Enhancing Landscape Connectivity in Detroit through Multifunctional Green Corridor Modeling and Design

by

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Abstract

Maintaining habitats is important for plants and animals. However, habitats in urban environments are fragmented due to urbanization. The fragmentation is a barrier for wildlife movement because landscape connectivity is decreased in urban environments. Previous studies in conservation ecology paid more attention to natural landscapes than urban environments. Other studies aimed at improving urban landscape connectivity were not practical because of restrictions in fully developed urban environments. This study provides practical conservation methods by taking advantage of existing vacant land to develop green infrastructure and increase landscape connectivity.

The city of Detroit is chosen as a case study because of its large potential to redevelop existing vacant land. The paper includes examining structural and functional connectivity by FRAGSTATS and Conefor, selecting core patches in ArcGIS, identifying potential corridors by the least-cost-path and evaluating corridors by gravity model. By comparing data before and after corridor built-up, results show that census tract-level connectivity metrics would be improved by developing proposed corridors. To further link research results with the city of Detroit, multi-functional green infrastructure typologies for vacant land re-development are provided.

This paper provides a systematic and scientific method for developing vacant lands and other available lands by green infrastructure network, which benefits both humans and wildlife. By developing green infrastructure network, both social connection and ecology connection will be achieved. Furthermore, this paper connects research with real world situations, providing a founded and practical strategy for other cities having similar vacant lands situation to Detroit to redevelop.

Keywords: Landscape connectivity; Vacant lands; Corridor; Green infrastructure Network; Gravity model; City of Detroit

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1 Introduction

1.1 Urbanization

Until 2014, worldwide, 54 percent of the population lived in urban areas. Currently, most of urbanization exists in developed regions such as Northern America and Europe. North America had 82 percent of its population in urban areas in 2014 (United Nations, 2014). For United States, by 2010, its urban population made up about 81 percent of its total population (The World Bank, 2010). The urbanization trend will continue. The United Nations states that about 66 percent of the population will live in urban areas by 2050, and the largest increases in urbanization will occur in Asia and Africa (United Nations, 2014). The United States has experienced urbanization almost throughout its entire history.

Urbanization indeed brings benefit to society. Cities, as crucial parts of modern development, contribute much to both our culture and economy, and provide the most opportunities for “education, employment, services, and cultural enrichment, and the expectation of better health” (Moore, Gould, & Keary, 2003, p. 269). Henderson (2012) stated that urbanization brought high gross domestic product (GDP), helped to expand education and political development, established economic institutions and markets, and enhanced the quality of urban life to some degree. However, with the expanding of urban regions by using more lands to meet the needs of growing populations, environmental issues and social risks arose, influencing the health of ecosystems and also human health.

Rapid urbanization causes the increasing of the urban-rural gradient (Mckinney, 2002), and is the main reason for land cover and land use change (Zhang, Wu, Zhen, & Shu, 2004). It results in the increase of urban temperatures (Kalnay & Cai, 2003), an increased risk of flooding, and reduces the capacity of carbon storage contributed by trees (Eigenbrod et al., 2011) and, the loss of habitat and biodiversity (Mckinney, 2002) etc. Less than ideal urban environments have negative impacts on people’s health because of the air pollution, lower water quality, and fast spreading diseases

(Moore, Gould, & Keary, 2003). Other social risks such as violence, poverty and unemployment also affect public health (Muggah, 2012). How to keep the sustainability in process of urban development has become society’s Achilles’ heel.

In urban areas, a large amount of newly constructed facilities and infrastructures obviously are accompanied with rapid urbanization. This results in a series of problems for urban residents: polluted water, solid waste, poor air quality, pestilence and diseases, “traffic-choked streets, inefficient movement of goods and services, and hazardous and unethical working conditions” (Eisenman, 2013, p. 289). In rural and natural areas, due to serious air and water pollution, habitats have been lost, and plants and other species are facing endangered situations (Rocha-Ortega & Castaño-Meneses, 2015; Yuan & Lu, 2016).

1.2 Urban Landscapes

There are different landscape elements in a landscape. In general, land is a mosaic of matrix, patch and corridors (Forman, 1995). Patch, in which species occur as discrete local populations connected by migration, is regarded as a non-linear, discrete homogenous surface that is different from its surroundings (Kotliar & Wiens, 1990). For example, in urban environment, clumped trees could be regarded as patches for birds. Matrix represents the background of patches (Forman, 1995). It includes all other land covers which are different from patch features. For instance, if tree clumps are patches, other land covers such as grass, river, built-up etc., all forms the matrix. A corridor is a homogenous surface that differs in its linear shape, such as streams and roads. For different organisms, landscape elements are not the same. Clumped trees are patches for birds, but not for human-beings. In this research, I focus on habitats for wildlife in an urban landscape.

1.2.1 Habitat Fragmentation

Habitat fragmentation is one of the serious issues caused by urbanization. Habitat fragmentation is usually defined as a process of “a large expanse of habitat transformed into a number of smaller patches of smaller total area, isolated from each other by a matrix of habitats unlike the original” and “the breaking apart of habitat”

(Wilcove, McLellan, & Dobson, 1986, p. 237). Habitat fragmentation results in “more and smaller patches” (Zhang, Wu, Zhen, 2004, p.2). It is a barrier that blocks organisms’ movements, and results in a reduction of overall landscape connectivity (see the specific definition of landscape connectivity in Sec 1.3) for many native species (Crist, Wilmer, & Aplet, 2005).

Over the last few decades, habitat fragmentation has been studied and researched as it has attracted much attention for the ecological effects it may cause. Biodiversity is facing major threats due to habitat loss and fragmentation (List, 2004). Fragmented habitats may: 1) reduce the population of species; 2) decrease the biodiversity, including species richness, population abundance and genetic variation within species; 3) reduce the habitat patch size; and 4) enlarge the isolation of patches (Fahrig, 2003). Many researchers focus on one or more of these four effects when studying habitat fragmentation. List (2004) utilizes occupancy data on six continents and indicates that patch size and isolation are the crucial factors needed to determine the occupancy rates of the subject species. Mckinney (2012, p. 884) plots the “species richness to urban-rural gradient” relationship and points out that there is a trend of increase in habitat fragmentation and decrease in species richness towards to the center of urban areas that are due to human activities and disturbances.

Therefore, to achieve the objective of maintaining the number of and variety of species, it is important to reduce the effect of habitat fragmentation. In this research, I will establish linkages between habitat patches, suggested by Bailey (2007), as a method to decrease the influence of fragmentation. .

1.2.2 Urban Green Space

One key component of habitat in urban environment is urban green space. Urban green space can be intuitively defined as parts of cities with vegetation, such as forests, grasslands, green roofs, streams, community gardens, river banks, and green walls (Wolch, Byrne, & Newell, 2014; Roy et al., 2012). Urban green space provides valuable habitats for a wide range of species in cities. For example tree canopies in urban green space are habitats for birds and insects to live; shrub lands may attract fruit-eating birds and mammals (Forman, 2014). However these ecological benefits of urban green space will be limited by their fragmentation.

In addition to ecological and habitat provisioning services, green spaces provide other benefits to health and well-being of residents living in urban areas (Roy Byrne & Pickering, 2012; Lee & Maheswaran, 2011). From a physical point of view, urban green space can reduce noise, relieve the “hot island” effect, help to control water pollution, and decrease rain runoff volume (Groenewegen, Van den Berg, De Vries & Verheij, 2006; Escobedo et al., 2011). These benefits can also affect the area of public physical health. For instance, Nowark et al., (2006) utilize hourly meteorological and pollution concentration data to reach the conclusion that urban tree cover can help to remove air pollution and that an integrated tree canopy such as an urban forest is able to effectively improve air quality. Urban green spaces also can provide opportunities for public activities including sports and gathering with friends (Brander & Koetse, 2011). Giles-Corti et al., (2003, p. 93) conduct “a cross-sectional survey and an environmental scan of recreational facilities” and conclude that respondents are more likely to engage in physical activities if they have easier access to public green spaces.

Green space also offers psychological aspects, such as offering urban residents a place that assist them to control stressful emotions and increases their positive emotions (Ulrich, 1983), and positive restorative experiences (Van den Berg, 2010). For instance, in his classic paper Ulrich (1984) studied the recovery conditions of post-surgical patients with different window views of either a brick wall or green natural space, and concluded that patients viewing green space had a reduced need for sleeping pills or tranquilizers and recovered better. The research of Fuller et al., (2007), told us that psychological benefits increased with larger green space areas and species richness.

Trees are the most important features in urban green spaces. They offer urban residents many benefits such as carbon capture, air quality improvement, stormwater control, and energy conservation (Roy et al., 2012). In this study, the tree canopy is regarded as a key feature in urban green space for analysis and discussion.

1.3 Habitat Connectivity

In order to maximize the ecological benefits of urban green spaces, this research focuses on increasing landscape connectivity among green spaces. Landscape connectivity is defined as “the degree to which the landscape facilitates or impedes movement among resource patches” (Taylor, Fahrig, Henein, Merriam, 1993, p. 571), linking spatial and functional structure of a geographical area (Correa Ayram, Mendoza, Etter, & Salicrup, 2015). The word “connectivity” is used by landscape ecologists to describe the structural and functional continuity of landscapes in space and time (Auffret & Cousins, 2015). In recent decades, despite increased interest in biodiversity assessments in urban environments, the ecological relevance of habitat connectivity in high fragmentation area requires more investigation (Braaker et al., 2014). Landscape connectivity is a key issue for biodiversity conservation in these areas.

Calabrese and Fagan (2004) distinguish three types of connectivity: structural connectivity, functional connectivity and actual connectivity. Structural connectivity mainly focuses on the physical structure between patches, for example, the degree of isolation among patches, whereas potential/function connectivity pays more attention to the behavior of organisms responding to the landscape structure and landscape matrix. There are some studies which use the term functional connectivity in place of functional connectivity (Uezu, Metzger & Vielliard, 2005). The actual connectivity is a concrete measurement based on individual movement between patches where the actual connectivity is derived from observation of individuals moving into or out of patches (Uezu, Metzger & Vielliard, 2005; Calabrese & Fagan, 2004). In other words, to measure the actual connectivity, the species’ movement must be quantified or observed. It is more complicated to measure potential/functional connectivity than structural connectivity, because functional connectivity requires the dispersal information of a certain species.

1.4 Research Significance and Goals

In recent decades, landscape connectivity has been widely studied in large spatial conservation ecologies that usually cover hundreds of square kilograms; conservation methods in this spatial scale with the goals of preserving habitat patches and restoring corridors with the reduction of human activity disturbance (Shepherd & Whittington, 2006). However, in urban landscape, it is hard to find a habitat without any human interaction; moreover, preserving a corridor that completely blocks humans out is also unrealistic. Humans and nature cannot be torn apart, especially in urban environments. Therefore, urban habitat conservation strategies should both take human beings and wildlife into account.

Previous studies have provided some theories and basic strategies for urban green network; however, from a practical perspective, current conservation strategies may be hindered because of restricted land use situation in fully developed urban landscape. Urban green network model in this research will be based on previous studies, but will further explore more a practical method for green infrastructure site selection. This paper provides a scientific methodology of green infrastructure development for city planners and designers. It could be a reference for selecting urban green infrastructure location, and developing green infrastructure with multifunction for both human and nature.

This research will look at the City of Detroit, a city with a large number of urban vacant lands available that could be used for green networks. First, this research will analyze the landscape connectivity using a multi-scale method, and then an urban core habitat will be explored. The urban corridor development will be based on the latest land cover and land use data. The gravity model is used to evaluate the urban corridor network. Finally, a possible green infrastructure design will be suggested to improve landscape connectivity in the city of Detroit.

With the process of urbanization and the rapid increase in human population, our understanding of landscape and ecology has changed. The concept of ecology and methods of geography are introduced to traditional landscape architecture and become assessment to support biodiversity conservation. This research aims to take advantage of landscape ecology to provide relevant information. In a renaissance of Detroit, this new concept could conserve critical urban green spaces, model potential corridors, and develop green space networks. Also, this research provides green infrastructure typologies for vacant land that could be a reference for city planners and designers in their efforts to build green networks and ecological cities in the future.

In the next section of this paper, theories, models and software for this research are outlined. In section 3, study area in Detroit is thoroughly described and detail methods for systematic green infrastructure planning are developed. The methods used in this study for evaluating landscape connectivity are also stated. Section 4 presents results of planning strategies. How proposed green network could improve landscape connectivity is analyzed by comparing pre and post-corridor development. To better connect research and real world, green infrastructure typologies are provided for case study area at last.

2 Theoretical Framework and Literature Review

In this section, the basic theories of measuring structural and functional landscape connectivity, graph theory and least-cost theory, along with their features, are stated in detail. The software and the necessary model for calculating structural landscape connectivity are also described and discussed in this section. How to theoretically conduct an evaluation of the structural landscape connectivity is also explained.

2.1 Graph Theory

The most common and widely used theory to support landscape connectivity measurement is graph theory (eg. Bunn, Urban, & Keitt, 2000), which has been applied in geography, information analysis and computer science. A graph or network contains points (nodes) that represent habitat patches, and lines (edges) that represent linkage or connectivity between patches (Minor & Urban, 2008; Phillips, Schwanghart, & Heckmann, 2015). Landscapes will be treated as a network of patches and/or habitats. Graph theory can support the measurement of either structural or functional/potential connectivity, and is suitable in either patch or landscape level

(Minor & Urban, 2008, Correa Ayram et al., 2015). The graph theory, which is suitable for computer aided calculation and analysis, lays the foundation of landscape connectivity analysis in this paper.

In a recent paper, Correa Ayram et al., (2015) reviewed 162 publications on landscape connectivity from 2000 to 2013 and found that more than 50 publications used methods relying on graph theory. For example, Bunn et al., (2000) examined habitat connectivity based on graph theory for American mink and Prothonotary warblers, two species with different dispersal abilities but sharing the same habitat. Other researchers associate landscape graph modelling with inter-patch movement models to calculate the functional connectivity (Bergerot et al., 2013). Kong et al., (2010) identified the potential paths in Jinan City, China, utilizing the least-cost path method and also developed green networks based on graph theory and the gravity model.

In my research, graph theory is employed to establish nodes and links in Geographic Information System (GIS) software where the latter can provide calculation data for the gravity model to locate urban greenspace networks.

2.2 Least-Cost Theory and Landscape Connectivity

The least-cost theory usually refers to “the least costly route” (Rudnick et al., 2012, p. 6) that species can utilize to move from one patch to another. In this theory, the species are assumed to take the cost of moving from one patch to another into account. This cost can be measured on a cost surface, a raster grid where the value of each cell is displayed, to reflect the risk of being preyed upon, the time and energy consumption caused by motion, and the “impact on future reproductive potential” (Rudnick et al., 2012, p. 6).

In practical application, the cost of a path always represents the unsuitability for an animal to choose to move, which means that species tend not to choose the higher cost path in their activities. In this way, the least-cost analysis can be considered as the “cost of traveling through different land use/cover types” (Lechner et al., 2017, p. 7). The cost surface for a least-cost analysis can be a result of all the social, environmental, economic, and engineering criteria effects, which means that the cost of each cell will be assigned under different assumptions. Therefore least-cost GIS modeling is actually empirically based (Byrd, Garrard & Brandy, 2016) and can be varied with the changing assumptions. Once the cost calculation assumptions are set, GIS software can calculate the cost value between two patches or two nodes to identify the least-cost one.

