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Enhancing landscape connectivity through multifunctional green infrastructure corridor modeling and design

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ABSTRACT

Landscape connectivity is critical for ecosystem health and biodiversity conservation, yet urbanization is increasing habitat fragmentation. Green corridors that connect isolated remnant habitat patches (e.g. parks) can increase connectivity and provide ecosystem services in cities. Vacant land, especially prevalent in shrinking cities, presents a unique opportunity to reconnect these landscapes. This paper provides a practical and replicable approach for assessing landscape connectivity patterns and identifying priority locations for green corridors. The methodology integrates social and ecological factors coupled with site-scale multifunctional greenway designs and is applied to the city of Detroit as a proof of concept. First, we use FRAGSTATS to evaluate structural landscape connectivity patterns at a census tract scale. A functional connectivity assessment based on graph theory and Conefor software is used to validate the results, which indicate that habitat is highly fragmented in Detroit. To identify opportunities to reduce this fragmentation, we use a least-cost path approach to map potential green corridors linking city parks through vacant parcels, alleys, and smaller green spaces, and prioritize these corridors using a gravity model and network analysis. To make the model more concrete and useful for decision-makers, we develop site-level multifunctional corridor design typologies. This study presents a novel approach to assessing urban connectivity and a multi-scalar, systematic methodology for planning urban green infrastructure networks that connects landscape ecology with practical planning and design considerations to maximize social and ecological functions.

1. Introduction

Urban green space provides a variety of ecosystem services, including reduced air, water, and noise pollution, local climate regulation, and recreation opportunities (Bolund and Hunhammar, 1999). Green space also serves as habitat for different species and is important for maintaining biodiversity on an increasingly urbanized planet (Kong et al., 2010). Yet because of urban development, green spaces have become increasingly fragmented, negatively impacting population abundance, genetic variation within species, and species richness (Fahrig, 2003; Mckinney, 2002).

Habitat connectivity plays an important role in ecosystem health and resilience to global environmental change (Thompson and Gonzalez, 2017). To enhance connectivity and ecosystem services, urban green spaces should be linked by corridors, forming a network facilitating dispersal and movement (Bennett, 1999; Vergnes et al., 2012). Planning these networks necessitates a strategic, comprehensive spatial planning approach, but city planning agencies face competing priorities and limited resources. Building an ecologically optimal network is therefore often unrealistic. More focus is needed on “conservation opportunity,” whereby feasibility is factored into the equation (Lechner et al., 2015, p. 700).

This paper presents a practical, systematic approach for planning and expanding urban green space networks to enhance landscape connectivity and maximize social and ecological benefits by taking advantage of vacant and underused land.

While in some cities land is at a premium, “shrinking” or legacy cities have abundant vacant lots that could be repurposed and potentially converted into greenways (Draus et al., 2018; Frazier and Bagchi-Sen, 2015). Detroit is arguably the best known case, but shrinking cities are a global phenomenon (Wiechmann, 2008). The United States has more than 20 cities that are losing population (Pallagst, 2008). In

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Fig. 1. Vacant land in the City of Detroit (Detroit Open Data, 2014). Vacant parcels across the entire city of Detroit are shown in black.

Europe, as many as 40 percent of the cities with over a million residents are shrinking (Haase et al., 2014), and even in China some cities are losing residents (Long and Wu, 2016). Recent studies of shrinking cities highlight the potential for vacant land to be developed into green infrastructure and to provide ecosystem services (Frazier and Bagchi-Sen, 2015; Haase et al., 2014; Kim et al., 2015). Moreover, even cities with growing populations typically have vacant land. The Phoenix metropolitan region, for example, with a growing population of over 3.5 million, is estimated to have approximately 90,000 privately-owned vacant parcels (Smith et al., 2017).

We use the City of Detroit as a case study to develop, refine, and evaluate a methodology for identifying green corridors through vacant or underused land to increase citywide connectivity. Detroit is a large North American city with a population of approximately 670,000 (US Census Bureau, 2016). Like other shrinking cities, Detroit is grappling with a declining population, economic problems, and high rates of vacancy and neighborhood blight (Fig. 1). Thirty percent of Detroit's housing stock is vacant (US Census Bureau, 2015), amounting to nearly 100,000 parcels (Detroit Land Bank Authority, 2017). High vacancy rates present social and environmental challenges. For example, polluted soils are a concern if vacant land contains heavy metals or construction debris, and vacant residential land may be perceived as unsafe and therefore limit residents' mobility and physical activity (Wineman et al., 2014). On the other hand, if vacant land functions as permeable green infrastructure it may provide valuable habitat and aid in stormwater management (Németh and Langhorst, 2014). Schilling and Logan (2008) suggest that a neighborhood-scale vacant land greening strategy could benefit Detroit residents by increasing property values and empowering communities. Indeed, Detroit Future City's high-profile redevelopment plan recommended replacing aging "grey infrastructure" with nature-based green infrastructure built on existing vacant land (Detroit Works, 2012).

From a citywide to site-level scale, this paper outlines an interdisciplinary modeling approach that links scientific theory to real-world planning and design. First, we assess the current spatial pattern of structural and functional landscape connectivity at a neighborhood scale across the city of Detroit. Second, we systematically map potential green space corridors through vacant parcels, alleys, and smaller public green spaces to connect the city's remaining core habitat patches using a least-cost path approach at a citywide scale. Potential corridors are prioritized using a gravity model, and different scenarios developed and evaluated. To make the model more concrete, we propose site-level multifunctional design typologies, drawing on illustrative examples of existing locations in Detroit.

This research advances our understanding of urban landscape connectivity and strategies for enhancing it. Our review of the literature suggests that connectivity studies to date have mostly focused on broader spatial scales encompassing multiple local jurisdictions. But land use planning decisions are often made at the municipal level (Randolph, 2003). Additionally, few studies compare both structural and functional connectivity, with most focusing on structural connectivity from a land use planning perspective or emphasizing ecologically-based functional connectivity (LaPoint et al., 2015). Although vacant land has been identified as an opportunity for greening strategies in shrinking cities (Schilling and Logan, 2008), systematic models that capitalize on vacant land to provide both social and ecological benefits are lacking. Next, we outline the methodology we used to address this gap.

2. Methodology

This multi-scalar landscape connectivity study has three components (Fig. 2). First, we assess greenspace connectivity at a census tract scale using FRAGSTATS software and validate the results using Conefor (Saura and Torné, 2009). Second, least-cost path analysis is used to identify feasible corridors to connect existing habitat patches (city parks) at a citywide scale. Corridors are prioritized with a gravity model and combined to create different green space network scenarios. These scenarios are evaluated based on their contribution to overall connectivity. Finally, site-level design typologies are developed for the corridors based on common land use arrangements.

