Effectiveness of Green Roofs for Urban Ecological Connectivity: A case study of Chicago, USA

Master of Ecosystem Restoration

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Alcalá de Henares, Spain. 28 September 2021

1 TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Green roofs (GR) are human made ecosystems, designed to mimic natural habitats in an urban environment and consist of a set of layers that guarantee desired conditions and services. Considering the current trends of urban expansion and development GR stand out as strategic solutions to many urban environmental problems. Despite their many environmental benefits, and because of the way implementation has been done, most GR projects lack connectivity with the rest of the urban landscape, this translates into a minimization of functionality at the urban landscape level. A connectivity analysis could provide a better understanding on how these systems contribute to local species dispersal and general movement through the hostile urban matrix. The objective of this study is to evaluate the role of GR in the ecological connectivity of a city considered a pioneer in the green roof implementation strategy. A case study for Chicago, Illinois was developed to assess how green roof placement relates to ecological connectivity of urban zones in addition to other green infrastructures like Parks, Urban Forests, and other open spaces. Throughout the analysis we found that Urban Forests are the major contributors to the Chicago's ecological connectivity and that Green Roofs do not particular benefit the network in this regard. GR mostly act as steppingstones facilitating movement to higher quality habitats. Finally, we propose a series of landscape patches that would be best to conserve and restore, and others as future green roof potential areas. A correct implementation of green elements in the urban landscape could serve as an ecological restauration method of anthropogenically transformed spaces like big cities and solve multiple ecological and environmental problems simultaneously. A set of recommendation based on our findings from both the literature review and the connectivity analysis is available as an outcome of this work.

Key words: ecological connectivity - urban connectivity – urban ecology – Green infrastructure

RESUMEN

Las cubiertas verdes (CV) son ecosistemas creados artificialmente, diseñados para imitar los hábitats naturales en un entorno urbano y consisten en un conjunto de capas que garantizan las condiciones y los servicios deseados. A la luz de las tendencias actuales de expansión y desarrollo urbano, las CV se destacan como una solución estratégica a muchos problemas ambientales de este entorno. A pesar de los múltiples beneficios ambientales citados pero debido a la forma en que se ha realizado la implementación, lo que la mayoría de los proyectos de cubiertas verdes carecen es un análisis de conectividad, esto se traduce en una minimización de la funcionalidad a nivel del paisaje urbano. Un análisis de conectividad brindar una mejor idea de como estos sistemas contribuyen a la dispersión de especies locales y a su movimiento general a través de la hostil matriz urbana. El objetivo de este estudio es evaluar el papel de las CV en la conectividad ecológica de una ciudad considerada pionera en la estrategia de implementación de cubiertas verdes. Se desarrolló un estudio de caso para Chicago, Illinois, para evaluar cómo la ubicación de los techos verdes se relaciona con la conectividad ecológica de las zonas urbanas, además de otras infraestructuras verdes como parques, bosques y otros espacios abiertos. A lo largo del análisis, encontramos que los bosques urbanos son los principales contribuyentes a la conectividad ecológica de Chicago y que los techos verdes no benefician en particular a la red en este sentido. Los GR actúan principalmente como peldaños que facilitan el movimiento hacia hábitats de mayor calidad Finalmente, proponemos un set de parches en el paisaje que seria mejor conservar o restaurar por su aportación a la conectividad, y otros como potenciales espacios de implementación de cubiertas verdes. Una correcta implementación de los elementos verdes del paisaje urbano podría servir como método de restauración ecológica de entornos transformados de manera antropogénica como las grandes urbes, y que solucionan más de un problema ecológico y ambiental de este entorno simultáneamente. Un conjunto de recomendaciones basadas en nuestros hallazgos tanto de la revisión de la literatura como del análisis de conectividad está disponible como resultado de este trabajo.

Palabras clave: conectividad ecológica– conectividad urbana – ecología urbana – Infraestructura verde.