The least-cost analysis in fact provides us with a convenient quantified method to evaluate each path. At the same time, the most important problem in this analysis is how to find a proper way to define the assigned “cost” value of each type of land use. This method indeed brings landscape connectivity research into a new era. In this paper, I employ the least-cost analysis to choose least-cost corridors by based on the cost surface which is produced by giving each cell different cost weight in ArcGIS.

2.3 Gravity Model and Metrics

After proposing potential corridors to development, I study their different contribution to the overall landscape connectivity. I introduce a new model to help us evaluate corridors which have stronger influence.

Gravity model is a simple modification of Newton’s equation for gravity in order to evaluate the spatial interaction between two nodes (Sklar & Costanza, 1990). It is useful and efficient to exploit gravity model to establish standards for choosing corridors with high interactions between two nodes. In Newton’s equation, the gravity is inversely proportional to the square of the distance. This concept is adopted in gravity model to identify the interaction between two nodes (Kong, Yin, Nakagoshi, & Zong, 2010).

$$G_{ab} = \frac{N_a N_b}{D_{ab}^2} \tag{1}$$

G_{ab} represents for the level of interaction of node a and node b. N_a and N_b are the corresponding assigned weight values. D_{ab} stands for the cumulative impedance between node a and node b. The node weight is defined using the weighted impedance, which is different according to different types of land, and their normalized patch sizes.

$$N_i = P_i \bullet S_i \qquad (2)$$

where N_i is the weight, P_i is the node weight, and S_i is the normalized patch size of node i. D_{ab} will be the ratio of cumulative impedance L_{ab} to maximum value of cumulative impedance L_{max} in this focused area.

$$D_{ab} = \frac{L_{ab}}{L_{\max}} \qquad (3)$$

It is noticeable that only the comparison between values of G_{ab} in different corridors are significant, not the values themselves. In other words, this final step is to compare the values of G_{ab} in different corridors so, in fact, it will not affect the results no matter what methods are used to rescale the assigned weight and impedance.

2.4 Software for Measuring Landscape Connectivity

There are many different methods and supporting software programs for assessing landscape connectivity based on graph theory. In this section, I introduced some of the most widely used approaches.

2.4.1 FRAGSTATS and Metrics

FRAGSTATS is a commonly used software for analyze structural connectivity (Correa Ayram et al., 2015). It has with various choices of landscape metrics that is used to analyze spatial patterns and qualify landscape structures. There are area density/edge metrics, shape metrics, connectivity metrics, diversity metrics, etc., which are grouped at to the patch level, class level and landscape level. These metrics are powerful and can support the spatial pattern analysis at all levels (McGarigal, Cushman, & E Ene, 2012).

Some researchers used FRAGSTATS to get basic statistics for a certain type of habitat. For example, Xun et al., (2014) uses both patch metrics core area (CA) and class metrics; for instance, landscape total core area (TCA), mean core area (MCA), landscape shape index (LSI) etc. to evaluate the quality of focal forest habitat. Tian et al., (2011) used FRAGSTATS to measure the landscape level connectivity in Hong Kong by dividing Hong Kong city into several 160-hectare hexagonal regions. Uy and Nakagoshi (2007) and Kong et al., (2010) have analyzed urban green space pattern changes over two years using landscape metrics such as patch density (PD) and cohesion to get an overall understanding of the structural connectivity of urban green spaces. Another researcher selected CONNECT in FRAGSTATS as a landscape metric and analyzed the connectivity change based on different dispersal distances (Bierwagen, 2007). Vergnes, et al., (2012) used four patch metrics in FRAGSTATS classes to understand the spatial composition of three land uses surrounding their target gardens.

Although FRAGSTATS is a powerful software to analyze spatial pattern, some researchers thought it had limitation because the measurement of structural connectivity might not represent ecological function (Li & Wu, 2004). But research of Correa Ayram et al.(2015) referencing from other studies agree that structural connectivity could indicate potential landscape connectivity.

2.4.2 Conefor and Metrics

Conefor is another software that is used to measure functional landscape connectivity(Correa Ayram, Mendoza, Etter, & Salicrup, 2015). This software is also the graph theory base, using nodes to represent patches and links to represent distance between patches. Conefor introduces two new metrics, the integral index of connectivity (IIC) and the probability of connectivity (PC), relying on the habitat availability concept; this software could support decision- making for landscape conservation (Saura & Torné, 2009). Regarding the two suggested metrics, the IIC is based on the binary connection model, by comparing the distance between patches with the threshold dispersal distance of a certain species; the PC comes from the probabilistic connection model, where the probability of dispersal success is a decreasing exponential function of distance between patches (Saura & Pascual-Hortal, 2007).

Conefor is also widely used. As the research of Correa Ayram et al., (2015) found that among the 130 pieces of literature they reviewed, 21% of the studies used Conefor to measure functional connectivity. Mitsova et al., (2011) use Conefor 2.2 to see the connectivity metrics changes of wetlands and other five areas under two scenarios. Xun et al., (2014) used Conefor to evaluate whether proposed orchard lands were valuable to improve habitat availability. Other researchers used Conefor to calculate the IIC of patches identified in weighted linear combination models, and used the result of dIIC (the delta of the Integral Index of Connectivity) to support the corridor decision (Shanthala Devi, Murthy, Bijan, & Jha, 2016).

The difference between functional and structural connectivity measurements is that the former one requires dispersal information of a certain species. Users must define the dispersal distance threshold, either binary connection or probability connection. It may take more effort to get dispersal information of species.

3 Methodology

This study proposes four sub-models, with various methods conducted to understand the landscape connectivity at different urban scales.

First, I use FRAGSTATS and Conefor to measure landscape connectivity. Although they are used in previous studies, only a few researchers used the model on a small scale that is similar to my research. Another reason I use two programs is that FRAGSTATS measures structural connectivity and Conefor measures functional connectivity; I want to prove whether structural connectivity can indicate functional connectivity. In my research, both programs are used to calculate different landscape matrices used as index measuring the landscape connectivity in a census tract scale. Then, core habitat patches were identified, given current land use constraints. Next, corridors were modeled using the least cost method, which took advantages of existing vacant land. Gravity model is used to calculate the gravity index, helping me to understand the different connection strength of corridors; network indices are used to evaluate different scenarios of network connectivity. The comparison of structural and functional connectivity between before-and-after corridor-developed census tracts further proved the ecological value of green infrastructure corridors. The overall framework work is represented in Figure 1.

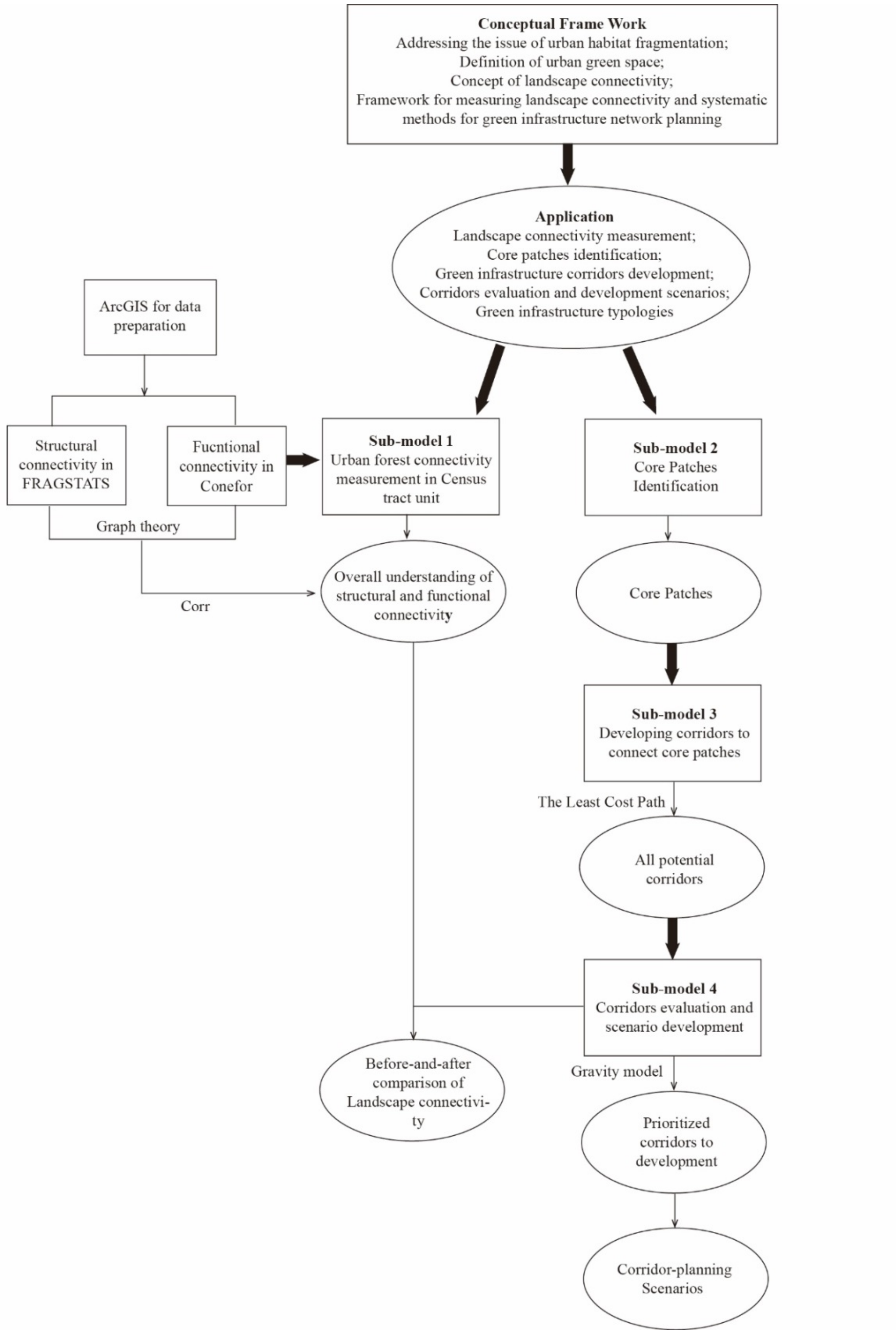

Figure 1. Schematic frame work

3.1 Study Area

This research focuses on the city of Detroit. This city is one of the 20 largest cities in North America, with 714,000 residents, and it possesses global economic assets (Detroit Future City, 2012). However, like many so-called “legacy cities” or “shrinking” cities, Detroit struggles with a declining population, economic problems, and high rates of vacancy and blight. Large numbers of researchers have been studying Detroit city for a long time to understand all kinds of issues and to look for solution for the city to be renewed. Some people suggested using green infrastructures for redevelopment which not only benefit the overall urban environment but also improve human-wellbeing. (Schilling & Logan, 2008; Lovell & Taylor, 2013). This research conducts a strategic method for green network planning in Detroit due to its huge opportunity for redeveloping vacant lands.

3.1.1 History

As the Ford Motor Company was founded in the early 20th century, Detroit established its place as the world’s automotive capital (Woodford, 2001). The fast growth of industrialization helped Detroit to become the fourth largest city in the US in 1920, and Detroit reached its peak population in 1950 with about 1.8 million people. However, in the next sixty years, after suburbanization, industrial restructuring and a decrease in the jobs available, Detroit was less than 10 percent of the state's population (Seelye, 2011). Detroit’s failure is not the result of a single factor but is due to several reasons, such as auto-oriented development and suburbanization (Saunders, 2012).

The city of Detroit was once proud of its fully mature industrialization, especially the automobile manufactors (Farley, Danziger, & Holzer, 2000), but finally Detroit became a shrinking city.

3.1.2 Existing Conditions

Current-day Detroit still possesses a large city size. However, this city is struggling with serious social issues including unemployment, poverty, and a high crime rate.

Along with its continuing population decline, Detroit has a high vacancy rate, shown in Figure 2. The estimated vacant housing unit rate was about 30 percent according to the U.S. Census Bureau (2015). Vacant land is commonly regarded as land that is unused or abandoned for a long time, with various types such as land with abandoned structures and land property no longer being used by humans (Pagano & Bowman, 2000; Németh & Langhorst, 2014). Many environmental issues and social issues have been caused by vacant land. For example, polluted soil is also a common feature in vacant land that contains heavy metals and construction debris; besides, largely vacant residential land viewed as a "walk-deterrent" would be an undesirable feature that discourages people's physical activities (Wineman et al., 2014). Therefore, I need to take care of the vacancy issue which influences human well-being in shrinking cities.

Figure 2. Vacant land in the City of Detroit

3.1.3 Opportunities

Vacant land and ecosystem services

Land use in legacy cities includes a lot of issues, but still there is an opportunity to benefit human well-being and solve environmental issues. Vacant land, a common occurrence in legacy cities, although accompanied by social and environmental issues, has the potential to benefit ecosystems and social well-being; for example, it could provide habitats and help with stormwater management (Németh & Langhorst, 2014). Haase et al., (2014) stated that proper land use in legacy cities could achieve ecosystem services such as the enhancement of urban biodiversity, and mitigate the local climate. Previous research studied trees on vacant urban land and found those trees could help city resident to reduce energy cost by carbon sequence, improve environmental quality and provide ecosystem services (Kim, Miller, & Nowak, 2015). Some researchers have proposed a vacant land greening strategy on a neighborhood scale that could benefit individuals by increasing property values, and as well as empowering the whole community (Schilling & Logan, 2008). Other researchers have started to think of the use of vacant land in a more systematic way, such as to form open space networks through vacant land in order to improve landscape connectivity (Frazier & Bagchi-Sen, 2015). Other researchers have proposed a vacant land greening strategy in neighborhood scale that could benefit individuals by increasing property values, and as well as empowering the whole community (Schilling & Logan, 2008).

While the city of Detroit faces many challenges, the large number of vacant lands present are unique opportunities for planning the future scenario for the city. One of the goals proposed in the recent Detroit Future City Plan for redesigning the city is to replace aging “grey infrastructure” with nature-based “green infrastructure” built on existing vacant lands (Detroit Future City, 2012). This research will generate a systematic green network strategy on the vacant land issue for green infrastructure developments.

3.2 Urban Habitat Pattern Analysis

This is the first sub-model of methodology, selecting urban forest as habitat object, by analyzing special pattern of urban forest to understand landscape connectivity of Detroit.

3.2.1 Data Sources

Data used in this research come from two sources. The original vegetation data is extracted from the 2012 Land Cover GIS data from the Southeast Michigan Council of Governments (SEMCOG) Open Data source; vacant lot data is from the 2012 Land use data, also from SEMCOG. The GIS boundary of Detroit census tract data is from the United States Census Bureau 2010 Tiger Shapefile. Parks and Recreation shapefile is 2010 data from Data Driven Detroit. Alleyways are extracted from road data which is from Data Driven Detroit Open Data source.

3.2.2 Spatial Scale Definition

The selection of appropriate scale is important for recording the vegetation spatial pattern in a reasonable spatial region. Since I measure landscape connectivity using tree canopy as the object, I want to select a suitable scale, not too large or too small, to represent the whole city landscape connectivity. In this study I used the census tract as the sample scale, numbering 296 census tracts in total.