2.1. Assessing landscape connectivity at a census tract and citywide scale

To identify how landscape connectivity varies across the city and to prioritize neighborhoods for future green development, we assess connectivity at both a census tract (average area 1.25 square kilometers, 296 in total) and citywide scale. There are three forms of connectivity: 1) *structural*; 2) *functional* or *potential*; and 3) *actual*. Structural connectivity is the physical structure between patches, potential/functional connectivity incorporates an individual organism's behavior in response to the landscape matrix, and actual connectivity is derived from empirical movement observations (Calabrese and Fagan, 2004; Uezu et al., 2005). Measuring potential/functional and actual connectivity is more

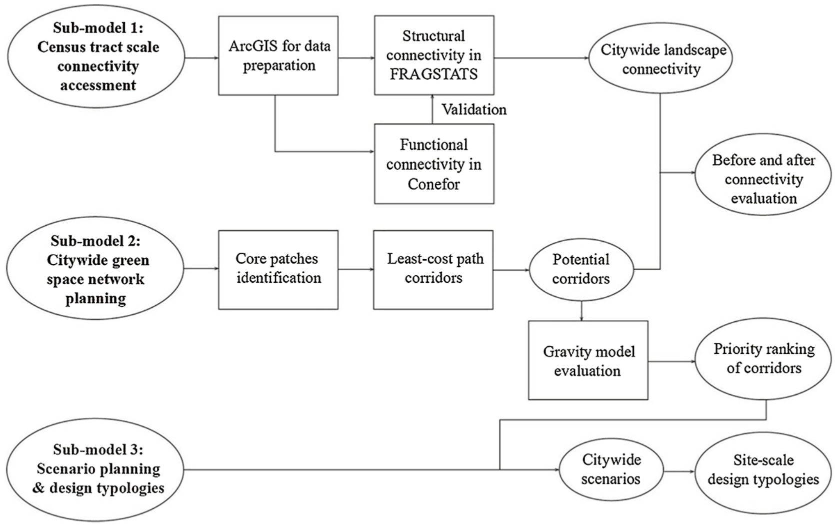


Fig. 2. The connectivity modeling process applied in Detroit. Squares represent processes and circles represent the outputs/results.

challenging than structural connectivity because species dispersal data is required. We are not focused on any particular species, so we considered habitat patches to be all areas of tree canopy in the Southeast Michigan Council of Governments (SEMCOG) one-meter resolution National Agricultural Program (NAIP) imagery dataset (Maheshwari and Vernier, 2012), assuming that trees would house the greatest variety of species. Tree canopy data was clipped by census tract boundaries (2010) into 296 raster files using a Python script in ArcGIS 10.4.

FRAGSTATS 4.2.1 (McGarigal et al., 2012) was then used to calculate class level landscape connectivity metrics for all census tracts and for the city as a whole. The tract-scale analysis reveals the variation in landscape connectivity across city neighborhoods, while the citywide scale shows the overall connectivity level. COHESION (see Appendix A), an index measuring the physical connectedness of the corresponding patch type (tree canopy), was examined for each tract individually and for the entire city. For every census tract unit and the entire city area we built a 20-meter buffer to reduce the impact of edge effects.

One limitation of FRAGSTATS is that it measures structural connectivity, which does not fully represent ecological functions (Kupfer, 2012; Li and Wu, 2004). However, structural connectivity may still serve as an indicator of functional connectivity (Correa Ayram et al., 2015) and thus landscape metrics arguably remain valuable (Kupfer, 2012). To validate this, we compared the FRAGSTATS results for a subset of the census tracts using a functional connectivity metric from Conefor, a software for measuring functional connectivity (Saura and Torné, 2009).

2.1.1. Validation using Conefor

Conefor uses graph theory, with points (nodes) representing habitat patches and lines (edges) denoting linkages between patches (Minor and Urban, 2008; Mitsova et al., 2011). We used the Conefor extension in ArcMap to calculate the integral index of connectivity (IIC), which compares the distance between patches with the threshold dispersal distance of a certain species (Saura and Torné, 2009), and which has been identified as the most suitable metric for landscape conservation planning (Pascual-Hortal and Saura, 2006; Bishop, 2015).

Of the 296 Detroit census tracts, 30 were randomly selected for Conefor analysis, and then the results compared with those from FRAGSTATS. The distance threshold for calculating IIC (see Appendix B) was set to 20 m with the assumption that it would be a reasonable distance for small, common urban species such as squirrels and birds to move (Bélisle and Desrochers, 2002; Bridgman et al., 2012). Pearson's correlation coefficients were used to examine the relationship between IIC and COHESION metrics for all 30 sampled census tracts. Conefor could not be used to calculate IIC at a citywide scale because the dataset exceeded the software's maximum capacity.

2.2. Citywide greenspace network planning model

The second sub-model focuses on identifying and connecting core habitat patches across the city. First, we identified core tree canopy habitat patches in Detroit. These patches were then connected by corridors using a least-cost path model. A gravity model was used to prioritize corridors.

2.2.1. Identifying core patches

Core patches refer to the areas of high quality habitat for different species that remain in the city (Yu et al., 2012). We initially attempted to account for potential edge effects by classifying core patches as those where the width was three times the average tree height (Firehock and Walker, 2015), with a minimum central area of 12 ha (0.2 square km), as suggested by Kong et al., (2010) and Xun et al., (2014). The spatial data was derived from a 2012 SEMCOG land cover layer based on 2010 aerial imagery with a one foot pixel resolution (resampled and classified at one meter) (Maheshwari and Vernier, 2012). Only two patches on the mainland met this criterion (left image, Fig. 3). Although core patches are limited—confirming the extent of habitat fragmentation in Detroit— remaining green spaces such as city parks would still likely provide valuable habitat and other ecosystem services (Fuller et al., 2007). Thus, we ultimately included all 16 city parks larger than 12 ha (right image, Fig. 3).

2.2.2. Mapping potential corridors using a least cost theory approach

We identified corridors to connect these core patches through a 'least-cost path' approach, referring to the 'easiest' route that wildlife can take from one patch to another (Etherington and Penelope Holland, 2013). In practice, the path cost is often indicated by the perceived difficulty for a species to traverse the landscape, and the least-cost route through the most favorable land cover types (Lechner et al., 2017).

The analysis assumes that vacant land, existing green spaces (parks and open space), and alleys would be the most suitable land use types for developing corridors, and we identified layers for the city of Detroit representing each of these (Table 1). Within each layer we assigned suitability scores to specific land uses. For example, vacant lots with trees were deemed more suitable than those with structures (Table 1). Then the analytic hierarchy process (AHP), a multi-criteria decision

