Detroit Workers for Environmental Justice	Local nonprofit
11. Eastside Community Network	Community development organization
12. Grandmont Rosedale Development Corporation	Community development organization
13. Greening of Detroit	Local nonprofit
14. Michigan Department of Environmental Quality	State government
15. Michigan Department of Environmental Quality	State government
16. Midtown Detroit, Inc.	Community development organization
17. Southeast Michigan Council of Governments	Regional planning organization
18. Southwest Detroit Environmental Vision	Local nonprofit
19. Tetra Tech, Inc.	Local consulting company
20. The Erb Family Foundation	Charitable foundation
21. The Nature Conservancy	International nonprofit
22. Urban Neighborhoods Initiative	Local nonprofit
23. United States Forest Service	Federal government

References

Ahern, J. (2007). Green infrastructure for cities: The spatial dimension. In V. Novotny, & P. Brown (Eds.), *Cities of the Future: Towards Integrated Sustainable Water and Landscape Management* (pp. 268–283). London: IWA Publishing.

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning*, *100*(4), 341–343. http://doi.org/10.1016/j.landurbplan.2011.02.021

Ahern, J. (2013). Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology*, *28*(6), 1203–1212. http://doi.org/10.1007/s10980-012-9799-z

Alcock, I., White, M. P., Wheeler, B. W., Fleming, L. E., & Depledge, M. H. (2014). Longitudinal E ff ects on Mental Health of Moving to Greener and Less Green Urban Areas. *Environmental Science & Technology*, *8*, 1247–1255. http://doi.org/10.1021/es403688w

Andersson, E., Barthel, S., Borgström, S., Colding, J., Elmqvist, T., Folke, C., & Gren, A. (2014). Reconnecting cities to the biosphere: Stewardship of green infrastructure and urban ecosystem services. *Ambio*, *43*(4), 445–453. http://doi.org/10.1007/s13280-014-0506-y

Batterman, S., Ganguly, R. (2013). High Resolution Spatial and Temporal Mapping of Air Pollution in Detroit Project Final Report. Ann Arbor, Michigan.

Batterman, S., & Ganguly, R. (2013). *High resolution spatial and temporal mapping of air pollution in detroit*. [Data file].

Benedict, M. A., & McMahon, E. T. (2002). Green infrastructure: Smart conservation for the 21 st century. *Renewable Resources Journal*, *20*(3), 12–17 [Retrieved from] http://www.rnrf.org/rrjtofc.html

Berkooz, C. B. (2011). Green infrastructure storms ahead. *Planning*, *77*(3), 19–24.

Beyer, H.L., Geospatial Modeling Environment, [Computer software] (2014), [Available from:] http://www.spatialecology.com.

Bounoua, L., Zhang, P., Mostovoy, G., Thome, K., Masek, J., Imhoff, M., . . . & Toure, A. M. (2015). Impact of urbanization on US surface climate. *Environmental Research Letters*, http://doi.org/10.1088/1748-9326/10/8/084010

Brand, F. S., & Jax, K. (2007). Focusing the meaning (s) of resilience: Resilience as a descriptive concept and a boundary object. *Ecology and Society*, *12*(1) [Retrieved from]. http://www.ecologyandsociety.org/vol12/iss1/art23/

Brink, E., Aalders, T., Ádám, D., Feller, R., Henselek, Y., Hoffmann, A., . . . & Wamsler, C. (2016). Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, *36*, 111–123. http://doi.org/http://dx.doi.org/10.1016/j.gloenvcha.2015.11.003

Burillo, D., Chester, M., Chang, A., & Thau, D. (2015). *Forecasting changes in urban heat island in the US southwest. tempe*. [Retrieved from]. https://repository.asu.edu/attachments/159669/content/burillo_uhi_southwest_cities.pdf

Campbell, S. (1996). Green cities, growing cities, just cities?: urban planning and the contradictions of sustainable development. *Journal of the American Planning Association*, *62*(3), 296–312. http://doi.org/10.1080/01944369608975696

Carson, T. B., Marasco, D. E., Culligan, P. J., & McGillis, W. R. (2013). Hydrological performance of extensive green roofs in New York City: Observations and multi-year modeling of three full-scale systems. *Environmental Research Letters*, *8*(2), 024036. http://doi.org/10.1088/1748-9326/8/2/024036