3.2.3 Urban Forest Spatial Pattern Analysis

In this section, I use two software programs to measure landscape connectivity, FRAGSTATS and Conefor. Both programs are widely used but with different mathematical methods in conducting landscape connectivity indices. The reason for using two different ways is that I want to study whether or not the structure can reflect the functional connectivity.

3.2.3.1 Connectivity analysis in FRAGSTATS

The census tract is the sample unit used to calculate the vegetation landscape metric. To prepare a suitable data format to calculate the landscape metric, the tree canopy data, originally in a vector format, was converted to raster format in a 1m * 1m resolution map in ArcMap 10.4. Then city-wide tree canopy raster data was clipped by census tract boundaries into 296 census tract scale raster with the help of a Python script in ArcGIS 10.4.

Then I treated every tree canopy clump as one patch. A patch meant a group of cells that were all identified as tree canopy, and different from any other cell directly connected to any cell within this clump group. Landscape connectivity measurement was based on all tree canopy clumps with in a census. The landscape metric used to represent tree canopy was COHESION. This index measures the physical connectedness of the corresponding patch type; here is the physical connectivity of the tree canopy. COHESION increases when tree canopies are more clumped (McGarigal, Cushman, & E Ene, 2012).

$$\text{COHESION} = [1-\frac{\sum_{i=1}^{n} p_{ij}}{\sum_{j=1}^{n} p_{ij}\sqrt{a_{ij}}}][1-\frac{1}{\sqrt{A}}]^{-1}(100) \qquad (4)$$

p_{ij} was the perimeter of patch ij in terms of number of cell surfaces

a_{ij} equaled to the area of patch ij in terms of number of cells

A was the total number of cells in a landscape

The landscape metric calculation was processed in FRAGSTATS 4.2.1 at class level.

3.2.3.2 Connectivity analysis in Conefor

FRAGSTATS focuses on the structural connectivity measurement, which may a limitation without a certain species to be considered into measurement process. I want to validate the results from FRAGSTATS to see how structural connectivity related with functional connectivity. Therefore this researcher also uses the Conefor program to measure the connectivity. This research uses the integral index of connectivity (IIC) recommended by (Saura & Torné, 2009). This metric relies on the habitat availability concept, and is sensitive to the loss of landscape element which means any two habitats located in a reachable distance based on dispersal information of a certain species (Saura & Torné, 2009).

$$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \cdot a_j}{1+nl_{nj}}}{A_L^2} \qquad (5)$$

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.

Data Preparation

The requirement for the input data is an ASCII txt file that contains the numerical data of node and link information. This input data can be produced by the Conefor extension in ArcMap10.4.

I used selected census tracts as samples to compare the result from FRAGSTATS and Conefor. The first step was selecting the sample census tracts. Since the process of conducting all 296 census tracts in Conefor was time costing, I randomly selected 30 census tracts as samples in Excel; each of the sample census tracts had a unique ID. Based on the unique ID, these 30 census tracts could be easily selected by the *attribute selection function* in ArcMap 10.4. These census tracts then were used as clip boundaries to clip tree canopy. Because the Conefor extension required a polygon feature as an input to produce .txt nodes and distance files, I used tree canopy vector data, which were downloaded from the SEMCOG Open Data source. Tree canopy then were clipped into 30 different small regions using the *clip tool* in a loop function in ArcGIS Python 2.7. After tree canopy polygons were clipped into those 30 census tract regions, the Conefor extension could convert the polygons into 30 node files and 30 connection files. In the node .txt file there were two columns of information, the node ID representing the tree canopy patch within a census tract, and the node attribute recording the area of each canopy patch. The connection file of each census tract had all the paired-node-ID and Euclidean distance information between paired nodes. The node file and connection file of the same census tract were imported into Conefor software when properly prepared.

The requirement for the input data is the ASCII txt file which contains the numerical data of the node and link information. This input data can be produced by the Conefor extension in ArcMap10.4.

Processing using the Conefor software

In this analysis, I calculate both the IIC and the PC. In the Conefor 2.6 setting windows, for one census tract, I chose PARTIAL for the connection file and DISTANCE as the connection type. For the metric IIC, the threshold was set as 20 meters. I assumed that 20-meter-distance was achievable for small animals to move from one tree clump to another, such as squirrels and birds, to conduct a non-stop movement. This process was repeated 30 times to calculate connections for all 30 census tract samples.

Regression analysis

A simple correlation and linear regression was processed in R studio to check the correlation relationship between IIC and the cohesion of the sampled census tracts.

3.3 Core Patches Identification

Core patches serve as habitat sources. In this second sub-model, I identify core patches in the city of Detroit by considering edge effect and patch central areas. These core patches will be connected by proposed corridors in the later section.

Patches exist in different scales, and their sizes vary from small to large. No matter what size a patch is, it will contain an edge and interior area/center area. Edge width is affected by natural and human interference such as wind and human activity, while the interior/core area is less disrupted (Forman, 1995). A large habitat is regarded as the core habitat that can support many large-home-range vertebrate (Forman, 1995). Many researchers used different criteria to select core patches to represent large habitats in their landscape connectivity analyses.

Existing core patches’ identification have been applied to different landscapes. Some researchers suggest the use of the perimeter area ratio index to help identify the core area since species richness was positively correlated with this index; other researchers used particular patch size, eg. 12 ha, as a criterion for the identification of the core area (Xun, Yu, & Liu, 2014; Kong, Yin, Nakagoshi, & Zong, 2010)

As I mentioned earlier, edge is also one part of a patch, and thus the identification of a patch would consider the edge effect area and the interior area. The edge width was equal to the average tree height multiplied by three; the interior area/core area equals the total area of a patch minus the edge area (Firehock & Walker, 2015). I used the method suggested by Firehock and Walker (2015), building a buffer from land cover types that were not considered as a land cover of patches intersecting patches; the intersected area represented the edge area, and the rest of the patches, which excluded the intersected areas, were interior/core areas.

In this study, 50 feet is used as the average height of urban trees, which represents the mature height of native woody plants in Detroit such as red oak and red maple, and 150 feet as the edge width. The land cover type treated as patch land cover was tree canopy; other land cover types tested were built-up, impervious, open and water. I built a 150-meter buffer for all non-forest canopy land cover polygons, and used this buffer polygon to intersect with tree canopy features. The intersected areas were edge area, and the rest of tree canopy was interior area. The process of buffer and intersection were all conducted in ArcGIS 10.4. Firehock and Walker (2015) suggested that if the interior area is larger than 100 acres (40 ha), patches that contained this interior would be core patches. However, the 40 ha interior area criterion was hard to apply in this case study. There was only one City Park meeting this criterion. Therefore, I removed the edge influence and adjusted by using overall size of 12-ha (0.2 km^2) suggested by Xun et al., (2014) and Kong et al., (2010), as criterion to select core patches. It mean, if a park has overall size equal or larger than 12 ha, it is core patch.

3.4 Corridor as a Conservation Process

In the third sub-model, at first, corridors are developed by the least cost path model between pair-wise core patches. Then gravity model is used to evaluate which corridors provided stronger connection between patches. After corridor developed, census tracts are sampled to compare COHESION and IIC in before-and-after situation.

3.4.1 Corridor Built-up by Least Cost Path Analysis

Corridors were built to connect core patches and city parks by the least cost path method in ArcGIS 10.4. This method was designed to build a path with the least cost cells in total between two points. In this analysis, let us make use of existing vacant lands, alleys and existing green spaces (parks and open space) within the city as the most suitable land to use for potential corridor selection. Vacant lands as previous section mentioned, have opportunities to be redeveloped. Alleys are parts of transportation networks in a city which have the potential to contribute landscape connectivity and enhance urban sustainability (Newell et al., 2013). Besides these two land use types, existing green spaces, regarded as one type of green infrastructure, will reduce cost in building corridor process.

The suitability of building corridors varies on different land use types. Analytic hierarchy process (AHP) is used as a first step to build a suitability land use map. AHP process is a multi-criteria decision making process to help research making decision by giving different important weights on factors (Engineering, Triantaphyllou, & Mann, 1995). Here I used AHP to produce suitability map based on existing land use. The next step was to divide the vacant lands into three categories, vacant land without buildings and trees, vacant land without buildings but with trees, and vacant land with buildings. A suitability score of 100 was given to vacant land without buildings but with trees, 80 for vacant only, and 60 for vacant land with buildings. This process was conducted in ArcMap 10.4 using the *selection by location* function. Green spaces were given a score ranging from 40 to 100 based on the size of corresponding green spaces. All the alleyways were given the suitability score of 100. The weighting for each type of land use I mentioned above was obtained by using the researcher pair comparison in the analytic hierarchy process, see Table 1.

Then the suitability map was converted to a cost surface map in order to conduct the least cost analysis. The cost surface map showed the inverted scores from the suitability map, which meant that higher suitability land uses such as vacant lands, existing green space and alley ways, would have lower costs, and other land uses with lower suitability would have higher costs. The *Minus* tool in ArcMap 10.4 was used to invert the suitability map to a cost surface map, and then standardized the cost surface map to make the cost range of 0-100.

The *cost path* tool was used in ArcMap to build a least cost corridor to connect core patches (source) and large city parks (destination). Table 1 lists the variables of land use.

Table 1. Variable of land use and AHP weight

Variables	Unit	Source	Description	Suitability Score	Weight
Green Space	m	Derived from SEMCOG Land use 2008 polygon feature	SEMCOG's 2008 land use data provides a general snapshot of land use in Southeast Michigan in the spring of 2008. It includes all city parks, public gardens, sports field and other public recreation area.	40-100 (>=12 ha, 100; 5 ha =< area < 12 ha, 80; 1 ha =< area < 5 ha, 60; < 1 ha, 40)	0.33
Alley	m	Obtained from Detroit Open Data alleyway layer linear feature	Usually this is a narrow passage between buildings; it could serve as the place for garbage cans or a location for municipal utilities.	100	0.53
Vacant Land	m	Obtained from Data Driven Detroit open data	Detroit parcel survey in 2013. Parcels were identified as unoccupied.	50-100	0.14

3.4.2 Corridor Evaluation Based on a Gravity Model

The corridors designed are based on least cost path analysis but provided less information about the relative significance between them, when they all represent connecting from one source to others. A gravity model can help to identify which corridor to develop first by calculating interactions between nodes, where a higher interaction score is given to corridors between higher quality habitat patches and with lower impedance (Kong, Yin, Nakagoshi, & Zong, 2010). Previous research calculated the interactions (G_{ab}) between each node as an index to evaluate corridor between nodes (Uy & Nakagoshi, 2007; Kong, Yin, Nakagoshi, & Zong 2010; Huang et al., 2016). Higher interaction meant corridors providing more significant links between two patches (Linhan, Gross, & Finn, 1995). Formula is presented as flow:

$$G_{ab}= N_aN_b/D_{ab}^2 \tag{6}$$

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.

$$N_a = (1/P_a) \cdot (S_a) \tag{7}$$

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

$$D_{ab}= L_{ab}/L_{max} \tag{8}$$

L_{ab} = the accumulation of resistance value between parks a and b corridors (9)

L_{max} = the maximum impedance value of all L_{ab} (of total corridors) (10)

Each cell had a certain land cover with a certain weight. For example, the tree canopy had low impedance. The node (park) weight was defined using the weighted impedance of difference types of land cover. The link weight was determined based on the type of land cover of each cell located in a corridor. Nodes represented core patches that were larger than 12 ha. The least cost path was processed between paired nodes by coding in Arc Python 2.7. Table 2 lists the land cover variable and the impedance values.

Table 2. Land cover variables for impedance value corridor and patches

Variables	Unit	Source	Description	Impedance values
Tree Canopy	m	Derived from SEMCOG Landcover 2012 polygon feature. Polygon features are converted to raster data	Represents the urban tree cover and shrub cover, but does not include herbaceous cover	1
Open Space	m	Derived from SEMCOG Landcover 2012 polygon feature. Polygon features are converted to raster data	Open space is the area with grass or lawn cover, excluding any other structures like building, utilities, trees, and etc.	5
Urban Bare	m	Derived from SEMCOG Landcover 2012 polygon feature. Polygon features are converted to raster data	Area neither covered with tree canopy, impervious surface, lawn/grass, or water, just bare soil on the surface.	80
Impervious Surface	m	Derived from SEMCOG Landcover 2012 polygon feature. Polygon features are converted to raster data	Land surface with impervious covers, or with impervious structures like concrete and asphalt. For example, paved roads and concrete building are included as being impervious.	100
Water	m	Derived from SEMCOG Landcover 2012 polygon feature. Polygon features are converted to raster data	Lakes, rivers, streams, and other ground water features	100

3.5 Corridor Scenario Development and Network Analysis

The corridors that are chosen as priorities for development are those meeting a certain gravity score threshold. I select top 10 corridors and present five corridor-development scenarios to explore how different scenarios will improve the overall connectivity for the city of Detroit. Two wildly used network indices have been calculated: beta (β), gamma (λ) (Linhan et al., 1995; Rudd et al., 2002; Uy & Nakagoshi, 2007； Kong, Yin, Nakagoshi, & Zong, 2010).

Beta equals to the number of links (*l)* divided by the number of nodes (*v*) (Forman, 2015).

$$\beta = \frac{l}{v} \tag{11}$$

Gamma equals to the number of links (*l)* divided by the maximum possible number of linkages (l_{max}) (Forman, 1995).

$$\lambda = \frac{l}{l_{\max}} = \frac{l}{3(v-2)} \tag{12}$$

Gamma indicates the network connectivity (Forman, 1995), and beta represents the node connection (Forman, 2015). The network influences the movement and flow in a landscape (Forman, 2015); therefore these indices will help to us to understand the movement pattern.

3.6 Connectivity Improvement on the Census Tract Scale

Besides city wide network analysis, I conduct landscape connectivity in census tract scale. 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 corridor features in ArcMap 10.4 using the *merge* toll. Then five census tracts were randomly selected as samples in which corridors would be developed. Corridor features were merged into existing tree canopy features in each census tract. Rest methods were the same with section 3.2.3.1 and 3.2.3.3 by FRAGSTATS and Conefor to calculate connectivity metrics and compare the new results with the old results for these five sampled census tracts.

4 Results

Both structural and functional connectivity results in census tracts were presented in maps to give a visual perspective of overall landscape connectivity of the city of Detroit. Correlation analysis result between structural and functional connectivity in sampled census tracts were also stated. The result of core patches and corridor development between pair-wise patches were shown in maps. Interaction results of paired patches and their corridors helped me to select top ten prioritized corridors. Different network scenarios for developing ten corridors were evaluated; each scenario resulted in contributing different network efficiency.

4.1 Census Tract Landscape Connectivity

Figure 3 shows the landscape connectivity result from FRAGSTATS. COHESION is used as the index, and ranges from 0-100. Higher COHESION indicates that patches are better connected physically. Compared with the tree canopy data, the high COHESION scores exist in census tracts where more tree canopy features and clumps of trees are located.