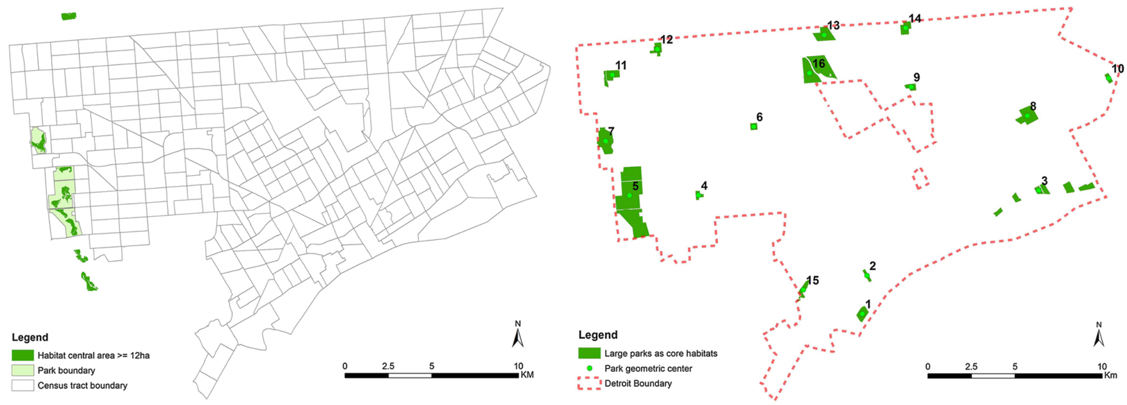


Fig. 3. Core habitat identification in Detroit. The map of Detroit on the left shows the locations of the only patches that qualified as core habitat based on the criteria recommended by Kong et al. (2010). The map of Detroit on the right shows the city parks > 12 ha, which we used as the core habitat patches instead.

Table 1
Land use layers, layer weights, and suitability scores used to generate cost surface for least-cost path analysis.

Land use Layer	Description	Suitability Scores	Weight (applied to layer)
Vacant Land	Detroit parcel survey conducted in 2013 (Data Driven Detroit, 2014)	Without structure, with trees = 100; Without structure and trees = 80; With structure = 60	0.53
Public green Space	All city parks, public gardens, sports field and other public recreation areas (SEMCOG, 2008)	40-100 (> = 12 ha, 100; 5 ha = < area < 12 ha, 80; 1 ha = < area < 5 ha, 60; < 1 ha, 40)	0.33
Alleys	All alleyways in Detroit, used by municipal utilities (Data Driven Detroit, 2009)	100	0.14

making methodology (Saaty, 1987), was used to assign different weights to the three layers based on the perceived feasibility of developing them into corridors. Vacant lands are prioritized as the most feasible layer because of their ease and need for redevelopment. Existing green spaces are assigned the second highest weight because they represent existing habitat remnants. While alleys are often impervious, these underutilized public right-of-way spaces can be successfully converted, as demonstrated by successful alley greening programs in other cities (Newell et al., 2013). These relative suitability values were based on the researchers' best judgements, drawing on the literature and knowledge of Detroit, but because they are subjective, this is a potential limitation of the research. Future applications could determine these costs through stakeholder consultations.

The final cost surface map was calculated by taking the inverse of the overall suitability score for each cell, which was determined by multiplying the suitability scores in each layer by the weights and adding them together. The cost surface map was standardized (using the *rescale* tool) so all cell values ranged from 0–100. The *cost path* tool was used in ArcMap to build the least cost (most suitable) corridors connecting all city parks/core patches.

2.2.3. Gravity model and metrics

The least-cost path analysis produced numerous corridors, thus we used a gravity model to help prioritize them. The gravity model calculates the interactions between nodes, where a higher interaction score is given to corridors connecting higher quality habitat patches and with lower impedance (Kong et al., 2010). Higher interaction means that corridors provide more significant links between two patches (Linhan et al., 1995). We used an equation adapted from Kong et al., (2010) (Appendix C).

Different land cover types (Maheshwari and Vernier, 2012) were assigned impedance values based on the researchers' assessment of how much additional effort would be needed to convert the land into a green corridor (Table 2). The weight assigned to each node (city parks over

Table 2
Land cover types used to calculate impedance value for corridors and patches (node and edge weights).

Variables	Description	Impedance values
Tree Canopy	Represents the urban tree cover and shrub cover, but does not include herbaceous cover.	1
Open Space	Open space includes grass or lawn cover, excluding all other structures like buildings, utilities, trees, etc.	5
Urban Bare	Areas not covered with tree canopy, impervious surface, lawn/grass, or water (just bare soil).	80
Impervious Surface	Areas with impervious land covers, or with impervious structures like concrete and asphalt. For example: paved roads and buildings.	100
Water	Lakes, rivers, streams, and other water features.	100

Table 3
Factors informing design typologies.

Factors	Design goals	Design strategy
Ecological functions	Facilitate movement of species	Networked green space
	Stormwater management	Bio-retention, rain garden etc.
	Mitigate the urban heat island	Increase vegetation cover, reduce impervious surface
	Improve air quality	Increase vegetation cover
Sociocultural benefits	Cultural services	Outdoor recreation places, playgrounds; Educational signs and posters to explain green infrastructure functions
	Legibility	Well-structured landscape elements
	Cues to care	Turf is mowed, plants in neat patterns, colorful flowers
	Coherence	Landscape in organized pattern (e.g. repeated elements and smooth texture)

12 ha) was determined by dividing the area of the park by the sum of the impedance values (from land cover types) (Table 2) of all cells within the park. Thus, larger parks are valued more highly, but this value is diminished if much of the land cover is undesirable (e.g. impervious surface). The edge weight, or the impedance value of the corridors themselves, was based on the perceived cumulative cost of developing that route as determined by summing the land cover ‘costs’ of each cell located along the corridor (for values see Table 2). In contrast to the node weight, higher edge weights lower the prioritization of a corridor. The least cost path was processed between paired nodes by coding in Arc Python 2.7.

2.2.4. Corridor scenario development and network analysis

We selected the 10 highest priority corridors based on the gravity model, developed five scenarios for their implementation, and then examined how they could impact overall connectivity for the city of Detroit. Two widely used network indices were calculated for each scenario: beta (β) and gamma (λ) (Kong et al., 2010; Linhan et al., 1995; Rudd et al., 2002; Uy and Nakagoshi, 2007).

Beta equals the number of links (l) divided by the number of nodes (v) (Forman, 2014)

$$\beta = \frac{l}{v}$$

Gamma equals the number of links (l) divided by the maximum possible number of linkages ($lmax$) (Forman, 2014).

$$\lambda = \frac{l}{l_{\max}} = \frac{l}{3(v-2)}$$

Gamma indicates the network connectivity, and beta represents the node connection which indicate possible movement patterns (Forman, 2014).

In addition to the network analysis, we examined connectivity at both census tract and citywide scales. It was assumed that all developed corridors would be covered with tree canopy, and therefore a new shapefile was created with original tree canopy features and new corridor features. For the analysis at a census tract scale, we randomly selected five sample census tracts in which corridors would be developed. For the citywide analysis, it was assumed that all potential corridors would be planted with trees, and the analysis conducted on the entire revised city landscape. Corridor features were merged into existing tree canopy features and FRAGSTATS and Conefor were used as described in Section 2.1 to recalculate connectivity metrics at a census tract scale, and FRAGSTATS for the whole city. Results were then compared with the original connectivity matrices to examine whether the corridors would increase overall connectivity.