Casal-Campos, A., Fu, G., Butler, D., & Moore, A. (2015). An integrated environmental assessment of green and gray infrastructure strategies for robust decision making. *Environmental Science & Technology*, 8307–8314. http://doi.org/10.1021/es506144f

Chelleri, L., Waters, J. J., Olazabal, M., & Minucci, G. (2015). Resilience trade-offs: Addressing multiple scales and temporal aspects of urban resilience. *Environment and Urbanization*, *27*(1), 181–198. http://doi.org/10.1177/0956247814550780

City of Detroit. (2015). *Parcel map. [Data file]*. [Available from]. https://data.detroitmi.gov/Property-Parcels/Parcel-Map/fxkw-udwf

Colding, J. (2007). Ecological land-use complementation for building resilience in urban ecosystems. *Landscape and Urban Planning*, *81*(1–2), 46–55. http://doi.org/10.1016/j.landurbplan.2006.10.016

Conine, A., Xiang, W. N., Young, J., & Whitley, D. (2004). Planning for multi-purpose greenways in Concord, north carolina. *Landscape and Urban Planning*, *68*(2–3), 271–287. http://doi.org/10.1016/S0169-2046(03)00159-2

Cutter, S. L., & Finch, C. (2008). Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(7), 2301–2306. http://dx.doi.org/10.1073/pnas.0710375105

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social Vulnerability to Environmental Hazards. *Social Science Quarterly*, *84*(2), 242–261. http://dx.doi.org/10.1111/1540-6237.8402002

Cutter, S. L. (1996). Vulnerability to environmental hazards. *Progress in Human Geography*, *20*(4), 529–539. http://doi.org/10.1177/030913259602000407

Detroit Water and Sewerage Department. (2015). *Green infrastructure progress report upper rouge tributary area*.

Danielsen, F., Sørensen, M. K., Olwig, M. F., Selvam, V., Parish, F., Burgess, N. D., . . . & Suryadiputra, N. (2005). The Asian tsunami: A protective role for coastal vegetation. *Science*, *310*(5748), 643. http://doi.org/10.1126/science.1118387

Data Driven Detroit. (2015). *Detroit Water & Sewerage waste water discharge event location data (2008–2014)*. [Data file]. [Available from:]. http://portal.datadrivendetroit.org/datasets/362e9b82411249c8a6aa3e3d4c20f800_0

Davoudi, S., Shaw, K., Haider, L., Jamila, Q., Allyson, E., Peterson, G. D., . . . & Porter, L. (2012). Resilience: A bridging concept or a dead end? reframing resilience: Challenges for planning theory and practice interacting traps: Resilience assessment of a pasture management system in Northern Afghanistan urban resilience: What does it mean in planni. *Planning Theory & Practice*, *13*(2), 299–333.

De Brucker, K., MacHaris, C., & Verbeke, A. (2013). Multi-criteria analysis and the resolution of sustainable development dilemmas: A stakeholder management approach. *European Journal of Operational Research*, *224*(1), 122–131. http://doi.org/10.1016/j.ejor.2012.02.021

Detroit Future City. (2016). *GLRI sites [Data file]*.

Dewar, M. (2006). Selling tax reverted land: Lessons from Cleveland and Detroit. *Journal of the American Planning Association*, *72*(2), 167–180. http://dx.doi.org/10.1080/01944360608976737

Dunn, A. D. (2010). Siting green infrastructure: Legal and policy solutions to alleviate urban poverty and promot healthy communities. *Environmental Affairs*, *37*, 41–66.

Dunning, M. C., & Durden, S. (2013). *Social vulnerability analysis: A comparison of tools*. VA Institute for Water Resources: Alexandria [Retreived from: http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/Social_Vulnerability_Analysis_Tools.pdf]

Eisenman, S. T. (2013). Frederick law olmsted, green infrastructure, and the evolving city. *Journal of Planning History*, *12*(4), 287–311. http://doi.org/10.1177/1538513212474227

Elmqvist, T., Gomez-Baggethun, E., & Langemeyer, J. (2016). Ecosystem services provided by urban green infrastructure. In *Routledge handbook of ecosystem services*. New York, NY: Routledge.