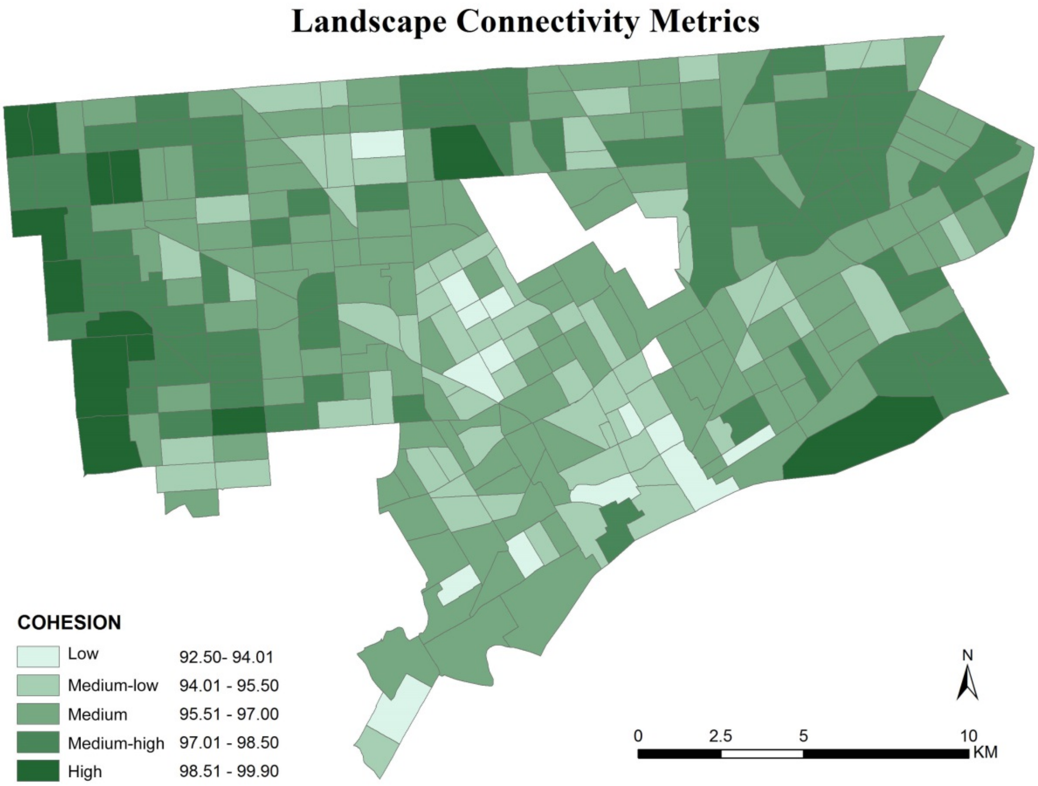

Figure 3. Cohesion Result Map

By comparing the connectivity results with the 2010 aerial photo, I can see an obvious pattern that census tracts with low cohesion scores have fewer tree canopies.

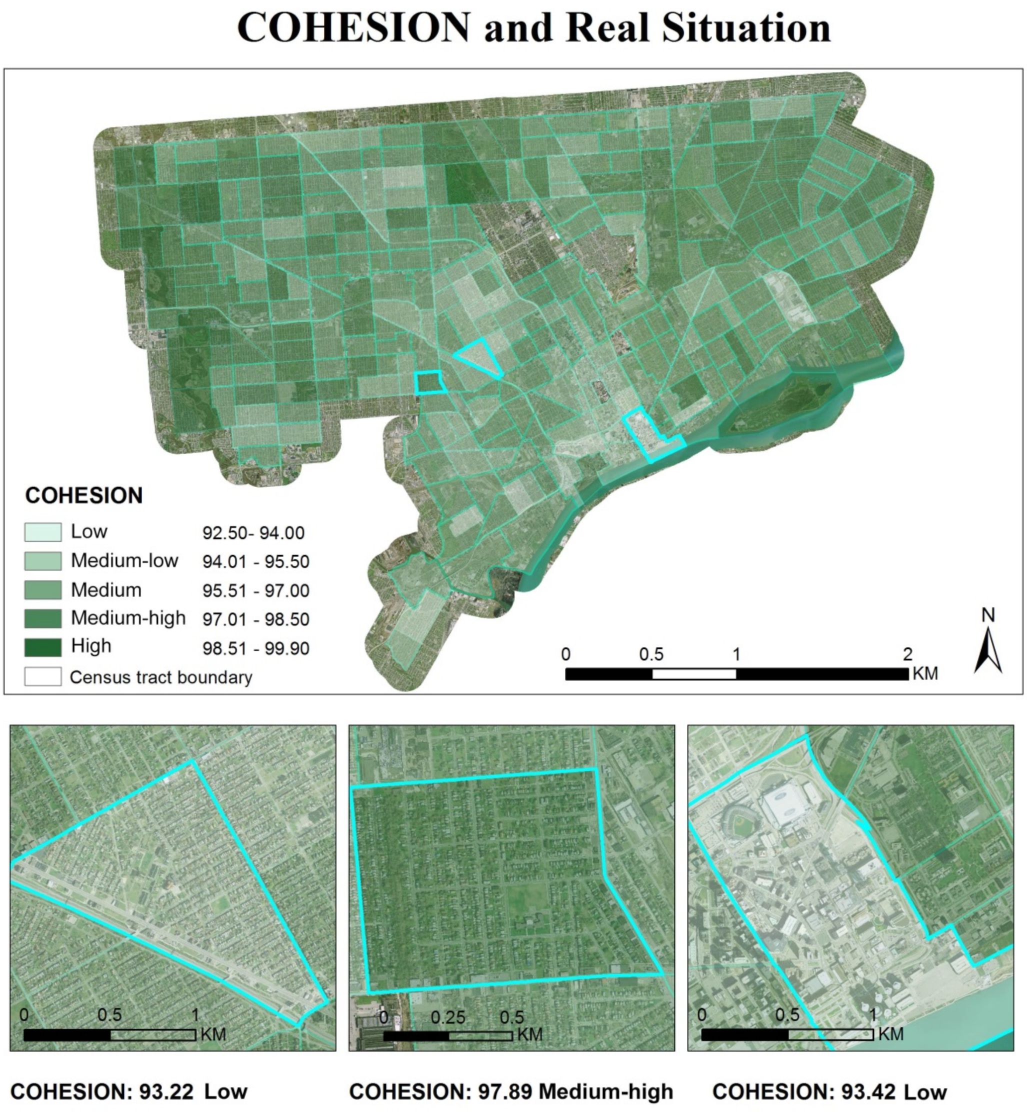

Figure 4. COHESION compared with the actual situation

In Figure 4, three census tracts with different COHESION results are selected as examples to see how real land cover is related to the COHESION scores. The bottom left image shows area for residential use surrounding an academy school with open fields. Although there is a large amount of residential land use and a school in the center, the COHESION score is not high because there are few tree canopy features. Most of the green features I see in this image are lawn and grass, which are not regarded as patch in this study. The image in the middle is also a residential area, but with high COHESION score. In this census tract, the tree canopies are clumped in blocks; the long block located on the west side of this census tract has clumped and connected trees in alleyway, forming a linear shape from north to south. The right corner image shows one census tract located in the Detroit downtown area. Commercial land use prioritizes this census tract. There is a low COHESION score because trees can hardly be seen in this region. The spatial distribution of COHESION with the Detroit land use is summarized in Table 3.

Table 3. COHESION distribution on a city-wide scale

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 that had low cohesion as there were fewer tree canopy clumps 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 score are spreading across the City of Detroit.
97.01-98.50	23.65	Medium-high	Most mid- to high cohesion areas tend to spread in the residential land use with a lot of vacant land in those census tracts.
98.51-99.16	4.39	High	Most high cohesion areas are the census tracts that already have large city parks with trees densely

	clumped, such as census tracts in Rouge River Park and the Detroit Golf Club.

I plot COHESION scores of each census tract in R to get a general tree canopy partial pattern for the city of Detroit. The COHESION is in a normal distribution, with a highest frequency of 96-97 COHESION; the mean is 96.25 and the median is 96.22. See Table 4.

Table 4. Summary of COHESION

	Min	Max	Mean	Median	Variance
COHESION	93.82	99.16	93.82	96.22	1.44

In order to see whether the structure connectivity had the potential to represent the functional connectivity, 30 census tracts have been randomly selected and their Integral Index of Connectivity (IIC) calculated and mapped in ArcGIS, as shown in Figure 5. Visually comparing these two maps, I can see some census tracts with high IIC that are also associated with high COHESION. For example, two census tracts located at the west edge of the City boundary represented high COHESION and IIC, while census tracts located in the center of Detroit had low COHESION and IIC. However, a map’s visual information might not fully represent the actual relationship between COHESION and IIC since their value ranges, comparing 93.82 to 99.16 and 0.025 to 0.35, are different.

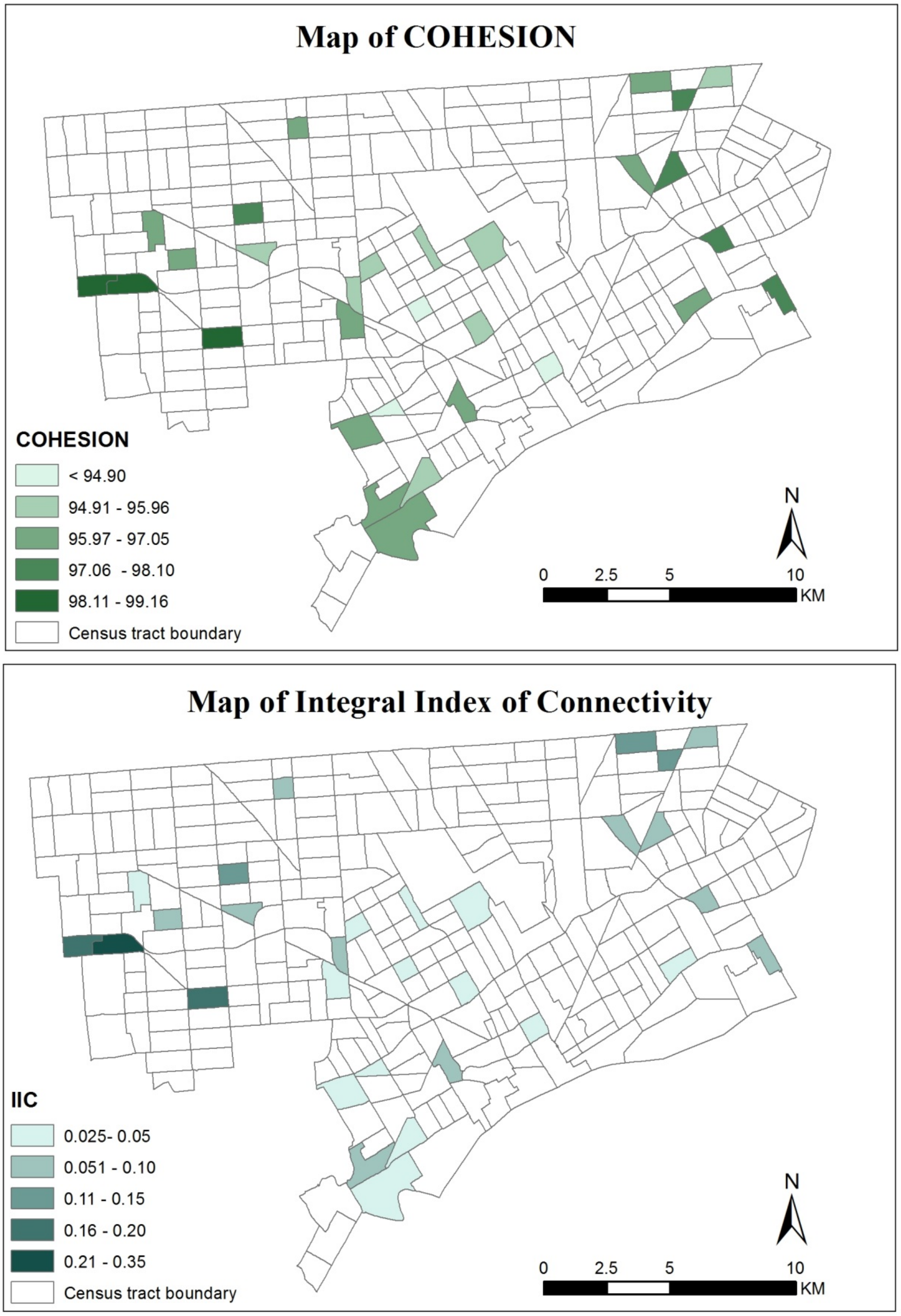

Figure 5. COHESION and IIC comparison

To further understand the statistical relationship between IIC and COHESION, a simple correlation analysis has been performed for IIC and COHESION based on data from the 30 census tracts. The correlation analysis between IIC and COHESION resulted in 0.769, which is relatively high. This shows that a high IIC may be associated with a high COHESION. This result aligns with previous research that structured connectivity can indicate the functional connectivity (Calabrese & Fagan, 2004).

4.2 Patch Identification

With a general understanding about the landscape connectivity of the whole city that large percentage of COHESION score in medium-low range (See Figure 4) representing good enough landscape connectivity, this researcher started to think about how landscape connectivity could be improved. The first step was to identify core patches. Core patches, as habitat sources, would be connected by corridors in next process.

The central/interior area is the result of total patch size minus the edge area. The edge area came from the buffer zone of non-natural land cover (commercial, residential, industrial, etc.). The first criterion is that core habitats should contain a central area with a size of not less than 12 ha, excluded edge areas. The second criterial is that core patches should be located on the mainland, not on an island. Figure 6 presents the only core habitat that has a central area larger than 12 ha. This core patch is the Rouge Park, located on the west edge of Detroit. Actually, there is another core patch, Belle Isle; this patch is excluded later due to the fact that this patch is on an island, separated by Detroit River, without physical connection with the mainland. No other core habitat exits because no other green space meets the criteria mentioned above. This result reflects the truth that habitats in the City of Detroit are highly fragmented. Although there are no other core patches in the city of Detroit which could be regarded as a habitat source, the only preserved natural area is still a benefits to the wild life, the urban environment and to human well-being.