2.3. Site-scale corridor design typologies

While it is important to work towards a connected green space network, most city greening efforts occur at a smaller scale, often one or a few parcels at a time. Therefore, we provide site-level design typologies for common existing vacant parcel arrangements to achieve the goal of creating multifunctional green infrastructure that provides social and ecological benefits (Lovell and Taylor, 2013). The design process was informed by site visits to Detroit, which revealed that many vacant lots were overgrown and not well maintained. Designs were developed using AutoCAD (AutoDesk Inc., 2017), Sketchup (Trimble Inc, 2017), Adobe Photoshop (Adobe System Inc, 2017a), and Illustrator (Adobe System Inc, 2017b).

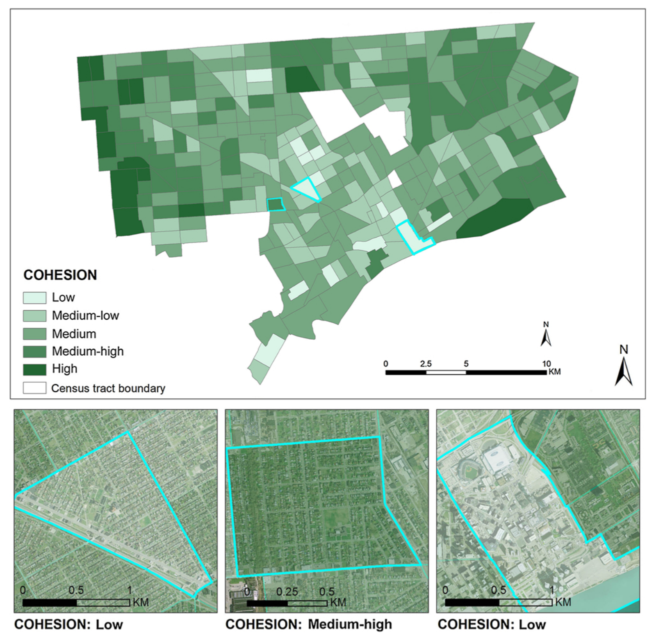


Fig. 4. COHESION analysis for all Detroit census tracts (top) and aerial photographs (bottom) of three different tracts to illustrate what low cohesion (left and right) and medium-high cohesion (middle) look like on the ground.

The design typologies were systematically developed based on eight ecological and sociocultural factors (Table 3). Four goals were identified to enhance environmental functions: facilitating the movement of different species, managing urban stormwater, mitigating the urban heat island, and improving air quality (Meerow and Newell, 2017). Four goals related to sociocultural benefits were also identified: cultural services, legibility, cues to care and coherence. To encourage social interaction and cultural ecosystem services we incorporated pedestrian paths and recreational spaces such as playgrounds, which could have educational signs/posters. Care was taken to design typologies that research suggests would be appealing to local residents. For example, typologies integrated concepts of *coherence*, *legibility,* and *cues to care*

Table 4
Citywide distribution of COHESION scores.

Cohesion Score	% in total census tracts	Connection Level	Distribution
93.82–94.00	4.73	Low	Most of the low connection census tracts are located Downtown and in the Midtown area; there are also some residential land use areas with low COHESION scores because they have fewer tree canopy clusters in those areas.
94.01–95.50	21.96	Low-medium	These are located in census tracts with fewer tree canopy clumps. Most are located in census tracts where the land use is residential.
95.51–97.00	45.27	Medium	Census tracts with medium scores are distributed across the City of Detroit.
97.01–98.50	23.65	Medium-high	Most mid- to high cohesion areas are in residential areas with lots of vacant land.
98.51–99.16	4.39	High	Most high cohesion areas are the census tracts that already have large city parks with dense trees.

into designs (Kaplan, 1988; Nassauer, 1995). Elements of *Coherence* include organized, repeated designs and smooth texture. A *legible* landscape is one with well-structured spaces that facilitate movement (Kaplan, 1988). *Cues to care* include mown turf, neatly arranged plants, colorful flowers, etc. that appears well-maintained and safe, since safety is a major concern for residents in high vacancy neighborhoods (Barham, 2006; Nassauer, 1995; Nassauer and Raskin, 2014).

3. Results

Our modeling suggests that habitats are fragmented in Detroit, but green corridors could be developed primarily using vacant land, the city's extensive alley system, and existing public green space to connect existing city parks and to facilitate connectivity.

3.1. Census tract landscape connectivity

Fig. 4 shows the results of the census tract structural connectivity based on the COHESION index. We find higher connectivity in southwest Detroit along the Rouge River. Perhaps unsurprisingly, the Downtown and Midtown neighborhoods have some of the lowest connectivity scores. When we overlay the connectivity scores with a 2010 aerial photo (Fig. 4), it is clear that census tracts with lower COHESION scores have less tree canopy. The bottom left image shows a residential neighborhood surrounding a school with sports fields with limited canopy cover. The residential area in the middle image, in contrast, has a high COHESION score and large blocks of tree canopy. The right image shows a tract in downtown with few trees and thus low COHESION. Table 4 summarizes the spatial distribution of COHESION scores and how they relate to the built environment in Detroit.

The comparison of COHESION and IIC for the 30 sampled census tracts is shown in Fig. 5. Visual comparison of these two maps suggests that tracts with a high IIC also tend to have a high COHESION score. For example, two census tracts in western Detroit (near the Rouge River Park) have a high COHESION and IIC, while census tracts located in the center of Detroit (Midtown) have low COHESION and IIC. This suggests that structural connectivity can serve as an indicator of functional connectivity. Quantitative analysis also confirms that IIC and COHESION are significantly positively correlated (Pearson's correlation coefficient of 0.769, significant at the $p < 0.05$ level).

3.2. Corridor mapping and analysis

The Least-cost path analysis resulted in 120 potential corridors (see Appendix D) running primarily through vacant parcels, alleyways and existing small green spaces. Given the city's limited resources, only a subset of these would realistically be developed. We used a gravity model to select the corridors that would enhance landscape connectivity most efficiently. Of the 120 corridors, only 27 met the minimum threshold of 0.3 for the gravity model results (see Appendix E) —as suggested by Kong et al. (2010).

Fig. 6 presents the top ten corridors with the highest gravity index. The highest scoring corridor would connect patch 5 - Rouge River Park with patch 7 - Eliza Howell Park. The first four corridors would connect patch 5 and 7, patch 11 and 12, patch 3 and 11, and patch 4 and 5, forming a 'Paul Revere' network shape (Hellmud, 1989), with every patch visited only once (the network typology is shown in Fig. 7). These four corridors form Scenario 1 (see Fig. 8a).