2 INTRODUCTION

2.1 BACKGROUND

During humankind evolution, the adaptation to environmental conditions and the ability to encompass lifestyle with ecological necessities has been key for the survival of humans and the endurance of biodiversity. Such adaptation has differed in scale and intensity depending on population needs and size. Now in the **"human-dominated epoch"** (Holmes, 2015), called the **Anthropocene**, we must recognize our problems and challenges to **strategically amend, restore, and plan for the future**. The concept of the Anthropocene is still revisited for definition and is constantly changing but, many studies point out the **Industrial Revolution as a turning point in human history** in which the modernization and development of technology lead to an exponential raise in human population (Harlem Brundtland, 1987), a change in atmospheric composition (Holmes, 2015) and a massive extinction and biodiversity loss. The change in population dynamics forced some economic trends towards the acquisition of goods and the demand for services in a more accelerated pace, the movement of people around the land and the occupation of ecologically valuable spaces. Socio economic changes related to the more recent decades are resulting on the other hand in a new way of settlement translated into a **movement to urban areas (UA) and the creation of suburban sites in contrast to rural countryside living**. The economy has also been transformed, evolving from a goods-based economy to a more service oriented economy in the last century (Grau y Aide, 2008), which according to some economic studies is the best growth model, and relieves some of the ecological pressures of the current crisis. All these changes have translated into an **abandonment of rural lands and the mobilization of people to cities**. Abandoned lands, on one hand have transitioned, due to ecological dynamics, into secondary forests, which encompasses many ecological benefits on its own (Perz, 2007). Urban areas on the other hand have experienced a different dynamic, hosting an increasing concentration of living organisms (not only humans) and having to provide the resources and services that these organism concentrations demand. These sites have expanded greatly both vertically and horizontally. **Many studies forecast that by 2050 more than half of human population would be living within urban areas** (Harlem Brundtland, 1987), which will create enormous pressures on concentrated spots of land that need to provide resources and other ecosystem services beyond the ecological carrying capacity. Similarly, big and dense **cities can be hotspots of contamination, ecological degradation, and habitat loss for many organisms** (Vijayaraghavan, 2016). The expansion of cities to accommodate the increasing population has been done by replacement of green areas that provide valuable ecological services and have degraded the land and contaminated air and water in these sites (Vijayaraghavan 2016; Smith and Roebber 2011, Figure 1). One of the most affected ecological attributes is connectivity (Taylor et al. 1993; Berardi et al. 2014; Madre et al. 2014) due to the disruption and disintegration of natural habitats. Connectivity is and ecological attribute at the landscape level which could be defined **as "*the degree to which the landscape facilitates or impedes movement among resource patches*"** (Taylor et al., 1993). Deterioration of connectivity makes ecosystems more vulnerable to stress and disturbances in many ways, among them the ability of organisms to move and spread across larger areas (Taylor et al., 1993; Saura y Torné, 2009; Madre et al., 2014), which affects population dynamics. Ecological connectivity allows plants and animals to move through the territory and colonize new areas in the landscape. **Connectivity also promotes diversity by facilitating the interactions among species** (Taylor et al., 1993), both at the functional and the genetic levels.