Ernstson, H., Barthel, S., & Andersson, E. (2010). Scale-Crossing brokers and network governance of urban ecosystem services: The case of stockholm. *Ecology and Society*, *4*(28) [Retrieved from]. http://www.ecologyandsociety.org/vol15/iss4/art28/

European Commission (1997). *EU Compendium of Spatial Planning Systems and Policies. Regional Development Studies Report 28*. Luxembourg.

Foster, J., Lowe, A., & Winkelman, S. (2011). *The value of green infrastructure for urban climate adaptation*. [Retrieved from]. http://ccap.org/assets/The-Value-of-Green-Infrastructure-for-Urban-Climate-Adaptation_CCAP-Feb-2011.pdf

Gallagher, J. (2010). *Reimagining detroit opportunities for redefining an american city*. Detroit, Michigan: Wayne State University Press.

Godschalk, R. D. (2003). Urban hazard mitigation: Creating resilient cities. *Natural Hazards Review*, *4*(3), 136–143. http://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136)

Goepel, K. D. (2013). Implementing the analytic hierarchy process as a standard method for multi-Criteria decision making In corporate enterprises ?A new AHP excel template with multiple inputs. *Proceedings of the international symposium on the analytic hierarchy process*, 1–10 [Retrieved from]. http://bpmsg.com/wp-content/uploads/2013/06/ISAHP_2013-13.03.13.Goepel.pdf

Greening of Detroit. (2016a). *Greening of detroit OpenTreeMap*. [Data retrieved from]. https://www.opentreemap.org/thegreeningofdetroitstreemap/map/

Greening of Detroit. (2016b). *Greening of detroit projects 53116 [Data file].*

Hansen, R., & Pauleit, S. (2014). From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. *Ambio*, *43*(4), 516–529. http://doi.org/10.1007/s13280-014-0510-2

Harlan, S. L., & Ruddell, D. M. (2011). Climate change and health in cities: Impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability*, *3*, 126–134. http://dx.doi.org/10.1016/j.cosust.2011.01.001

Herrmann, D. L., Schwarz, K., Shuster, W. D., Berland, A., Chaffin, B. C., Garmestani, A. S., & Hopton, M. E. (2016). Ecology for the shrinking city. *Bioscience*, *66*(11), 965–973. http://doi.org/10.1093/biosci/biw062

Heynen, N. (2006). Green urban political ecologies: Toward a better understanding of inner-city environmental change. *Environment and Planning A*, *38*(3), 499–516. http://doi.org/10.1068/a37365

Hoang, L., Fenner, R. A., & Skenderian, M. (2016). A conceptual approach for evaluating the multiple benefits of urban flood management practices. *Flood Risk Management*, http://doi.org/10.1002/jfr.12267

Itkonen, P., Viinikka, A., Heikinheimo, V., Kopperoinen, L. (2015). ESGreenBelt: A preliminary study on spatial data and analysis methods for assessing the ecosystem services and connectivity of the protected areas network of the Green Belt of Fennoscandia. Helsinki. Retrieved from www.ym.fi/julkaisut.

Hazards and Vulnerability Research Institute (2015). Social Vulnerability Index 2006-2010 Detroit Census Tract [Data file].

Jaffe, M., Zellner, M., Minor, E., Gonzalez-Meler, M., Cotner, L., Bucci, M.D., Miller, B., The illinois green infrastructure study: A report to the Illinois Environmental Protection Agency on the criteria in section 15 of Public Act 96-0026, The Illinois Green Infrastructure for Clean Water Act of 2009, 2010, Chicago, IL. [Retrieved from] http://www.epa.state.il.us/green-infrastructure/docs/draft-final-report.pdf.

Jankowski, P., & Nyerges, T. (2001). *GIS for group decision making*. New York, NY: Taylor & Francis.