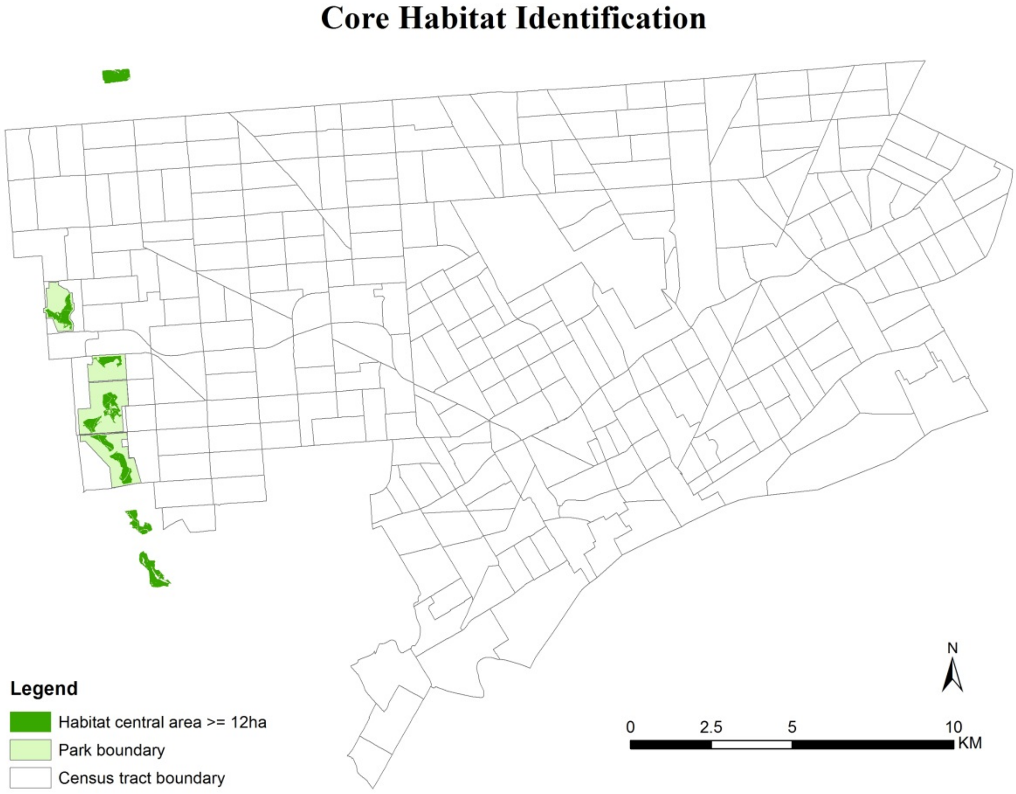

Figure 6. Core Habitats in the City of Detroit

Facing the challenge that there is no other large patch within in the city of Detroit as habitat sources which could be connected later, I modified the criteria of identification core patches. In order to complete the research goal to improve the overall connectivity for the city of Detroit, it was necessary to remove consideration of the edge effect and just use size as the criteria. Large urban green spaces such as city parks are the main green infrastructures in urban environments, and although they may not be large enough or may not have vegetation density to be treated as “real core patches” they still provide habitat functions to support wildlife and biodiversity to some degree (Fuller, Irvine, Devine-Wright, Warren, & Gaston, 2007). Therefore, city parks were chosen as objects and the park size has been used as the new criteria. A park larger than 12 ha has been identified as a new core patch, as shown in Figure 7. By using these new criteria, 16 city parks have been identified as habitat sources for building connections later.

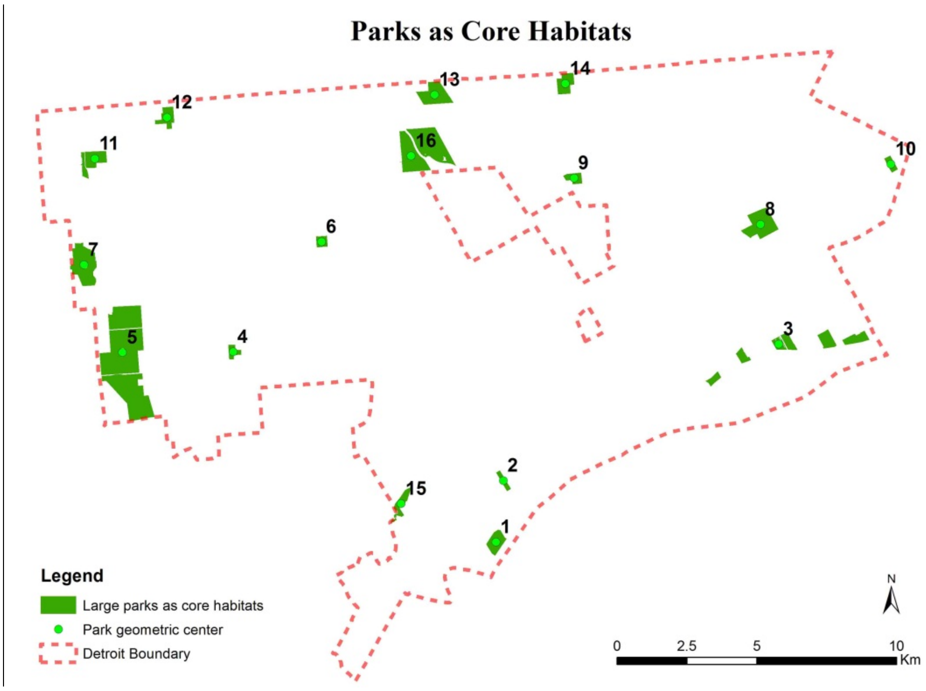

Figure 7. Large City Parks as Habitat Sources

4.3 Corridor Build-Up and Evaluation by Gravity Model

The process of building a corridor is based on the least cost path method. Using high suitability scores, which means a low cost to build a path to vacant land, alleyways and existing small green spaces (while assessing a high cost for the rest of lands such as roads, commercial areas, residential areas etc.,) led to building pairs of least cost paths among large parks (core patches/source habitat), resulting in 120 potential corridors in total.

Although there are 120 potential corridors, they cannot be developed at once. Since the development itself is a critical process, it is important to select the corridors that will enhance the landscape connectivity most efficiently. The gravity model was used to determine the best corridors based on the accumulated resistant values of potential corridors and the accumulated resistant value of patches connecting to the potential corridor.

The threshold 0.3 suggested by Kong et al., (2010) was chosen, which resulted in a choice of 27 corridors of the 120 total corridors. Table 5 shows corridors between two patches that meet the gravity index's 0.3 threshold criteria.

Table 5. 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

* Gravity index less than 0.3

The top 10 corridors with highest gravity index results were selected, with the goal of finding out how much connectivity could be increased if I develop those top ten corridors.

4.4 Network Evaluation in Different Scenarios

Figure 9 shows the top ten corridors within the highest gravity index. The corridor with the highest gravity index would connect patch 5 and patch 7, thus connecting the Rouge River Park (patch 5) with the Eliza Howell Park (patch 7). 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 (Hellmund, 1989), with every patch visited only once (the network typology is shown in Figure 8). The first four corridors are named in the Paul Revere network shape as shown in Scenario 1 (see Figure 10a).

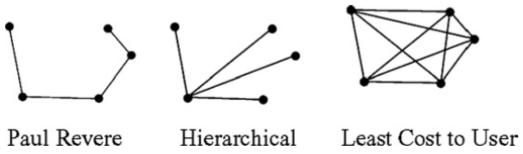

Figure 8. Network typologies (Hellmund, 1989)

Scenario 2 is a situation in which the fifth and sixth corridors would be built between patch 4 and 7, and patch 7 and 12. In this scenario, two small circuits formed, with a one to one connection among patches 5, 7 and 4, and a one to one connection among patches 7, 11 and 12, shown in Figure 10b. These two circuits formed the Least Cost to User network type, which minimizes the travel cost between two patches (Hellmund, 1989).

Scenario 3 represents the 8th corridor, to be connected between patch 5 and patch 11, a more complexed and developed Least Cost to User network formed on the west side of Detroit (see Figure 10c). The rest three corridors are located in different places in the city; none of these three corridors conform to the network typology provided by Hellmund (1989). Scenario 4 is the development of all the top ten corridors, as Figure 9 shows.

The reason for developing different scenarios is to see how each scenario can contribute to green space network to help the determination of networks spatial pattern (Linhan, Gross, & Finn, 1995).

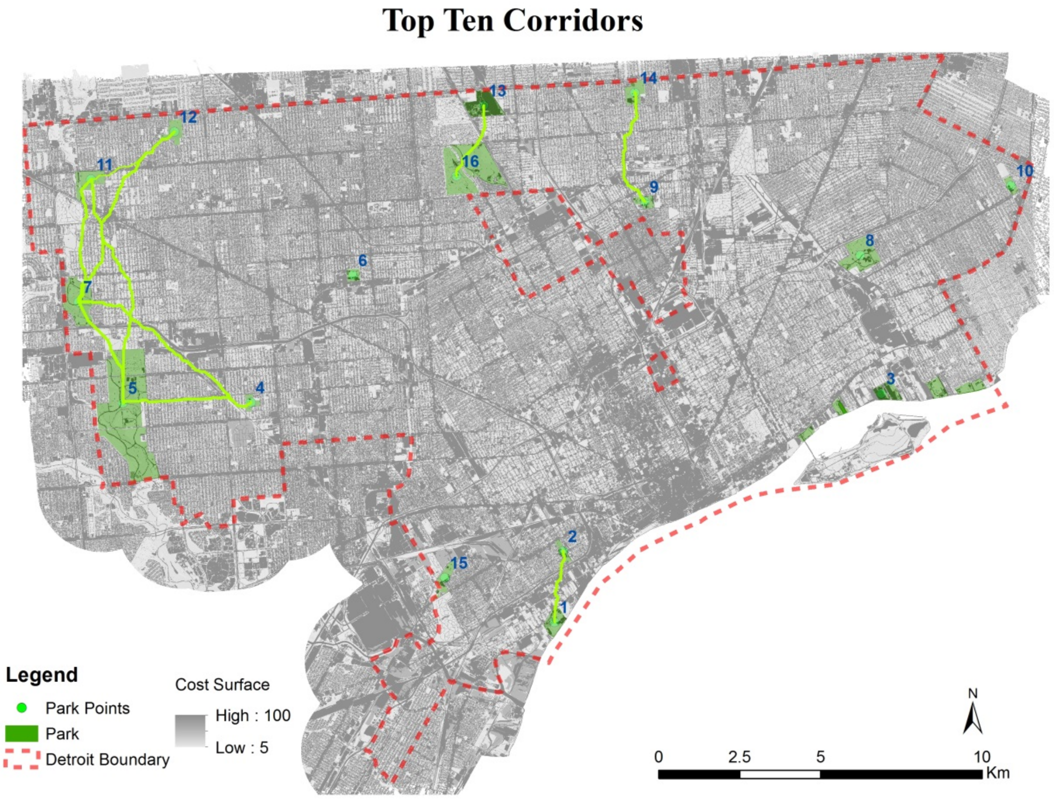

Figure 9. Top ten corridors with high gravity scores

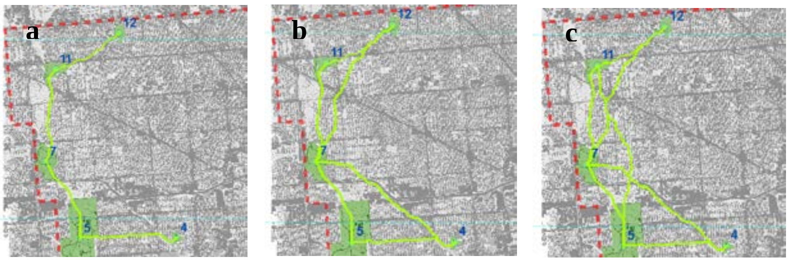

Figure 10. Top four corridors in different network typologies

I conducted network analysis for different corridor development scenarios, using four network indices: beta (β), gamma (λ) to help to us to understand the movement pattern. Based on threshold results, I use 27 as maximum possible number of links. . Table 6 shows the result of network indices based on different scenarios.

Table 6. Network indices results

Network	Nodes	Links	Beta(β)	Gamma(λ)
Ideal Scenario (>0.3)	16	27	1.69	1

Scenario 1 (Figure 10a)	16	4	0.25	0.15
Scenario 2 (Figure 10b)	16	6	0.38	0.22
Scenario 3 (Figure 10c)	16	7	0.44	0.26
Scenario 4 (Figure 9)	16	10	0.63	0.37

As shown in Table 6, scenario 2 has two more links with 0.13 increases in node connection (beta) and 0.07 increases in network connectivity (gamma). Scenario 3 has one more links than scenario 2, with 0.06 increases in beta and 0.03 increases in gamma. Scenario 4 has 10 links, with 0.19 higher than beta in scenario 3 and 0.11 higher than gamma in scenario 3. From Figure 10 and Figure 9, we can see that there is no circuit in scenario 1, two circuits in scenario 2, three circuits in scenario 3, and three circuits in scenario 4. Although scenario 4 has the highest node connection and network connectivity, there is no increase in the number of circuits.

4.5 Comparisons with Previous Structural and Functional Connectivity

Besides the commonly used indexes above, the structural and functional connectivity was compared between corridors and without corridors at the census tract scale; five census tracts were randomly selected where one or more potential corridors could be built in each census tract. The evaluation here does not consider the gravity index of each corridor; this evaluation aims at proving that structural and functional connectivity will been increased after the corridors are implemented. It is assumed that the new corridors would be covered with tree canopy. The new corridor features have been merged into the original canopy features in these five census tracts, and COHESION and IIC recalculated using the previous process. The results are compared in Table 7.

Table 7. Structure and function connectivity changes

Census Tract ID	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

* Before corridor built-up

** After corridor built-up

From these five census tract samples, it is clear that the IIC and the COHESION are both improved after the corridors are developed. The mean of COHESION increase is 0.76; the average increase of IIC is 0.02.

5 Discussion and Green Network Typology Suggestion

The results of urban habitat spatial pattern shows highly fragmented habitat conditions existing in the city of Detroit. Other studies of different urban areas also show that habitats are lacking connectivity (Kong, Yin, Nakagoshi, & Zong, 2010; Tian, Jim, Tao, & Shi, 2011). Beyond using FRAGSTATS to measure structural connectivity, this study also measured functional connectivity by using the Conefor software. With the correlation analysis between structural connectivity and functional connectivity, the statement of structural connectivity can represent functional connectivity has some evidence to support. Although the measurements did not use a single species, this result still provides a basic understanding of the whole city landscape connectivity. There are still some limitations, however. If an object that was treated as a patch changes, for example, using open with grass as land cover, or by using both tree canopy and grass as patches, the result of the COHESION will change. Moreover, if the distance threshold changes when calculating IIC, the IIC will decrease if the threshold is larger than 20 meters.

In this study, core patches were identified taking account of both core size and edge effect. However, on a city wide scale, this study did not identify any other core habitats in addition to the Rouge River Park, which lead to change the selection criteria and finally identified 16 large city parks as core habitats. Although some of these parks do not have dense trees, they are relatively large and that has the potential to increase the vegetation density. If increase canopy cover, these parks could be high quality stepping stones for animal rest and search food, as well as places for people public recreation. There is still space to improvement, by rethinking the criteria of selecting core patches. Just use size as selecting criterion may have some limitations. For those parks with few tree canopy cover, what are reasonable criteria? For the reason that green spaces in urban area are used for both human and wildlife, future studies could think about whether they can reduce habitat core size criteria but take human activity influence into account within an urban green space zone.

The method of identifying potential corridors was similar with other research studies by the least-cost-path (Bunn et al., 2000; Kong, Yin, Nakagoshi, & Zong, 2010b), but variables used for corridor identification were different from variables used for corridor evaluation by gravity model. The cost surface for least-cost-path considered current land use, and took advantage of existing vacant land, small parks and alley ways. Variables used for evaluating corridors by gravity model were actual land cover information. The land cover of paths where potential corridors would be built, such as trees, open field, impervious area and etc. In this way, I considered reality land use in corridor building process and actual land cover in corridor evaluation process.In different scenarios, corridor development would have different effects on the overall connectivity. Clearly, the best situation is developing all that corridors that have relatively high gravity results. If it is not possible to develop all the corridors with high gravity results, the study suggests that scenario 4, which forms a complex circuit and improves the connectivity most effectively based on connectivity index results, is the best option.

This study further proves that no matter which corridor is developed either the structure connectivity or functional connectivity will be improved. This result is based on the assumption that developed corridors will be 100 percent covered with tree canopies. However, in the real world, some green infrastructure may not have canopy cover instead of herbaceous cover. It is possible that landscape connectivity will not be increased as much as that shown in Table 7, if corridors do not have 100 percentage canopy cover. This overall methodology is a practical way for city planners and designers to develop systematic green infrastructure networks, and could be used as a reference for legacy cities, such as the city of Detroit, to redevelop vacant lands to improve the urban environment, facilitate the movement of species between patches, and enhance human well-being.