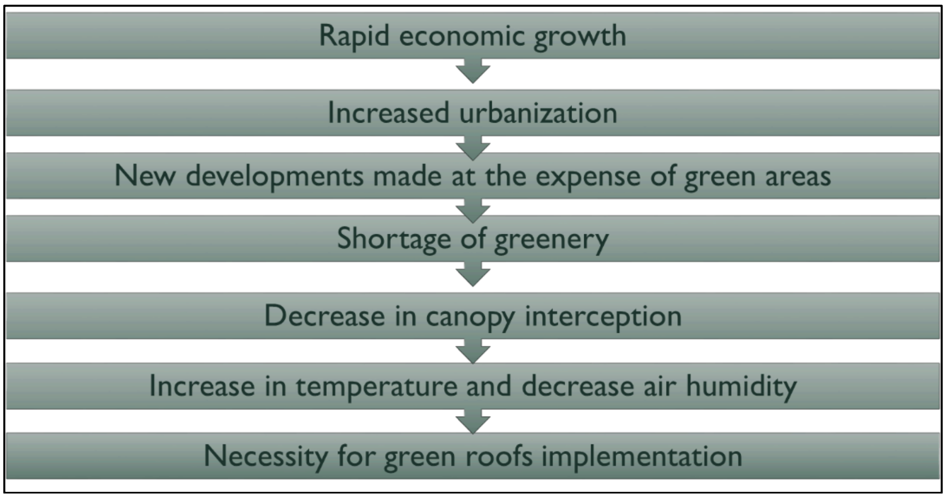

***Figure 1**. Development of green roof necessity. Figure by Author*

Connectivity is not the only ecological aspect affected by urban expansion; the agglomeration of people in the UA increases contamination in direct and indirect ways. For instance, buildings are responsible for 40% of global energy use and 33% of greenhouse gas emissions (Berardi et al., 2014), which **reduces air quality** (Li and Babcock 2014). Air contamination becomes more of a global issue than a punctual source contamination as cities grow larger and emissions increase. Moreover, **river and stream contamination is**

increased by the concentration of runoff and by dissolved and suspended contaminants in cities moved by the runoff (Teemusk y Mander, 2007). Runoff in cities is not only larger in quantity but also faster in velocity, due to the lack of roughness in most surfaces and the absence of soil infiltration due to paving (Mentens et al., 2006; Carpenter y Kaluvakolanu, 2011). To face these and other environmental problems in urban sites, mitigation and restoration tools and strategies are needed. Many international agendas are focused on the reduction of contaminants and the control of emissions (Karteris et al., 2016), but few address **adaptation strategies than can simultaneously alleviate the environmental pressure in urban zones**. The combination these strategies (mitigation, adaptation, and restoration) is key for the endurance of ecological services in all lands, but more urgent in urban zones. Some countries have already directed their efforts in this scope. A prominent example of urban adaptation to ecological stress is Singapore, which has implemented public policies to promote green infrastructure in urban zones (Wong et al., 2003; Peng Lihua, 2012). **Some of the policies move through a government oriented framework** (Carter y Fowler, 2008) to force all new designs to incorporate not only the use of sustainable resources in the construction phase, but also the inclusion of sustainable elements such as Green Roofs (GR) and walls, permeable parking lots, Parks and yards, etc. Finally, the other commonly used strategy is the **application of monetary incentives at the corporative and the individual level** to promote green infrastructure installment (Carter y Fowler, 2008; Dvorak y Volder, 2010a; Olsen, 2015).

2.1.1 Green Roofs (GR)

GR are human designed ecosystems that contain a set of layers that provide a range of conditions for the allocation of ecological functionality (Oberndorfer et al., 2007; Peng Lihua, 2012; Berardi et al., 2014; Bozorg Chenani et al., 2014; Vijayaraghavan, 2016). GR provide an **array of ecological benefits** (Oberndorfer et al., 2007; Berardi et al., 2014; Vijayaraghavan, 2016) that could improve the urban environment if applied correctly worldwide.

2.1.1.1 Design

These novel ecosystems (Green Roofs**) are divided into two categories: intensive or extensive** (Figure 2). This classification is based on the depth of the substrate layer. GR > 200 mm in depth correspond to the intensive category and GR <200 mm in depth are extensive.

Another way to classify GR is according to their installation method; GR can be modular, pre-cultivated or complete systems (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014. Table 1). The most common layers in a GR are: protection layer, root barrier layer, drainage layer, filter layer, water retention layer, substrate, and vegetation (Bozorg Chenani, Lehvävirta, and Häkkinen 2014, Figure 3). Substrate and vegetation are the most variable layers, and classification of GR are based mainly on those attributes; they dictate the characterization of the ecological conditions for the plant community and provide the resources for the development of the individuals.