Jennings, V., Gaither, C. J., & Gragg, R. S. (2012). Promoting environmental justice through urban green space access: A synopsis. *Environmental Justice*, *5*(1), 1–7. http://doi.org/10.1089/env.2011.0007

Jim, C. Y., Yo, Alex, Y., & Byrne, J. A. (2015). Charting the green and climate-adaptive city. *Landscape and Urban Planning*, *138*, 51–53. http://doi.org/10.1016/j.landurbplan.2015.03.007

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., . . . & Bonn, A. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas – perspectives on indicators, knowledge gaps, barriers and opportunities for action. *Ecology and Society*, *21*(2) http://doi.org/10.5751/ES-08373-210239

Kambites, C., & Owen, S. (2006). Renewed prospects for green infrastructure planning in the UK 1. *Planning Practice and Research*, http://doi.org/10.1080/02697450601173413

Kardan, O., Gozdyra, P., Misic, B., Palmer, F., Moola, F., Lyle, J., . . . & Marc, G. (2015). Neighborhood greenspace and health in a large urban center. *Scientific Reports*, *5*(11610), 11610. http://doi.org/10.1038/srep11610

Kong, F., Yin, H., Nakagoshi, N., & Zong, Y. (2010). Urban green space network development for biodiversity conservation: Identification based on graph theory and gravity modeling. *Landscape and Urban Planning*, *95*(1–2), 16–27. http://doi.org/10.1016/j.landurbplan.2009.11.001

Kremer, P., Hamstead, Z. A., & McPhearson, T. (2016). The value of urban ecosystem services in New York City: A spatially explicit multicriteria analysis of landscape scale valuation scenarios. *Environmental Science & Policy*, *62*, 57–68. http://doi.org/10.1016/j.envsci.2016.04.012

Kuo, F. E., & Sullivan, W. C. (2001). Environment and crime in the inner city: Does vegetation reduce crime? *Environment and Behavior*, *33*(3), 343–367. http://doi.org/10.1177/0013916501333002

Larsen, L. (2015). Urban climate and adaptation strategies. *Frontiers in Ecology and the Environment*, *13*(9), 486–492. http://doi.org/10.1890/150103

Lennon, M., & Scott, M. (2014). Delivering ecosystems services via spatial planning: Reviewing the possibilities and implications of a green infrastructure approach. *Town Planning Review*, *85*(5), 563–587. http://doi.org/10.3828/tpr.2014.35

Lo, M., & Balbus, J. (2015). Making green infrastructure healthier infrastructure. *Infection Ecology and Epidemiology*, *5*, 1–11. http://doi.org/10.3402/iee.v5.30082

Lovasi, G. S., Quinn, J. W., Neckerman, K. M., Perzanowski, M. S., & Rundle, A. (2008). Children living in areas with more street tress have lowe asthma prevalence. *Journal of Epidemiology & Community Health*, *62*, 647–649.

Lovell, S. T., & Taylor, J. R. (2013). Supplying urban ecosystem services through multifunctional green infrastructure in the United States. *Landscape Ecology*, *28*(8), 1447–1463. http://doi.org/10.1007/s10980-013-9912-y

Maas, J., Dillen, S. M. E., Van Verheij, R. A., & Groenewegen, P. P. (2009). pp. 586–595. *Health & Place Social contacts as a possible mechanism behind the relation between green space and health* (15) http://doi.org/10.1016/j.healthplace.2008.09.006

Maas, J., Spreeuwenberg, P., Van Winsum-Westra, M., Verheij, R. A., de Vries, S., & Groenewegen, P. P. (2009). Is green space in the living environment associated with people's feelings of social safety? *Environment and Planning A*, *41*(7), 1763–1777. http://doi.org/10.1068/a4196

McGarigal, K., Cushman, S.A., Ene, E. (2012). FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. [Computer software], 2012, [Available from:] http://www.umass.edu/landeco/research/fragstats/fragstats.htm.

Madureira, H., & Andresen, T. (2013). Planning for multifunctional urban green infrastructures: Promises and challenges. *Urban Design International*, *19*(1), 38–49. http://doi.org/10.1057/udi.2013.11

Malczewski, J. (1999). *GIS and multicriteria decision analysis*. New York, NY: John Wiley & Sons.

Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science*, *20*(7), 703–726. http://doi.org/10.1080/13658810600661508

Meerow, S., & Newell, J. P. (2016). Urban resilience for whom, what, when, where, and why? *Urban Geography*., http://doi.org/10.1080/02723638.2016.1206395

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, *147*, 38–49. http://doi.org/10.1016/j.landurbplan.2015.11.011

Mell, I. C. (2008). Green Infrstructure: Concepts and planning. *Forum*, *8*, 69–80.