In Scenario 2, the fifth and sixth corridors connect patch 4 and 7, and patch 7 and 12 respectively. Two small circuits are formed, with a

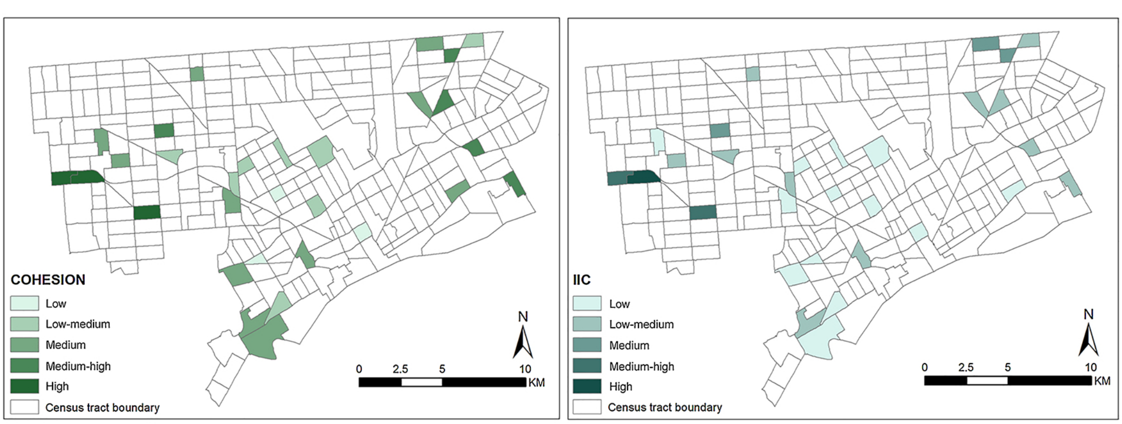


Fig. 5. COHESION scores of the 30 sampled census tracts representing structural connectivity (left), and corresponding Integral Index of Connectivity (IIC) scores representing functional connectivity (right).

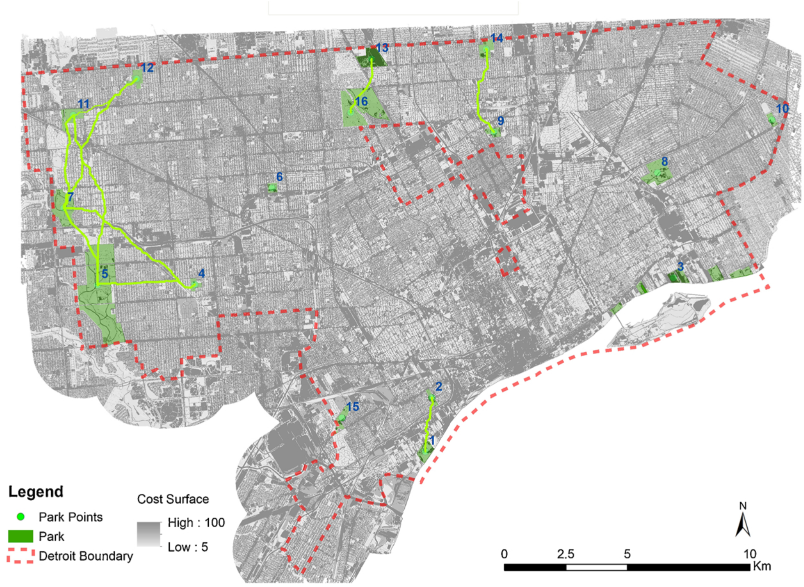


Fig. 6. Top ten corridors with high gravity scores: The ten highest priority corridors are shown in light green along with the core habitat patches (parks) on an aerial image of the City of Detroit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

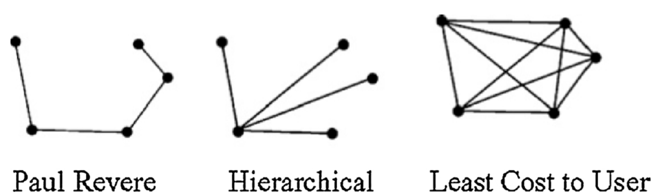


Fig. 7. Network typologies (Hellmud, 1989).

one-to-one connection among patches 5, 7 and 4, and a one-to-one connection between patches 7, 11 and 12 (shown in Fig. 8b). These two circuits form the 'Least Cost to User' network type, which minimizes the travel cost between two patches (Hellmud, 1989).

Scenario 3 includes the 8th corridor, connecting patch 5 and patch 11, forming a more complex 'Least Cost to User' network in western Detroit (see Fig. 8c). The remaining three corridors are located in different areas of the city; none of these three corridors conform to the network typology provided by Hellmud, (1989). Nevertheless, we included a scenario (4) where all top ten corridors are developed (Fig. 6).

We analyzed these different scenarios to see how they each contribute to the connectivity of the overall green space network (Linhan et al., 1995). Table 5 summarizes the network analysis results (beta (β) and gamma (λ)) for the different corridor development scenarios.

Table 5
Network analysis results.

Network	Nodes	Links	Beta(β)	Gamma(λ)
Ideal Scenario (> 0.3)	16	27	1.69	1
Scenario 1 (Fig. 8a)	16	4	0.25	0.15
Scenario 2 (Fig. 8b)	16	6	0.38	0.22
Scenario 3 (Fig. 8c)	16	7	0.44	0.26
Scenario 4 (Fig. 6)	16	10	0.63	0.37

Scenario 2 provides two more links than Scenario 1, with a corresponding 0.13 increase in node connection (beta) and 0.07 increase in network connectivity (gamma). Scenario 3 has one more link than scenario 2, leading to a 0.06 increase in beta and a 0.03 increase in gamma. Scenario 4 has ten links, with a 0.19 higher beta than scenario 3 and 0.11 higher gamma. Although scenario 4 has the highest number of node connections and network connectivity, there is no increase in the number of circuits.

Besides the commonly used indices above, we examined how adding the corridors would impact structural and functional connectivity at a census tract scale. For all five sampled census tracts, IIC and COHESION

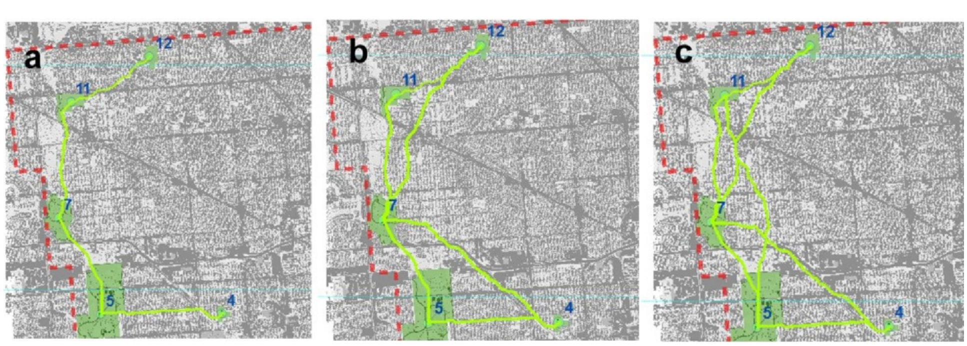


Fig. 8. Three network typology scenarios for the top four corridors as determined by the gravity index Fig. 8a (left) represents Scenario 1: 'Paul Revere' network shape, Fig. 8b (middle) represents Scenario 2: a simple 'Least Cost to User' network type, and 8c (right) Scenario 3: a more complex 'Least Cost to User' network.

Table 6
Structural and functional connectivity changes before corridor scenarios are applied (current situation) and after.