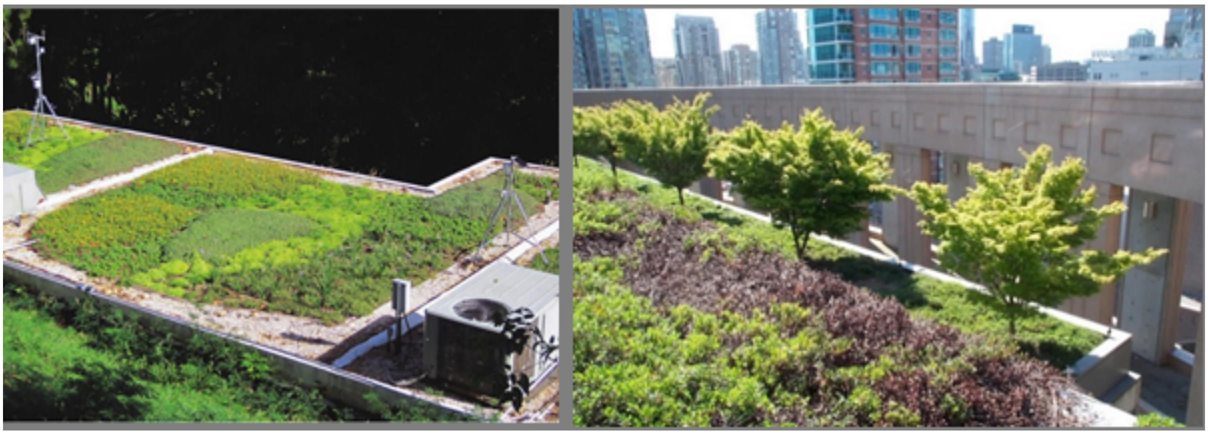

Figure 2. *Extensive green roof at International Institute of Tropical Forestry in San Juan, Puerto Rico (left); Intensive green roof at the Vancouver Public Library (right).*

The design of the GR would respond directly to the use and objectives of the feature; for example, some Green Roofs are used as urban gardens and are commonly referred to as **"garden roofs"**, whereas the main purpose is to establish a place to cultivate food and similar goods for the mitigation and reduction of the carbon footprint by shortening distances between the producers and the consumers. GR are also called "**living roofs**", because of their provision of habitat for wildlife, which is one of the most cited benefits for these structures, and "**eco-roofs**" for their multiple ecological functionality (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014). Another related type of "eco-roof" is a "cool roof", which is often found in combination with GR as mitigation strategy to the urban heat island effect and other climatic urban problems. **Cool roofs constitute highly reflective surfaces**, mostly white, that reflect most of the light and energy, increasing the albedo of roofs and minimizing the amounts of solar radiation absorbed by these surfaces; this turns into building surface and air temperature reduction (Li and Norford 2016; Peng Lihua 2012, Figure 4).

Table 1. *Green roof classification attributes.* Source: (Berardi at al. 2014)

Substrate Depth		Installment Type		
Extensive (depth >200 mm)	Intensive (depth <200 mm)	Modular	Pre-cultivated	Complete
Inaccessible	Accessible	Low weight	Regular weight	High weight
Low plant diversity	High plant diversity	Fast installation	Simple installation	Complex installation
High cost	Low cost	Low cost	Average cost	High cost
Irrigation not necessary	Irrigation necessary	Pre planted	Pre planted	Layered system
Simple maintenance	Complex maintenance	Simple maintenance	Simple maintenance	Complex maintenance

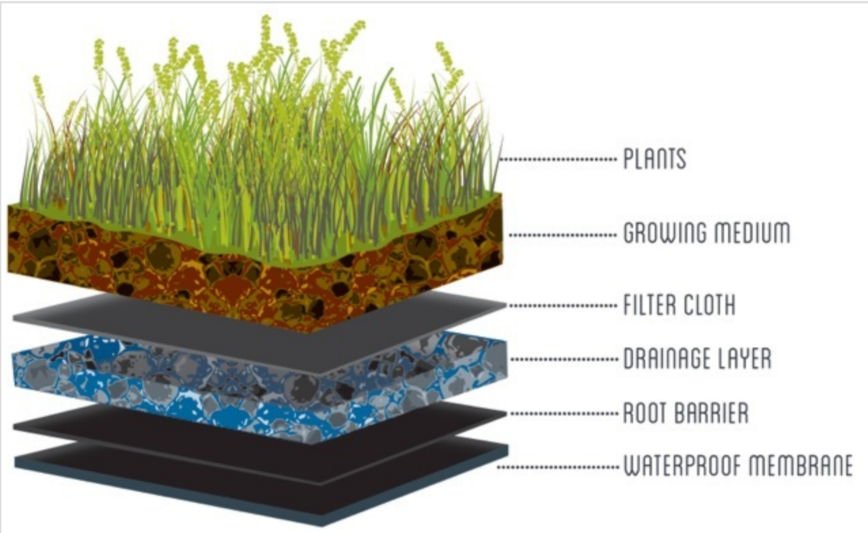

Figure 3. *Green Roofs basic layer composition.* Source: (Restoration Gardens Inc., 2018)