Mell, I. (2016). *Global Green Infrastructure: Lessons for successful policy-making, investment and management*. New York, NY: Routledge.

Mitchell, M. G. E., Bennett, E. M., & Gonzalez, A. (2013). Linking landscape connectivity and ecosystem service provision: Current knowledge and research gaps. *Ecosystems*, *16*(5), 894–908. http://doi.org/10.1007/s10021-013-9647-2

Motor City Mapping. (2014). *Motor city mapping, winter 2013-14 certified results: [Data file]*. [Available from:]. http://d3.d3.opendata.arcgis.com/datasets/7cfed5afb7654e2495ef4c1ead320aa5_0

Nassauer, J. I., & Raskin, J. (2014). Urban vacancy and land use legacies: A frontier for urban ecological research, design, and planning. *Landscape and Urban Planning*, *125*, 245–253. http://doi.org/10.1016/j.landurbplan.2013.10.008

Newell, J. P., Seymour, M., Yee, T., Renteria, J., Longcore, T., Wolch, J. R., & Shishkovsky, A. (2013). Green Alley Programs: Planning for a sustainable urban infrastructure? *Cities*, *31*, 144–155. http://doi.org/10.1016/j.cities.2012.07.004

Norton, B. A., Coutts, A. M., Livesley, S. J., Harris, R. J., Hunter, A. M., & Williams, N. S. G. (2015). Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and Urban Planning*, *134*, 127–138. http://doi.org/10.1016/j.landurbplan.2014.10.018

O'Loughlin, G., Huber, W., & Chocat, B. (1996). Rainfall-runoff processes and modelling. *Journal of Hydraulic Research*, *34*(6), 733–751. http://doi.org/10.1080/00221689609498447

O'Neill, M. S., Carter, R., Kish, J. K., Gronlund, C. J., White-Newsome, J. L., Manarolla, X., . . . & Schwartz, J. D. (2009). Preventing heat-related morbidity and mortality: New approaches in a changing climate. *Maturitas*, *64*, 98–103. http://doi.org/10.1016/j.maturitas.2009.08.005

Palmer, B. M. A., Liu, J., Matthews, J. H., & Mumba, M. (2015). Water security: Gray or green? Manage water in a green way. *Science*, *349*(6248), 584–585. http://dx.doi.org/10.1126/science.aac7778

Pataki, D. E., Carreiro, M. M., Cherrier, J., Grulke, N. E., Jennings, V., Pincetl, S., . . . & Zipperer, W. C. (2011). Coupling biogeochemical cycles in urban environments: Ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, *9*(1), 27–36. http://dx.doi.org/10.1890/090220

Prell, C., Hubacek, K., & Reed, M. (2009). Stakeholder Analysis and Social Network Analysis in Natural Resource Management. *Society & Natural Resources*, *22*(6), 501–518. http://dx.doi.org/10.1080/08941920802199202

Pugh, T. A. M., Mackenzie, A. R., Whyatt, J. D., & Hewitt, C. N. (2012). Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environmental Science & Technology*, *46*(14), 7692–7699. http://doi.org/10.1021/es300826w

Rung, L., Broyles, S. T., Mowen a, J., Gustat, J., & Sothern, M. S. (2011). Escaping to and being active in neighbourhood parks: Park use in a post-disaster setting. *Disasters*, *35*(2), 383–403. http://doi.org/10.1111/j.1467-7717.2010.01217.x

SEMCOG. (2008). *Land use. [Data file]*. http://semcog.org/plans-for-the-region/environment/land-use

SEMCOG. (2010). *SEMCOG Land cover for developing a green infrastructure vision. [Data file].*

SEMCOG. (2016). *Access to parks. [Data file].* [Available from SEMCOG website:]. /http://maps.semcog.org/accessparks

Safransky, S. (2014). pp. 237–248. *Greening the urban frontier: Race, property, and resettlement in Detroit. Geoforum* (56) http://dx.doi.org/10.1016/j.geoforum.2014.06.003

Sandström, U. G. (2002). Green infrastructure planning in urban Sweden. *Planning Practice & Research*, *17*(4), 373–385. http://doi.org/10.1080/02697450320000074461

Schilling, J., & Logan, J. (2008). Greening the rust belt: A green infrastructure model for right sizing america's shrinking cities. *Journal of the American Planning Association*, *74*(4), 451–466. http://doi.org/10.1080/01944360802354956