Census Tract ID/ Citywide	COHESION Before*	COHESION after**	IIC Before	IIC After
26163507000	95.89	97.03	0.080	0.084
26163543600	97.94	98.36	0.070	0.079
26163543800	98.21	99.36	0.156	0.204
26163545300	98.17	98.51	0.158	0.186
26163546600	97.00	97.75	0.122	0.136
Citywide	88.80	99.05	–***	–***

* Before proposed corridor is built.
** After proposed corridor is built.
*** Dataset had over 240,000 nodes at city scale, which exceeded the computing capacity of Conefor (Saura and Torné, 2007, pp. 44–45).

increase with corridor development (Table 6). The average increase at census tract scale in COHESION is 0.76; IIC is 0.02. Even looking at the city as a whole, there is a 10.25 increase in COHESION.

3.3. Corridor design typologies

We present three design typologies for potential green infrastructure development strategies that correspond to different site conditions, which represent common vacant land types in Detroit: 1) commercial vacant land; 2) alleyways separating commercial and residential land; 3) residential vacant land. The first typology is designed for vacant commercial land parcels, exemplified by vacant land near Joy Road (Fig. 9, left image). Here vacant commercial land is adjacent to a main road, with limited tree canopy and no buffer between commercial and residential zones. These conditions are common in Detroit and other legacy cities, and in these cases implementing a small green space (such as a pocket park) is recommended (Fig. 9). This park would provide cultural services such as recreation, physical activity, and social contact (Lovell and Taylor, 2013). Adding street trees in rows with mown grass emphasizes the neatness of the landscape, upholding cohesion, legibility and cues to care while also mitigating the urban heat island effect.

The second typology focuses on areas where vacant residential land is located in close proximity to commercial areas, separated by an alleyway (Fig. 10, left). For these areas, the proposed design (Fig. 10, right) takes advantage of the vacant parcel to implement a bio-retention basin, which would capture stormwater and reduce harmful combined sewer system (CSS) overflows. With proper planting design, bio-retention basins can provide aesthetic value and pollinator habitat (Hunter, 2011). A pedestrian path and tree buffer are also suggested to separate commercial from residential parcels. The proposed pedestrian pathway can improve public transportation, and is further separated from the street to provide a safer environment for walking and biking.

The third typology is designed for building a corridor through a generic vacant residential property (e.g. Fig. 11). In many Detroit neighborhoods, storm and sewer water from parcels flows into CSS pipes under adjacent alleyways. When the system backs up, it can flood basements. To address this, small bio-retention basins are developed on vacant properties and catch basins along the streets. Bio-retention basins are connected to catch basins intended to retain the stormwater from the road before it enters the underground sewer system. Additionally, vacant land could be fitted with playgrounds, supporting outdoor activities (Fig. 11), strengthening community cohesion, and improving opportunities for recreation in the surrounding neighborhood. Fig. 12 shows how residential vacant land like that shown in Fig. 11 could be converted from a combined sewer system (top) to a bio-retention system (bottom) as part of corridor development.

4. Discussion

In the preceding sections we proposed a multi-scalar methodology for analyzing landscape connectivity patterns and planning a multifunctional urban green space network, which we then applied to the City of Detroit. Now we discuss the significance of this research with respect to understanding of landscape connectivity, green space network design, and multifunctional green infrastructure planning.

4.1. Connectivity analysis

Like many urban landscape connectivity studies, we find some neighborhoods in Detroit with denser, more connected tree canopy, but these are highly fragmented (Kong et al., 2010; Tian et al., 2011). These findings support the development of new green corridors to facilitate movement between existing habitat patches.

Most of this literature, however, focuses on either structural connectivity or functional connectivity. Relatively few studies have compared these two approaches. According to LaPoint et al. (2015, p. 873) this greatly limits opportunities to "inform urban planners hoping to design ecologically friendly towns and cities". Our study helps to fill this gap by using Conefor to validate the FRAGSTATS indicator. The fact that we find the two metrics to be highly correlated suggests that even though structural connectivity metrics do not take into account species dispersal data, results may still be indicative of functional connectivity. Although this study only assesses functional connectivity for a sample of 30 census tracts based on a rough approximation of species movement, future studies could employ our methodology to simultaneously assess structural and functional connectivity. It would

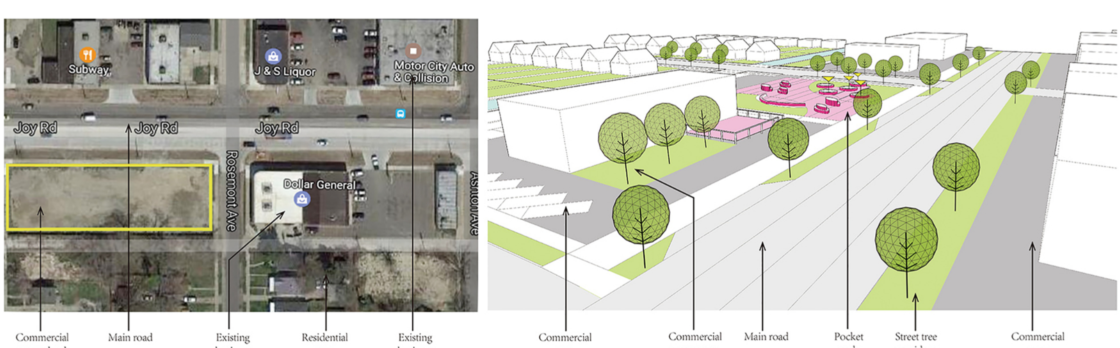


Fig. 9. Corridor design typology 1: Commercial vacant land (yellow) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

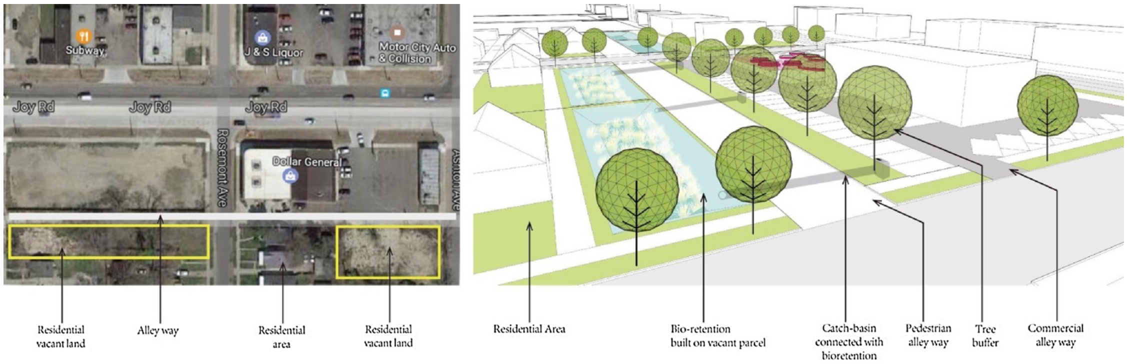


Fig. 10. Corridor design typology 2: Alleys between commercial and residential lands.

also be interesting to examine how connectivity metrics change if open spaces with grass cover were included as habitat patches, since these areas would likely provide habitat to certain species, or if a distance threshold larger or smaller than 20 m were used in the Conefor calculations.