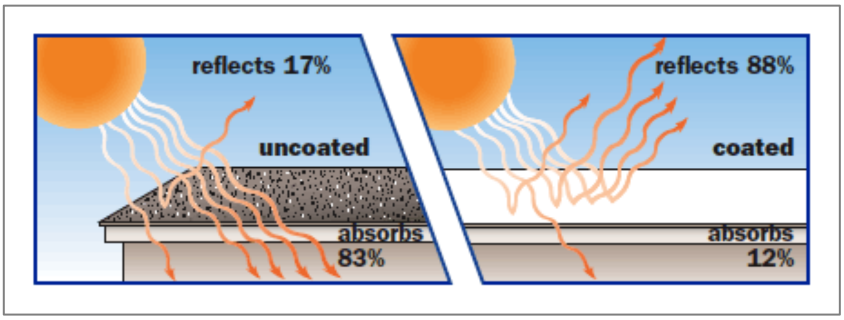

Figure 4. *Cool roof diagram.* Source: https://www.seasidemaintenance.com/cool-roofs.

2.1.1.2 GR Potential benefits

Environmental benefits related to Green Roofs include **thermal regulation** of the building and **reduction of the heat island effect** in cities (Razzaghmanesh et al., 2016), **storm water decrease** (Nagase y Dunnett, 2012), **runoff water quality improvement** (Teemusk y Mander, 2007), **noise and air pollution decrease** (Van Renterghem y Botteldooren, 2011; Vijayaraghavan, 2016), **climate change mitigation** (Peng Lihua 2012; Li and Babcock 2014), **diversity conservation** (Vijayaraghavan, 2016), **connectivity increase** in urban zones (Peng Lihua, 2012; Madre et al., 2014; Williams et al., 2014), among others. But to achieve some of these benefits, **GR must be carefully designed to optimize** roof space and achieve as most ecological benefits as possible. Once local GR design is optimized a second step is to focus on the **placement of GR in the city to facilitate ecological connectivity**, i.e., species movement and colonization, both from ground level to the GR (height dependent) and throughout the urban matrix. GR placement should be done in combination with cities existing green infrastructure (i.e., Urban Forests, Parks, gardens, other open spaces) placing **GR in strategic places to create corridors, stepping-stones, or connecting nodes** for either as many species as possible, species of conservation interest, or for both. Connectivity of the green infrastructure in cities is key in achieving the ecological benefits and services expected from these elements (Madre et al., 2014). **In isolation, individual patches of greenery cannot maximize their functionality and are affected largely by border effects** (Speak, 2013). Studies have pointed out that while green infrastructures occupy larger but concentrated areas and could be hotspots for ecological resources and services, they are insufficient in providing high quality ecological services by themselves; it is the **dispersed positioning of green infrastructures along the city what optimizes ecological functioning** (Peng Lihua, 2012; Speak, 2013; Madre et al., 2014).

There are other aspects that add value to the inclusion of GR in urban environments. For instance GR are being used to **augment roof structural stability and durability** (Bozorg Chenani et al., 2014), by the creation of an isolation layer between the roof and the degrading factors, such as solar radiation, wind and rainfall. They also **increase property value** by the incorporation of sustainable elements and the enrichment of aesthetics (Olsen, 2015). Economic benefits include the creation of a **new market for the construction and maintenance** of these systems as well as employment (Tolderlund, 2010). GR also provide an

environmental satisfaction to the user (Beyhan y Erbaş, 2013), closely linked to aesthetics, natural areas perception, and intrinsic value.