Snäll, T., Lehtomäki, J., Arponen, A., Elith, J., & Moilanen, A. (2015). Green infrastructure design based on spatial conservation prioritization and modeling of biodiversity features and ecosystem services. *Environmental Management*, 251–256. http://doi.org/10.1007/s00267-015-0613-y

Stone, B. (2012). *The city and the coming climate : climate change in the places we live*. New York, NY: Cambridge University Press.
Strom, S., Nathan, K., & Woland, J. (2009). *Site engineering for landscape architects* (5th ed.). Hoboken, NJ: John Wiley & Sons.
Taha, H. (1996). Modeling impacts of increased urban vegetation on ozone air quality in the South Coast Air Basin. *Atmospheric Environment*, *30*(20), 3423–3430. http://doi.org/10.1016/1352-2310
Takano, T., Nakamura, K., & Watanabe, M. (2002). Urban residential environments and senior citizens' longevity in megacity areas: The importance of walkable green spaces. *Journal of Epidemiology and Community Health*, *56*(12), 913–918. http://doi.org/10.1136/jech.56.12.913
Tetra Tech. (2016). *Green infrastructure projects in URT. [Data file].*
Thorne, C. R., Lawson, E. C., Ozawa, C., Hamlin, S. L., & Smith, L. A. (2015). Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management. *Journal of Flood Risk Management*, http://doi.org/10.1111/jfr3.12218
Tischendorf, L., & Fahrig, L. (2000). On the usage and measurement of landscape connectivity. *Oikos*, *90*(1), 7–19. http://doi.org/10.1034/j.1600-0706.2000.900102.x/j
Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., & James, P. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landscape and Urban Planning*, *81*(3), 167–178. http://doi.org/10.1016/j.landurbplan.2007.02.001
Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). *Global Climate Change Impacts in the United States*. Cambridge University Press.
Voskamp, I. M., & Van de Ven, F. H. M. (2015). Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. *Building and Environment*, *83*, 159–167. http://doi.org/10.1016/j.buildenv.2014.07.018
Vries, S. D., Verheij, R. A., Groenewegen, P. P., & Spreeuwenberg, P. (2003). Natural environments – healthy environments? An exploratory analysis of the relationship between greenspace and health. *Environment and Planning A*, *35*(10), 1717–1731. http://doi.org/10.1068/a35111
Waddell, P. (2002). UrbanSim — Modeling urban development for land use, transportation, and environmental planning. *Journal of the American Planning Association*, *68*(3), 297–314. http://doi.org/10.1080/01944360208976274
Ward, T. C., Roe, J., Aspinall, P., Mitchell, R., Clow, A., & Miller, D. (2012). More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landscape and Urban Planning*, *105*(3), 221–229. http://doi.org/10.1016/j.landurbplan.2011.12.015
Wardekker, J. A., de Jong, A., Knoop, J. M., & van der Jeroen, S. P. (2010). Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. *Technological Forecasting and Social Change*, *77*(6), 987–998. http://doi.org/10.1016/j.techfore.2009.11.005
Wilkinson, C. (2011). Social-ecological resilience: Insights and issues for planning theory. *Planning Theory*, *11*(2), 148–169. http://doi.org/10.1177/1473095211426274
Wilson, E., & Piper, J. (2010). *Spatial planning and climate change*. New York, NY: Routledge.
Wolch, J., Wilson, J. P., & Fehrenbach, J. (2005). Parks and park funding in los angeles: An equity-Mapping analysis. *Urban Geography*, *26*(1), 4–35.
Wolch, J., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities just green enough. *Landscape and Urban Planning*, *125*, 234–244. http://doi.org/10.1016/j.landurbplan.2014.01.017
World Health Organization. (2013). *Health effects of particulate matter.*
World Health Organization. (2014). *Burden of disease from ambient air pollution for 2012.*
Robert, R. F. (2011). Planting the living city. *Journal of the American Planning Association*, *77*(4), 368–381. http://doi.org/10.1080/01944363.2011.616996
Yuan, F., & Bauer, M. E. (2007). Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. *Remote Sensing of Environment*, *106*(3), 375–386. http://doi.org/10.1016/j.rse.2006.09.003

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