4.2. Green space network analysis

We provide a replicable approach for designing a network of green corridors to improve connectivity across the city, building on existing methodologies (e.g. Kong et al., 2010). In this study, we apply the commonly used least-cost path method to identify optimal routes for green corridors connecting parks. However, where previous studies generally use cost values based on land use data to create both least cost paths (corridors) and the gravity model (Kong et al., 2010), we consider both land use and land cover. The cost surface layer used for the least-cost path assessment comes from a suitability map derived from land use information. This allows us to take into account the political feasibility of developing corridors through particular locations. For example, we prioritize vacant land and alleys over privately owned lots. This determination would not be possible using land cover types, which do not reflect political or social designations. We do, however, use land cover types to rank these feasible corridors, in this case prioritizing routes based on the ecological value of the current land cover. For example, routes connecting parks with large areas of tree canopy are prioritized over those with impervious surfaces.

As expected, our network analysis suggests that as more of the identified high-priority corridors are developed, connectivity will increase. The ideal scenario would be to develop all of these corridors. If this is not possible, scenario 4, which forms a complex circuit and improves the connectivity most effectively based on connectivity index results would be the best option. These results assume that developed corridors will be entirely covered by tree canopy. In reality, some green infrastructure would likely have herbaceous cover. We therefore acknowledge that for tree-dwelling species, landscape connectivity might not be increased as much as anticipated.

Another distinguishing feature of our methodology is the fact that we prioritize vacant land and alleyways, which makes the results easier to implement, since these areas are more accessible and likely less expensive for a city to develop. Often green infrastructure projects are planned individually at site scale, with little consideration of how social and environmental connectivity can be increased by connecting it with other green infrastructure projects. Our model can help decision-makers to think at multiple scales, not only designing specific sites to provide ecosystem services, but also considering how the site fits into the larger green space network.

Finally, our methodology relies on readily available datasets such as land use/land cover, road and alley networks, and vacant parcels as well as free software (besides ArcGIS), thus the approach could be easily applied in other shrinking cities, even if municipal governments have limited technical and financial resources. While it was outside the scope of this project to survey local stakeholders (e.g. city planners, elected officials) using AHP, future applications of the model could do so to determine the most appropriate weights for model criteria, thereby increasing the practical utility of the results.

4.3. Multifunctional green infrastructure planning

We present a multi-scalar approach for planning multifunctional green infrastructure; from citywide prioritization to site-scale design. City planners can play a critical role in strategically conserving and linking remaining habitat patches and green spaces in urban areas to increase connectivity (Lovell and Taylor, 2013). By prioritizing vacant parcels and alleyways, corridors identified through our model should also provide important social benefits. They can foster stronger community connections by linking residential neighborhoods (Ernstson

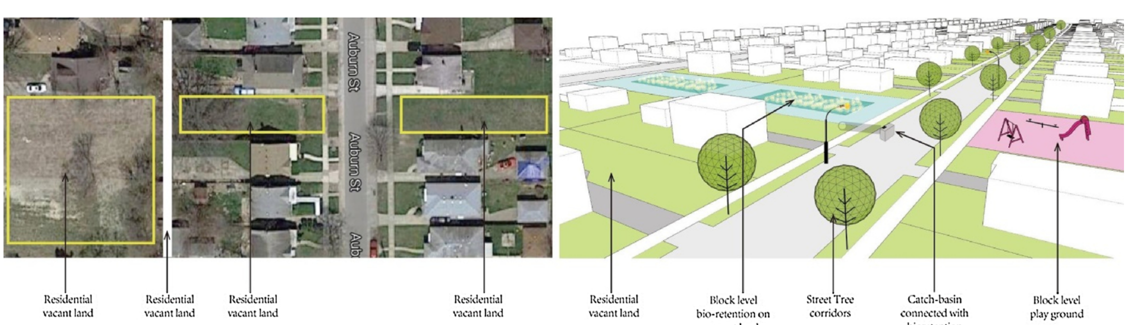


Fig. 11. Design typology 3: Residential vacant land with block level bio-retention, playgrounds, and street trees.

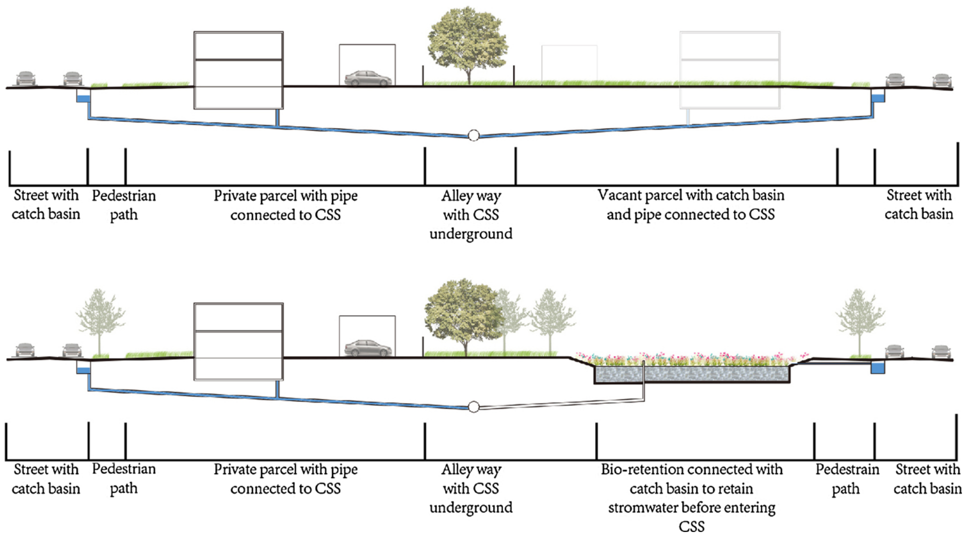


Fig. 12. Cross-section of residential vacant converted from a combined sewer system (top) to a bio-retention system (bottom).

et al., 2009) and increase access to green spaces and recreation facilities in underserved areas (Heynen et al., 2006; O'Brien et al., 2017). Our site-scale design typologies also combine ecological and social functions with landscape architecture best practices such as 'cues to care' (Nassauer and Raskin, 2014) to influence people's perceptions of the new landscape. The designs are specifically intended to balance ecological function with stormwater management, mitigation of the urban heat island, recreation opportunities, and more. Nevertheless, if this approach and the designs were to be implemented, it would be critical to engage the community and diverse stakeholders throughout the process. Additionally, as with all urban greening projects, care must be taken to try and avoid gentrification (Wolch et al., 2014).