6 Green Infrastructure Typology Recommendations

To make this green network associated with the real-world situation, this study is based on multi-scale green infrastructure first develops green infrastructure typology by relying on the real situation in Detroit. The following typologies selection are based on multifunctional green infrastructure suggestion proposed by Meerow and Newell, (2017) aiming to provide different ways of addressing the solution of environmental issues such as urban stormwater management, mitigate urban heat island and increasing landscape connectivity, as well as enhancing human well-being.

The following typologies have been developed for the corridor development. The first typology is designed for vacant commercial land parcels, using vacant land near Joy Road as an example. Figure 11 shows this type of vacant commercial land located adjacent to one main road, with almost no tree canopy covering the road, through a road within the commercial land use area such as Joy Road. There were no street trees as a buffer; both air pollution and noise move easily from the road and commercial areas to nearby residential zones. This kind of vacant commercial parcel near roads with little tree canopy is very common in Detroit. Main roads such as Joy Road and Warren Avenue share similar conditions. For this kind of vacant land, implementing a small green space such as a pocket park is recommended (Figure 12). The pocket park can increase the tree canopy cover, provide habitats for small animals and also give people a place to rest. Another suggestion is to increase the number of trees along the street. Street trees can help to reduce the urban heat islands, and also serve as a green corridor to increase species movement.

Figure 11. Commercial vacant land (red) and residential vacant land (yellow)

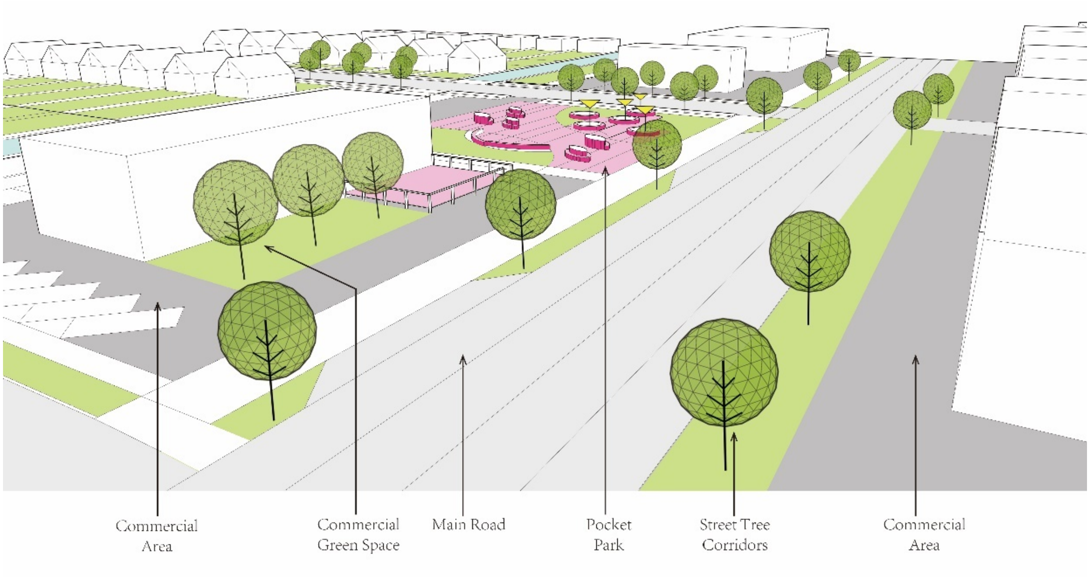

Figure 12. Pocket parks and street trees as corridor typology

Another situation is that vacant residential land can be located close to commercial land (see Figure 11 yellow mark). It shows the existing condition of the residential area just near the commercial parcel. In between, there are alleyways for service drive use to separate the two different parcels of land. In this situation, a green typology is proposed as shown in Figure 13 which takes advantage of one parcel vacant land near the commercial land. This type of land could be used for multiple purposes aiming at providing ecological function and improving human wellbeing. Since Detroit is facing a combined sewer overflow issue, this study suggests the implementation of a bio-retention basin to retain the storm water before it enters the combined sewer pipe. Also, in this green typology a pedestrian alleyway and tree buffer could also be applied. A tree buffer near the pedestrian alleyway would separate the commercial area from the residential area, helping to block the noise and pollution from main streets; also, by providing a pedestrian pathway completely away from traffic on the main street, people will enjoy a safer environment for walking or biking.

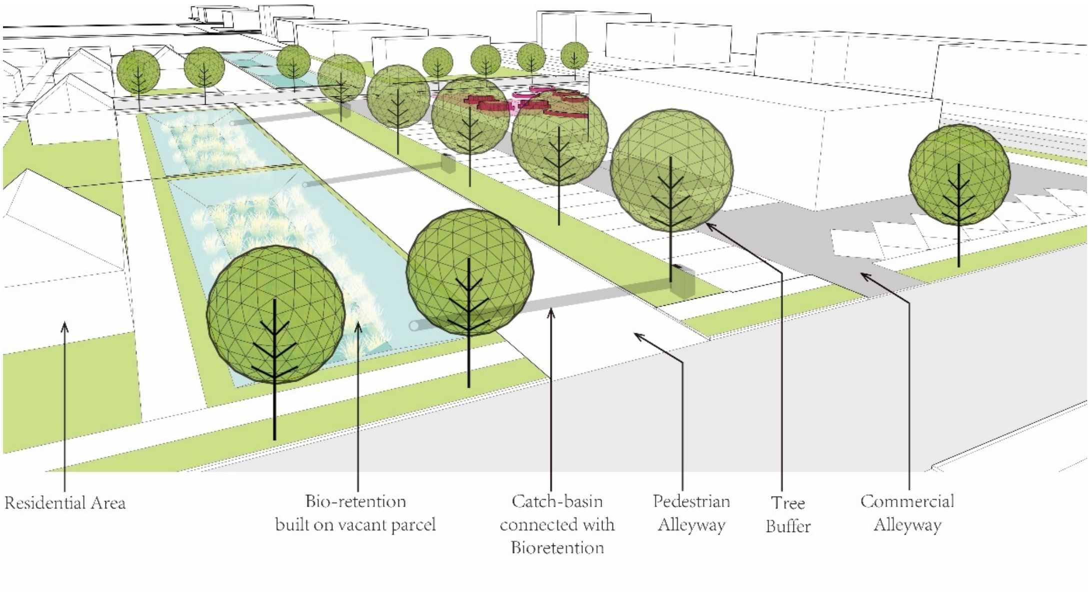

Figure 13. Green alleys between commercial and residential as corridor typology

Figure 14. Residential vacant (red mark) lands near roads

Figure 15. Residential block vacant land (red mark)

Besides vacant lands near commercial areas, there are two other kinds of vacant land existing in residential areas. Figure 14 shows the vacant land near the east-west roads, and Figure 15 shows the vacant land in blocks. Conducting a field visit and interviewing people in the local neighborhood revealed that catch basins were placed in all north-south and east-west streets, and underground combined sewer pipes were located in the north-south axis of every block. During storms, storm water from the residential parcel flows towards the streets, enters the catch basin and then enters the combined sewer under the alleyway. The first purpose of green infrastructure typology is solving the basement flooding issue.

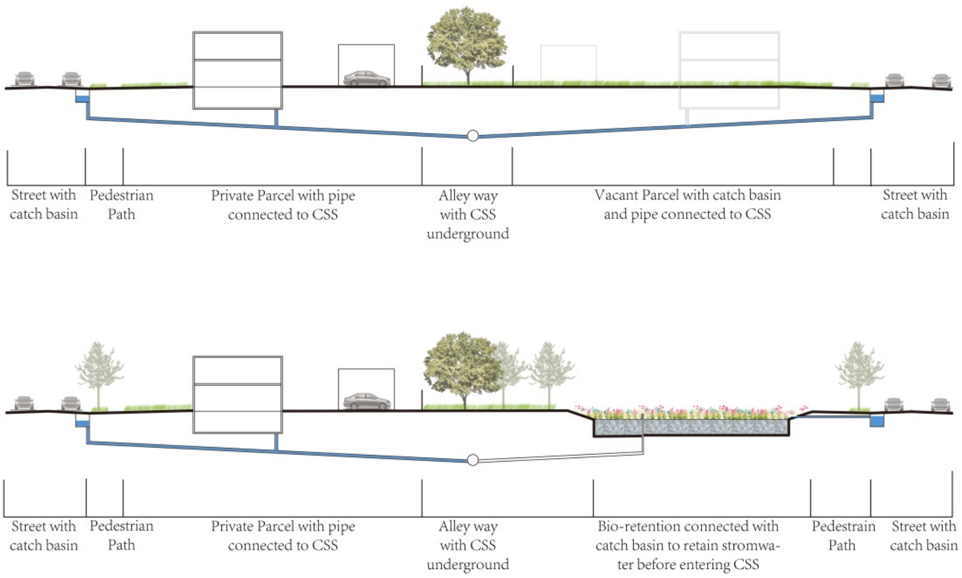

Figure 16. Combined sewer system, before-and-after design

Figure 16 shows the existing combined sewer system (above) and bio-retention typology with street trees, corridors and bio-retention. These bio-retentions connect with catch basins intended to retain the storm water from the road before it enters the underground sewer system. For block-level vacant land, the green infrastructure typology with bio-retention and grassland open playgrounds will be applied to every half block. This typology would help to reduce the pressure of combined sewer system (CSS) during storm events; moreover, by using pollinator-preferred plants, this typology could provide the pollinator habitats as well as aesthetic value.

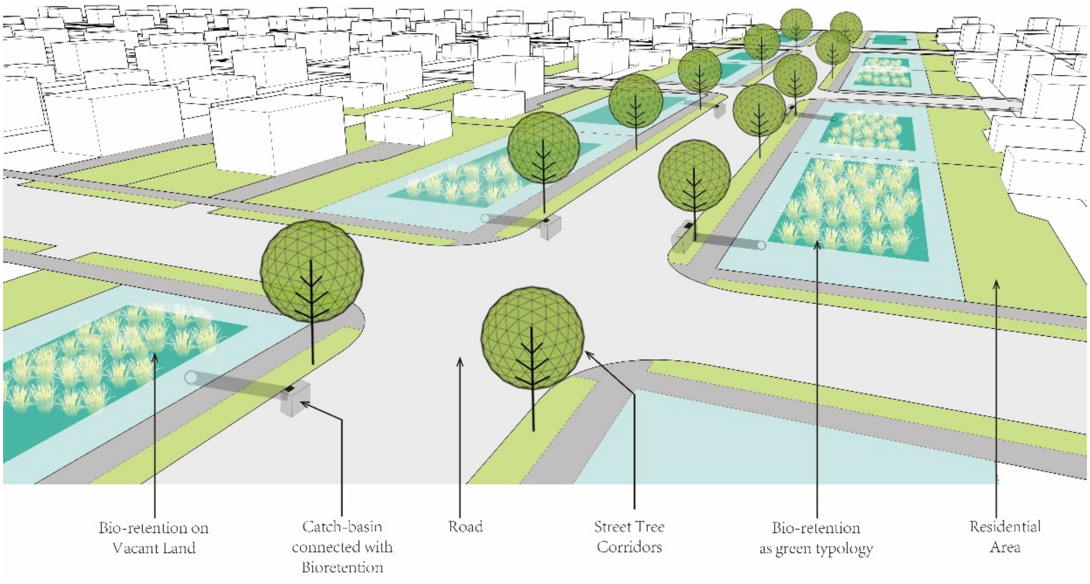

Figure 17. Bio-retention gardens and street trees as corridor typology

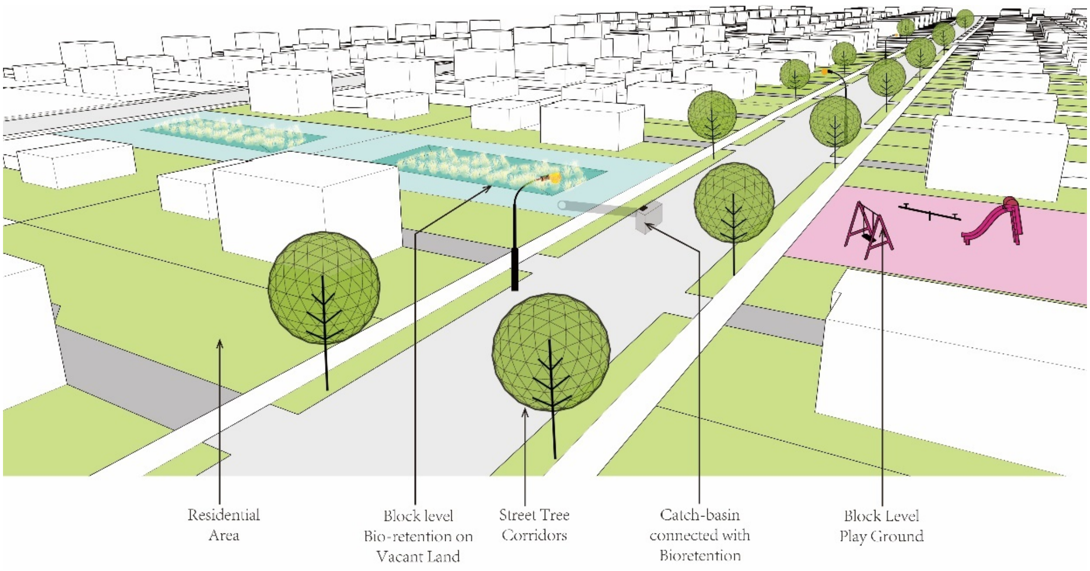

Figure 18. Block level bio-retention, playground and street trees as corridor typology

If there are more residential vacant parcels near the east-west streets, connecting vacant lands into a bio-retention corridor is suggested (see Figure 17). Stormwater systems use streets as networks by connecting vacant land in an east-west direction and turning it into a bio-retention corridor could retain the storm water before it enters the main storm water pipe.

For vacant residential block level land, Figure 18, the suggested typology combines playgrounds and bio-retention on the vacant land. Besides the ecological function provided by bio-retention, this green typology will improve the surrounding neighborhood's accessibility to green space, satisfying the residents' need for daily activities.

7 Conclusions

This research integrates various theories and models for building a systematic methodology for implementing green infrastructure in cities like Detroit. To understand landscape connectivity, methods were used to measure structural connectivity by FRAGSTATS, which are also used in previous studies such as Tian, Jim, Tao, & Shi, (2011) and Kong, Yin, Nakagoshi, & Zong, (2010). This research also explores the functional connectivity using Conefor to measure Integral Index of Connectivity (IIC), which is often used to guide conservation planning to improving habitat connectivity, for example, Saura & Rubio, (2010); Mitsova et al., (2011).

Correlation analysis between structural and functional connectivity further proves the ecological value of green landscaping in urban centers. The overall connectivity of Detroit is low, especially in areas with high industrial and commercial concentrations. With the goal of improving the city landscape connectivity, core patches are identified before corridors are developed. Potential corridor planning is based the least-cost path method which is already applied by Linhan et al., (1995), Uy & Nakagoshi, (2007) and Kong, Yin, Nakagoshi, & Zong, (2010). Gravity models help to select paired core patches and associated corridors. Part of this method that differs from previous studies is that this study puts vacant land, existing alley ways, and existing small green spaces in important positions in the least-cost path process, highlighting practical considerations. The gravity model uses accumulated impedance based on land cover of corridor cells such as tree canopies, impervious surface, built-up etc. After prioritizing corridors, different scenarios are presented and quantified connectivity by network analysis.

Proposed green infrastructure corridors are proved to significantly enhance both structural and functional connectivity. With proper planning and design strategies, as green infrastructure typology examples suggested in this research, vacant lands will not be regarded as undesirable places anymore; instead, they will become key components of urban green, contributing to ecological functions and mitigating environmental hazards. They will also be parts of urban green scenes with aesthetic value, or neighborhood walking paths that help to increase the accessibility to urban green space. Overall, this planning model is a green infrastructure network system which will be a part of urban sustainable systems to enhance city resilience and contribute to sustainable urban development.

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Appendix A

Table 8. COHESION results of all census tracts in Detroit

Census Tract ID	Land cover	COHESION	PD
26163520300	Trees	92.52	165.556
26163531400	Trees	92.85	839.726
26163531500	Trees	93.03	786.29
26163516600	Trees	93.08	351.259
26163533400	Trees	93.22	679.622
26163523200	Trees	93.23	643.111
26163524200	Trees	93.32	743.829
26163517200	Trees	93.42	77.897
26163531300	Trees	93.67	599.585
26163524700	Trees	93.82	857.802
26163517300	Trees	93.82	316.968
26163521400	Trees	93.87	287.465
26163538600	Trees	93.93	864.277
26163533200	Trees	93.96	818.426
26163523300	Trees	94.1	694.945
26163521800	Trees	94.14	198.356
26163531100	Trees	94.15	586.875
26163520800	Trees	94.22	95.25
26163518000	Trees	94.22	214.383
26163531600	Trees	94.29	592.518
26163533100	Trees	94.34	614.582
26163520400	Trees	94.42	405.963
26163520200	Trees	94.45	250.283
26163517500	Trees	94.48	256.926
26163524800	Trees	94.56	638.111
26163514500	Trees	94.63	943.963
26163521100	Trees	94.63	248.168
26163533600	Trees	94.63	660.957
26163530400	Trees	94.64	495.423
26163525800	Trees	94.65	581.497
26163525700	Trees	94.69	500.085
26163522500	Trees	94.69	158.7
26163506100	Trees	94.73	734.435
26163539200	Trees	94.77	950.97
26163501900	Trees	94.78	892.057
26163536200	Trees	94.79	1017.881
26163516900	Trees	94.8	730.478
26163531700	Trees	94.8	466.461
26163539100	Trees	94.84	1145.987

26163534100	Trees	94.92	930.511
26163530500	Trees	94.94	714.575
26163531200	Trees	94.96	848.212
26163539400	Trees	95	748.641
26163526300	Trees	95.05	474.4
26163533300	Trees	95.07	963.241
26163514200	Trees	95.08	834.103
26163542400	Trees	95.09	959.048
26163533500	Trees	95.12	748.524
26163538700	Trees	95.13	867.046
26163526400	Trees	95.14	562.844
26163521900	Trees	95.15	549.583
26163515900	Trees	95.16	585.686
26163532400	Trees	95.16	507.818
26163545900	Trees	95.17	1019.73
26163538500	Trees	95.18	830.149
26163510600	Trees	95.19	453.948
26163521500	Trees	95.22	465.885
26163534200	Trees	95.26	973.174
26163531900	Trees	95.27	320.031
26163516200	Trees	95.27	635.462
26163542100	Trees	95.28	1004.381
26163545600	Trees	95.29	1098.923
26163985200	Trees	95.29	82.531
26163542900	Trees	95.32	1265.102
26163527300	Trees	95.35	691.331
26163520700	Trees	95.36	72.58
26163525600	Trees	95.37	559.806
26163534700	Trees	95.37	1006.778
26163507200	Trees	95.39	651.573
26163511900	Trees	95.41	386.695
26163522400	Trees	95.45	370.973
26163535600	Trees	95.45	1098.899
26163507100	Trees	95.45	746.978
26163506900	Trees	95.47	1145.208
26163510700	Trees	95.48	503.676
26163545800	Trees	95.48	905.581
26163500200	Trees	95.48	884.193
26163503100	Trees	95.49	645.304
26163530900	Trees	95.49	576.143
26163524100	Trees	95.51	332.598
26163537700	Trees	95.52	780.165
26163538900	Trees	95.52	747.238
26163506800	Trees	95.56	728.495

26163502000	Trees	95.58	707.48
26163515300	Trees	95.61	493.429
26163523400	Trees	95.64	640.207
26163532600	Trees	95.65	421.741
26163511300	Trees	95.65	670.868
26163517100	Trees	95.67	424.971
26163527200	Trees	95.68	718.212
26163540900	Trees	95.69	1060.702
26163514100	Trees	95.69	768.944
26163518400	Trees	95.69	477.307
26163523100	Trees	95.7	287.839
26163531800	Trees	95.73	396.785
26163507500	Trees	95.73	713.879
26163511400	Trees	95.74	597.308
26163506200	Trees	95.76	499.74
26163500100	Trees	95.76	852.137
26163510500	Trees	95.77	565.392
26163523800	Trees	95.78	677.124
26163536700	Trees	95.8	773.144
26163516800	Trees	95.81	495.975
26163512100	Trees	95.81	642.294
26163511200	Trees	95.81	337.477
26163506500	Trees	95.81	1032.247
26163985000	Trees	95.83	114.106
26163507000	Trees	95.89	972.405
26163539500	Trees	95.89	514.902
26163536400	Trees	95.89	696.125
26163537800	Trees	95.9	681.14
26163522300	Trees	95.93	412.57
26163532700	Trees	95.93	377.575
26163522200	Trees	95.94	623.876
26163538400	Trees	95.99	866.72
26163533700	Trees	96	533.145
26163513600	Trees	96	707.729
26163513900	Trees	96	669.784
26163524000	Trees	96	295.184
26163532200	Trees	96.02	631.586
26163526000	Trees	96.05	359.066
26163545700	Trees	96.06	927.991
26163522000	Trees	96.08	357.305
26163526200	Trees	96.12	485.329
26163545500	Trees	96.12	1005.394
26163515700	Trees	96.12	153.581
26163533900	Trees	96.13	223.21

26163504700	Trees	96.14	539.356
26163518900	Trees	96.14	166.338
26163516000	Trees	96.15	748.676
26163530200	Trees	96.15	526.054
26163516300	Trees	96.17	472.986
26163516500	Trees	96.17	83.347
26163505200	Trees	96.19	558.384
26163543400	Trees	96.19	772.753
26163539300	Trees	96.22	591.304
26163524300	Trees	96.24	640.077
26163543000	Trees	96.25	825.272
26163526100	Trees	96.25	468.083
26163536300	Trees	96.25	954.738
26163535300	Trees	96.26	702.853
26163507400	Trees	96.29	723.37
26163500700	Trees	96.29	711.333
26163521300	Trees	96.29	414.122
26163537000	Trees	96.31	996.531
26163518800	Trees	96.31	466.478
26163534500	Trees	96.32	477.067
26163517000	Trees	96.33	526.916
26163542800	Trees	96.33	922.495
26163500900	Trees	96.34	513.657
26163534400	Trees	96.35	890.017
26163536500	Trees	96.38	619.67
26163501100	Trees	96.39	641.835
26163535700	Trees	96.4	766.538
26163504900	Trees	96.4	626.372
26163539600	Trees	96.41	479.381
26163530100	Trees	96.45	655.431
26163524900	Trees	96.45	263.831
26163525400	Trees	96.45	578.934
26163501300	Trees	96.47	589.496
26163514300	Trees	96.49	506.115
26163501000	Trees	96.49	583.556
26163543100	Trees	96.49	849.036
26163506700	Trees	96.5	517.586
26163512400	Trees	96.5	525.828
26163536800	Trees	96.5	656.246
26163537100	Trees	96.51	701.82
26163512900	Trees	96.53	430.558
26163500800	Trees	96.55	629.645
26163506600	Trees	96.56	733.353
26163538800	Trees	96.58	697.137

26163535100	Trees	96.59	655.949
26163518500	Trees	96.6	570.363
26163522100	Trees	96.61	583.937
26163534300	Trees	96.61	898.787
26163525500	Trees	96.62	509.847
26163532300	Trees	96.62	755.894
26163540500	Trees	96.64	635.792
26163541500	Trees	96.64	902.04
26163540100	Trees	96.64	1025.052
26163516100	Trees	96.64	398.545
26163546700	Trees	96.65	602.16
26163524500	Trees	96.68	228.232
26163540600	Trees	96.69	656.512
26163537600	Trees	96.7	840.91
26163501800	Trees	96.72	649.39
26163518600	Trees	96.72	540.733
26163530800	Trees	96.73	592.791
26163515200	Trees	96.74	670.544
26163542600	Trees	96.75	804.812
26163526500	Trees	96.75	567.783
26163539000	Trees	96.75	879.135
26163516400	Trees	96.8	421.232
26163985100	Trees	96.8	136.914
26163536600	Trees	96.8	480.919
26163546100	Trees	96.81	507.514
26163510400	Trees	96.81	402.405
26163543200	Trees	96.81	958.306
26163533000	Trees	96.82	571.976
26163535400	Trees	96.82	465.585
26163512200	Trees	96.84	349.973
26163505100	Trees	96.87	327.734
26163503300	Trees	96.88	698.726
26163525000	Trees	96.89	191.43
26163501600	Trees	96.92	446.62
26163542300	Trees	96.95	698.294
26163530300	Trees	96.95	352.724
26163515600	Trees	96.96	688.948
26163537300	Trees	96.97	705.322
26163539700	Trees	96.97	456.164
26163507800	Trees	96.99	436.166
26163542200	Trees	96.99	877.674
26163546600	Trees	97	715.066
26163540300	Trees	97.01	600.624
26163501200	Trees	97.01	546.444

26163535000	Trees	97.02	609.882
26163503500	Trees	97.02	476.853
26163501400	Trees	97.03	533.595
26163500500	Trees	97.03	564.146
26163503200	Trees	97.05	830.961
26163541000	Trees	97.08	728.352
26163542500	Trees	97.09	775.117
26163504100	Trees	97.1	587.4
26163512300	Trees	97.11	488.625
26163512600	Trees	97.12	536.095
26163535500	Trees	97.12	799.227
26163513700	Trees	97.13	211.839
26163546000	Trees	97.14	791.507
26163506300	Trees	97.18	321.61
26163537500	Trees	97.19	929.637
26163536900	Trees	97.19	676.245
26163504300	Trees	97.2	518.985
26163503400	Trees	97.2	503.492
26163535200	Trees	97.21	681.11
26163503600	Trees	97.22	574.027
26163507900	Trees	97.23	581.132
26163985300	Trees	97.24	173.22
26163513300	Trees	97.25	214.7
26163500300	Trees	97.28	577.249
26163511000	Trees	97.3	250.362
26163508100	Trees	97.32	800.355
26163540700	Trees	97.32	636.945
26163546500	Trees	97.33	691.924
26163505000	Trees	97.34	395.236
26163505400	Trees	97.35	519.983
26163500600	Trees	97.35	508.189
26163513200	Trees	97.36	600.239
26163501500	Trees	97.4	537.926
26163507300	Trees	97.42	632.119
26163501700	Trees	97.45	556.593
26163537200	Trees	97.45	385.756
26163505500	Trees	97.46	352.841
26163503900	Trees	97.47	472.912
26163536100	Trees	97.48	872.109
26163546800	Trees	97.5	632.823
26163546900	Trees	97.5	419.634
26163504000	Trees	97.53	510.556
26163540200	Trees	97.56	768.714
26163508000	Trees	97.59	228.535

26163540800	Trees	97.63	889.509
26163540400	Trees	97.63	456.398
26163538100	Trees	97.63	658.11
26163504200	Trees	97.67	487.81
26163543500	Trees	97.69	841.799
26163504400	Trees	97.69	471.373
26163545200	Trees	97.71	696.486
26163506400	Trees	97.76	396.317
26163515400	Trees	97.76	733.428
26163544200	Trees	97.83	904.469
26163500400	Trees	97.83	333.831
26163543700	Trees	97.86	554.718
26163534600	Trees	97.89	571.895
26163545100	Trees	97.92	526.306
26163543600	Trees	97.94	634.984
26163538200	Trees	98.09	620.3
26163544000	Trees	98.15	715.312
26163541300	Trees	98.16	661.783
26163545300	Trees	98.17	583.789
26163504800	Trees	98.18	190.031
26163542700	Trees	98.19	260.353
26163543800	Trees	98.21	619.214
26163516700	Trees	98.26	594.53
26163541400	Trees	98.37	474.083
26163541100	Trees	98.55	689.553
26163546400	Trees	98.67	395.59
26163541800	Trees	98.69	667.51
26163545400	Trees	98.7	200.483
26163541200	Trees	98.71	551.632
26163538300	Trees	98.83	344.216
26163541700	Trees	99.11	498.834
26163544300	Trees	99.16	690.807
26163543900	Trees	99.16	291.395
26163985500	Trees	99.2	147.533
26163546200	Trees	99.23	344.447
26163546300	Trees	99.53	305.228
26163544100	Trees	99.6	414.892

Appendix B

Table 9. Integral Index of Connectivity (IIC) and COHESION results comparison of sampled census tracts

Census Tract ID	IIC	COHESION
26163500200	0.074	95.48
26163503200	0.107	97.05
26163503400	0.128	97.2
26163503900	0.095	97.47
26163505200	0.053	96.19
26163511400	0.026	95.74
26163512300	0.073	97.11
26163513200	0.074	97.36
26163513600	0.044	96
26163517300	0.041	93.82
26163521300	0.068	96.29
26163522400	0.048	95.45
26163523800	0.043	95.78
26163524300	0.057	96.24
26163524900	0.025	96.45
26163525800	0.048	94.65
26163526000	0.037	96.05
26163530500	0.035	94.94
26163531900	0.037	95.27
26163533200	0.036	93.96
26163534100	0.060	94.92
26163534500	0.038	96.32
26163537500	0.123	97.19
26163537800	0.066	95.9
26163538800	0.094	96.58
26163542800	0.095	96.33
26163543400	0.045	96.19
26163543900	0.342	99.16
26163544000	0.201	98.15
26163545300	0.158	98.17