4.4. Possible future applications and extensions

While our methodology is particularly relevant for shrinking cities planning to extend their green space network as a redevelopment strategy, the multi-scalar planning framework could be applied in other contexts to enhance urban sustainability and resilience. Many cities in both the global South and North currently have vacant or blighted areas or may lose population in the future (Pallagst et al., 2009; Che et al., 2013). Moreover, a similar approach could be applied wherever planners seek to combat fragmentation and develop multifunctional green space networks as part of smart growth or sustainable development efforts. Establishing these attractive networks could help attract residents back into urban cores, reducing the pace of suburbanization, and thus habitat fragmentation on the urban fringe.

While our modeling approach could help inform green space network planning, it does not incorporate all factors that need to be considered as part of a spatial planning process, such as existing municipal facilities, stakeholder preferences, and local regulations. Ideally, a wide range of stakeholders representing various government agencies, the private sector, and community groups should be included in the model criteria selection, weighting, and design processes. This would allow our model to be adjusted to fit local priorities and constraints, which is critical for the success of green infrastructure (Mesimäki et al., 2017; Schilling and Logan, 2008). For example, following the approach of Hadavi et al., (2018), residents could be surveyed to determine what specific landscape features would increase their satisfaction with the neighborhood and use of public greenspaces. As Draus et al., (2018, p. 10) reveal through their case study of a successful green infrastructure project in Detroit, because of the city's complex social and political history fraught with racism and environmental injustice, it is "important to engage different communities' expectations, fears and historically legitimate suspicions." Similarly, the design typologies presented for Detroit should be adjusted based on specific site conditions including water table depth, soil composition and underground pipes. Vacant lots in legacy cities, for example, often have contaminated soils. It would be helpful to engage local communities in the planning process so that they are committed to monitoring and maintaining green infrastructure. Finally, there is a need for more in-depth case studies of what designs yield different ecological and community benefits. (Draus et al., 2018; Hunter and Askarinejad, 2015).

5. Conclusion

This research integrates landscape ecology and graph theory, spatial modeling, and landscape design to develop a methodology for planning multifunctional green infrastructure that fosters social-ecological sustainability and resilience. Spatial patterns of landscape connectivity across the City of Detroit were determined using structural connectivity at both census tract and citywide scales. Results were validated using a functional connectivity index, and the high correlation between these results suggests that simple metrics of structural connectivity may serve as useful indicators of functional connectivity and guide green space planning. We also found that landscape connectivity varied across the City of Detroit, but core habitat patches were limited. Linking city parks together with green corridors could improve connectivity, and we propose a pragmatic approach for planning these corridors that takes advantage of vacant land, alleys, and existing small green spaces.

Proposed green infrastructure corridors were shown to enhance both structural and functional connectivity. With strategic planning and community-engaged design – perhaps informed by the design typologies provided – extensive vacant lands could become key components of urban green space, providing valuable social-ecological functions and mitigating environmental hazards.

In an increasingly urbanized world, it is essential to enhance ecosystems within cities, but urban nature needs to be multifunctional (Bai, 2018). City officials must grapple with limited resources and competing priorities. This study shows how cities might begin systematically planning more socially and ecologically beneficial green infrastructure networks.

Appendix A

A Algorithm to calculate COHESION

$$\text{COHESION} = \left[1 - \frac{\sum_{i=1}^{n} p_{ij}}{\sum_{j=1}^{n} p_{ij}\sqrt{a_{ij}}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{-1}(100)$$

(McGarigal et al., 2012).

p_{ij} was the perimeter of patch ij in terms of number of cell surfaces
a_{ij} was equal to the area of patch ij in terms of number of cells
A was the total number of cells in a landscape

B Algorithm to calculate IIC

$$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \cdot a_j}{1 + nl_{nj}}}{A_L^2}$$

(Saura and Torné, 2009)

n = the total number of nodes in the landscape; here, it means the total number of tree canopy features in a census tract.
a_i and a_j are the attributes of nodes i and j. In this research, it uses the area of the tree canopy feature.
nl_{ij} is the number of links of the shortest path between i and j;
A_L = total landscape area, including habitat and non-habitat areas. A_L is optional for users, and does not affect the calculation of IIC.

C. Gravity model equation (adopted from Kong et al., 2010)

$$G_{ab} = N_a N_b / D_{ab}{}^2$$

G_{ab} indicates the interaction between nodes (parks) a and b, N is the weight value of corresponding node. D_{ab} is standard value of resistance (impedance) between nodes (parks) a and b.

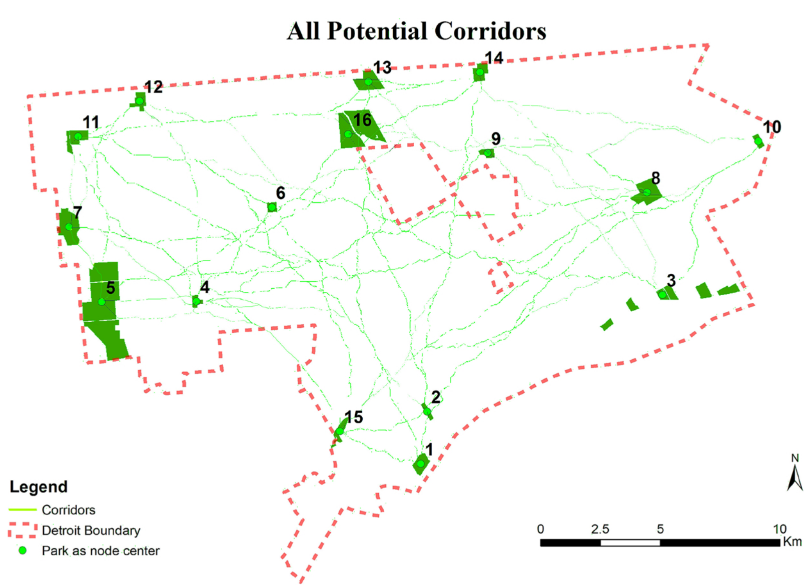
$$N_a = (1/P_a) \cdot (S_a)$$

Where P_a is resistance/impedance value of park a; S_a is size of park a.

$$D_{ab} = L_{ab}/L_{max}$$

L_{ab} = the accumulation of resistance value between parks a and b corridors
$Lmax$ = the maximum impedance value of all L_{ab} (of total corridors)

D. Map of all 120 potential corridors identified to increase green space connectivity in Detroit



E Corridors beyond the threshold

Patch ID (Node)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	1.35*	…	…	…	…	…	…	…	…	…	…	…	…	0.76	…
2		0	…	…	…	…	…	…	…	…	…	…	…	…	0.78	…
3			0	…	…	…	…	0.60	…	…	…	…	…	…	…	…
4				0	3.55	0.89	2.48	…	…	…	1.04	1.16	…	…	0.48	0.55
5					0	…	15.57	…	…	…	1.43	1.21	…	…	…	…
6						0		…	…	…	…	0.55	…	…	…	0.81
7							0	…	…	…	5.61	2.03	…	…	…	…
8								0	0.55	0.36	…	…	…	0.35	…	…
9									0	…	…	…	…	1.51	…	1.07
10										0	…	…	…	…	…	…
11											0	11.64	…	…	…	…
12												0	…	…	…	0.38
13													0		…	1.40
14														0	…	0.70
15															0	…
16																0

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