Appendix C

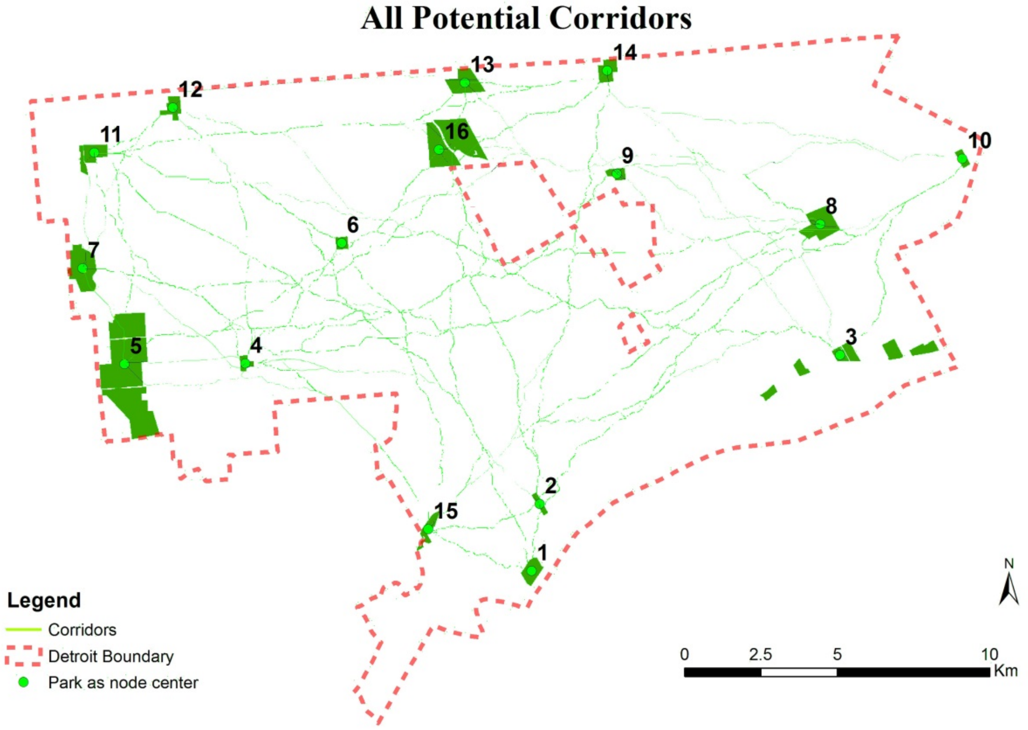

Figure 19. 120 Potential corridors connecting all patches

Appendix D

Table 10. Gravity model results of all 120 corridors

Park a ID	Lab (km)	*Pa* (km)	*Sa* (ha)	*Na* = *Sa/Pa*	*Dab* = *Lab/Lmax*	*Dab* squar.	Park *b* ID	*Pb*(km)	*Sb*(ha)	*Nb* = *Sb/Pb*	*Gab*
5	10.59	3043.04	450.25	0.15	0.04	0.0014	7	676.05	101.89	0.15	15.57
11	20.55	239.57	50.09	0.21	0.07	0.0054	12	103.26	31.03	0.30	11.64
7	20.98	676.05	101.89	0.15	0.07	0.0056	11	239.57	50.09	0.21	5.61
4	30.82	50.99	14.86	0.29	0.11	0.0121	5	3043.04	450.25	0.15	3.55
4	37.23	50.99	14.86	0.29	0.13	0.0177	7	676.05	101.89	0.15	2.48
7	41.80	676.05	101.89	0.15	0.15	0.0223	12	103.26	31.03	0.30	2.03
9	28.12	173.23	19.19	0.11	0.10	0.0101	14	265.18	36.45	0.14	1.51
5	41.21	3043.04	450.25	0.15	0.15	0.0217	11	239.57	50.09	0.21	1.43
13	16.73	2199.20	66.16	0.03	0.06	0.0036	16	1229.21	204.19	0.17	1.40
1	21.79	512.56	36.55	0.07	0.08	0.0061	2	105.37	12.11	0.11	1.35
5	53.61	3043.04	450.25	0.15	0.19	0.0367	12	103.26	31.03	0.30	1.21
4	76.96	50.99	14.86	0.29	0.28	0.0757	12	103.26	31.03	0.30	1.16
9	36.67	173.23	19.19	0.11	0.13	0.0172	16	1229.21	204.19	0.17	1.07
4	67.78	50.99	14.86	0.29	0.24	0.0587	11	239.57	50.09	0.21	1.04
4	46.92	50.99	14.86	0.29	0.17	0.0281	6	173.21	14.85	0.09	0.89
6	37.18	173.21	14.85	0.09	0.13	0.0177	16	1229.21	204.19	0.17	0.81
2	40.18	105.37	12.11	0.11	0.14	0.0206	15	186.87	26.13	0.14	0.78
1	32.13	512.56	36.55	0.07	0.11	0.0132	15	186.87	26.13	0.14	0.76
14	50.58	265.18	36.45	0.14	0.18	0.0327	16	1229.21	204.19	0.17	0.70
3	32.30	1794.96	107.99	0.06	0.12	0.0133	8	629.71	83.28	0.13	0.60
4	82.75	50.99	14.86	0.29	0.30	0.0875	16	1229.21	204.19	0.17	0.55
6	60.45	173.21	14.85	0.09	0.22	0.0467	12	103.26	31.03	0.30	0.55
8	45.77	629.71	83.28	0.13	0.16	0.0268	9	173.23	19.19	0.11	0.55
4	81.77	50.99	14.86	0.29	0.29	0.0854	15	186.87	26.13	0.14	0.48
12	101.94	103.26	31.03	0.30	0.36	0.1328	16	1229.21	204.19	0.17	0.38
8	58.38	629.71	83.28	0.13	0.21	0.0435	10	116.95	14.05	0.12	0.36
8	63.54	629.71	83.28	0.13	0.23	0.0516	14	265.18	36.45	0.14	0.35
6	70.94	173.21	14.85	0.09	0.25	0.0643	11	239.57	50.09	0.21	0.28
2	99.59	105.37	12.11	0.11	0.36	0.1267	4	50.99	14.86	0.29	0.26
8	88.56	629.71	83.28	0.13	0.32	0.1002	16	1229.21	204.19	0.17	0.22
5	69.03	3043.04	450.25	0.15	0.25	0.0609	6	173.21	14.85	0.09	0.21
15	100.22	186.87	26.13	0.14	0.36	0.1283	16	1229.21	204.19	0.17	0.18
5	105.13	3043.04	450.25	0.15	0.38	0.1412	16	1229.21	204.19	0.17	0.17
4	121.38	50.99	14.86	0.29	0.43	0.1883	9	173.23	19.19	0.11	0.17
6	79.85	173.21	14.85	0.09	0.29	0.0815	7	676.05	101.89	0.15	0.16
12	145.14	103.26	31.03	0.30	0.52	0.2692	15	186.87	26.13	0.14	0.16
4	142.11	50.99	14.86	0.29	0.51	0.2581	14	265.18	36.45	0.14	0.16
2	99.86	105.37	12.11	0.11	0.36	0.1274	16	1229.21	204.19	0.17	0.15

11	136.82	239.57	50.09	0.21	0.49	0.2392	16	1229.21	204.19	0.17	0.15
2	136.74	105.37	12.11	0.11	0.49	0.2389	12	103.26	31.03	0.30	0.14
7	117.99	676.05	101.89	0.15	0.42	0.1779	16	1229.21	204.19	0.17	0.14
2	75.42	105.37	12.11	0.11	0.27	0.0727	6	173.21	14.85	0.09	0.14
13	49.59	2199.20	66.16	0.03	0.18	0.0314	14	265.18	36.45	0.14	0.13
9	142.28	173.23	19.19	0.11	0.51	0.2587	12	103.26	31.03	0.30	0.13
3	68.49	1794.96	107.99	0.06	0.24	0.0599	10	116.95	14.05	0.12	0.12
6	89.22	173.21	14.85	0.09	0.32	0.1017	15	186.87	26.13	0.14	0.12
6	80.43	173.21	14.85	0.09	0.29	0.0827	9	173.23	19.19	0.11	0.11
4	162.57	50.99	14.86	0.29	0.58	0.3377	8	629.71	83.28	0.13	0.11
9	48.32	173.23	19.19	0.11	0.17	0.0298	13	2199.20	66.16	0.03	0.11
6	91.63	173.21	14.85	0.09	0.33	0.1073	14	265.18	36.45	0.14	0.11
2	104.92	105.37	12.11	0.11	0.38	0.1407	8	629.71	83.28	0.13	0.11
1	122.73	512.56	36.55	0.07	0.44	0.1925	4	50.99	14.86	0.29	0.11
3	69.83	1794.96	107.99	0.06	0.25	0.0623	9	173.23	19.19	0.11	0.11
11	148.14	239.57	50.09	0.21	0.53	0.2804	15	186.87	26.13	0.14	0.10
5	125.02	3043.04	450.25	0.15	0.45	0.1997	15	186.87	26.13	0.14	0.10
9	101.21	173.23	19.19	0.11	0.36	0.1309	10	116.95	14.05	0.12	0.10
7	127.65	676.05	101.89	0.15	0.46	0.2082	15	186.87	26.13	0.14	0.10
8	120.12	629.71	83.28	0.13	0.43	0.1844	15	186.87	26.13	0.14	0.10
12	183.42	103.26	31.03	0.30	0.66	0.4299	14	265.18	36.45	0.14	0.10
10	118.26	116.95	14.05	0.12	0.42	0.1787	14	265.18	36.45	0.14	0.09
2	104.58	105.37	12.11	0.11	0.37	0.1398	9	173.23	19.19	0.11	0.09
9	116.08	173.23	19.19	0.11	0.41	0.1722	15	186.87	26.13	0.14	0.09
8	194.17	629.71	83.28	0.13	0.69	0.4818	12	103.26	31.03	0.30	0.08
3	90.16	1794.96	107.99	0.06	0.32	0.1039	14	265.18	36.45	0.14	0.08
2	130.12	105.37	12.11	0.11	0.47	0.2164	5	3043.04	450.25	0.15	0.08
10	140.96	116.95	14.05	0.12	0.50	0.2539	16	1229.21	204.19	0.17	0.08
14	138.72	265.18	36.45	0.14	0.50	0.2459	15	186.87	26.13	0.14	0.08
2	127.44	105.37	12.11	0.11	0.46	0.2075	14	265.18	36.45	0.14	0.08
6	52.55	173.21	14.85	0.09	0.19	0.0353	13	2199.20	66.16	0.03	0.07
2	137.68	105.37	12.11	0.11	0.49	0.2422	7	676.05	101.89	0.15	0.07
4	98.13	50.99	14.86	0.29	0.35	0.1230	13	2199.20	66.16	0.03	0.07
2	163.43	105.37	12.11	0.11	0.58	0.3413	11	239.57	50.09	0.21	0.07
3	105.43	1794.96	107.99	0.06	0.38	0.1420	16	1229.21	204.19	0.17	0.07
1	159.88	512.56	36.55	0.07	0.57	0.3266	12	103.26	31.03	0.30	0.07
1	120.83	512.56	36.55	0.07	0.43	0.1866	16	1229.21	204.19	0.17	0.06
11	189.63	239.57	50.09	0.21	0.68	0.4595	14	265.18	36.45	0.14	0.06
5	159.58	3043.04	450.25	0.15	0.57	0.3254	14	265.18	36.45	0.14	0.06
6	120.65	173.21	14.85	0.09	0.43	0.1860	8	629.71	83.28	0.13	0.06
9	175.45	173.23	19.19	0.11	0.63	0.3934	11	239.57	50.09	0.21	0.06
4	224.01	50.99	14.86	0.29	0.80	0.6412	10	116.95	14.05	0.12	0.05
7	172.44	676.05	101.89	0.15	0.62	0.3800	14	265.18	36.45	0.14	0.05
2	100.72	105.37	12.11	0.11	0.36	0.1296	3	1794.96	107.99	0.06	0.05

5	157.32	3043.04	450.25	0.15	0.56	0.3163	9	173.23	19.19	0.11	0.05
7	161.32	676.05	101.89	0.15	0.58	0.3326	9	173.23	19.19	0.11	0.05
1	98.56	512.56	36.55	0.07	0.35	0.1241	6	173.21	14.85	0.09	0.05
3	170.74	1794.96	107.99	0.06	0.61	0.3725	4	50.99	14.86	0.29	0.05
10	246.57	116.95	14.05	0.12	0.88	0.7769	12	103.26	31.03	0.30	0.05
3	122.05	1794.96	107.99	0.06	0.44	0.1903	15	186.87	26.13	0.14	0.04
1	129.52	512.56	36.55	0.07	0.46	0.2144	8	629.71	83.28	0.13	0.04
2	158.43	105.37	12.11	0.11	0.57	0.3207	10	116.95	14.05	0.12	0.04
8	227.34	629.71	83.28	0.13	0.81	0.6605	11	239.57	50.09	0.21	0.04
12	130.43	103.26	31.03	0.30	0.47	0.2174	13	2199.20	66.16	0.03	0.04
10	179.80	116.95	14.05	0.12	0.64	0.4131	15	186.87	26.13	0.14	0.04
1	125.55	512.56	36.55	0.07	0.45	0.2014	9	173.23	19.19	0.11	0.04
5	199.40	3043.04	450.25	0.15	0.71	0.5081	8	629.71	83.28	0.13	0.04
7	202.50	676.05	101.89	0.15	0.72	0.5240	8	629.71	83.28	0.13	0.04
1	153.26	512.56	36.55	0.07	0.55	0.3002	5	3043.04	450.25	0.15	0.04
1	148.41	512.56	36.55	0.07	0.53	0.2814	14	265.18	36.45	0.14	0.03
3	204.61	1794.96	107.99	0.06	0.73	0.5350	12	103.26	31.03	0.30	0.03
1	186.48	512.56	36.55	0.07	0.67	0.4444	11	239.57	50.09	0.21	0.03
1	160.82	512.56	36.55	0.07	0.57	0.3305	7	676.05	101.89	0.15	0.03
8	100.21	629.71	83.28	0.13	0.36	0.1283	13	2199.20	66.16	0.03	0.03
6	177.67	173.21	14.85	0.09	0.64	0.4034	10	116.95	14.05	0.12	0.03
10	279.74	116.95	14.05	0.12	1.00	1.0000	11	239.57	50.09	0.21	0.03
13	116.89	2199.20	66.16	0.03	0.42	0.1746	15	186.87	26.13	0.14	0.02
5	120.41	3043.04	450.25	0.15	0.43	0.1853	13	2199.20	66.16	0.03	0.02
3	131.25	1794.96	107.99	0.06	0.47	0.2201	6	173.21	14.85	0.09	0.02
11	146.77	239.57	50.09	0.21	0.52	0.2753	13	2199.20	66.16	0.03	0.02
3	209.11	1794.96	107.99	0.06	0.75	0.5588	11	239.57	50.09	0.21	0.02
1	125.32	512.56	36.55	0.07	0.45	0.2007	3	1794.96	107.99	0.06	0.02
5	260.84	3043.04	450.25	0.15	0.93	0.8694	10	116.95	14.05	0.12	0.02
7	263.94	676.05	101.89	0.15	0.94	0.8902	10	116.95	14.05	0.12	0.02
1	183.03	512.56	36.55	0.07	0.65	0.4281	10	116.95	14.05	0.12	0.02
7	133.36	676.05	101.89	0.15	0.48	0.2273	13	2199.20	66.16	0.03	0.02
2	117.28	105.37	12.11	0.11	0.42	0.1758	13	2199.20	66.16	0.03	0.02
3	209.38	1794.96	107.99	0.06	0.75	0.5602	7	676.05	101.89	0.15	0.02
3	208.48	1794.96	107.99	0.06	0.75	0.5554	5	3043.04	450.25	0.15	0.02
10	152.61	116.95	14.05	0.12	0.55	0.2976	13	2199.20	66.16	0.03	0.01
3	117.08	1794.96	107.99	0.06	0.42	0.1752	13	2199.20	66.16	0.03	0.01
1	138.25	512.56	36.55	0.07	0.49	0.2442	13	2199.20	66.16	0.03	0.01