2.1.1.3 GR Limitations

Although the list of GR benefits seems to be self-explanatory and to stand out on its own in the battle for green infrastructure inclusion in global climate and urban restoration discussions, GR implementation is complex and needs to be addressed cautiously. **Plant species selection and design are the main problems for GR implementation and functioning**. In most cases the attributes used to select plant species for GR are mainly based on aesthetics and less on ecological adaptation or stability to local environmental conditions (Berardi et al., 2014). Another commonly used criteria for species selection is historical use, meaning a "predetermined" list of species proven to withstand certain environmental conditions in some climatic regions and used by the pioneers of GR installation. In many cases, these widely used species do not fit with the local conditions and necessities (Vijayaraghavan, 2016). On the other hand, **maintenance of GR is not always performed**, leading to colonization by generalist plant species that differ greatly from the designed plant community, and that incorporates elements that can be harmful to the building (i.e. trees and other deep root species) (Van Mechelen et al., 2015). Design **decisions are often based on material accessibility and price** and in most cases **ecological aspects regarding the composition of substrate and vegetation layers are ignored** (Dvorak and Volder 2013; Van Mechelen et al. 2015). Regarding ecological connectivity, most GR are small patches that act as isolated islands with no connection with other "natural" elements inside and outside the city. Consequently, they do not effectively contribute to the mitigation of environmental urban problems.

Research efforts have focused on punctual services provided by GR, but **little information exists on the integration of GR in the urban landscape**. One particular study concluded that the biodiversity conservation benefit from GR has most likely been overestimated as most GR in cities lack connectivity and do not assure species movement (Williams et al., 2014). Therefore studies are needed to evaluate how GR relate and connect with both urban green elements (isolated trees, Parks, pasture and scrublands, and small Urban Forests) and environments surrounding the cities (agricultural fields, abandoned or bare land) (Bolaños-Silva y Moscoso-Hurtado, 2011). Also, **GR placement poses a difficulty**

in older cities which are formed by buildings that date to different engineering times which may not withstand the incorporation of another weight element.

Tropical GR have been installed with little knowledge on how these novel ecosystems perform compared with those in Mediterranean and wet temperate zones (Tan Yok y Sia, 2008). Design features have not been evaluated to adapt to local conditions and threats, and substrate and vegetation attributes are being used regardless of these differences.

Another important aspect to consider when attempting the installment of GR is the inclusion of good filtering systems, this is due to a major concern in the community of public planners and among ecologist regarding **water contamination because of nutrient pulses coming from fertilizers and pesticides** used on GR (Teemusk y Mander, 2007; Bozorg Chenani et al., 2014).

2.1.1.4 GR Around the world

GR have been part of human history even longer than we can scientifically recall. Some suggest that the **Babylon hanging gardens** and the plants used to decorate the ziggurats in Mesopotamia were early examples of green roof and green wall implementation (Berardi et al., 2014). Since then and with the increase of knowledge and technology, these "novel" ecosystems have only increased in value, popularity, and importance. More recent **precursors of the technique of green roof design** are Germany and the Scandinavian countries. Since the popularity of these new ecosystems has increased and the necessity for restoration in UA has become a major issue in global environmental agendas, various countries have taken steps forward in the evaluation of urban connectivity and the inclusion of GR as part of their strategies for restoring urban sites. Countries around the world have **mandated by law that new designs incorporate GR and/or other sustainable elements in their designs** (Oberndorfer et al., 2007); some examples are: Toronto (ordinance in 2009), New York (ordinance in 2011), Singapore, Japan, Germany, France, Argentina, and others at different times and rates (Figure 5).

Figure 5. *1: Chicago City Hall (Illinois, EU), 2: Nanyang Technological University (Singapore, Singapore), 3: Robertson Building (Toronto, Canada), 4: Adelaide Zoo (Adelaide, Australia), 5: Munich Airport (Munich, Germany). Collage by Author.*

The implementation of different mitigation tactics around the world has not been uniform; some countries have moved faster than others in the use of clean energy, the reduction of emissions, and the incorporation of the environmental planning in their political agendas. Other countries even starting long after initial precursors have made great achievements in shorter periods of time. This study analyzes how **green roof implementation in the city of Chicago has contributed to its ecological connectivity within the different elements of the green infrastructure of the urban area.**

2.1.2 Ecological connectivity

Ecosystem ecological attributes can be evaluated from different perspectives in each environment. An aspect to evaluate is the level at which elements of the ecosystem are connected in a given time and space. **Ecological connectivity's definition takes in consideration the movement as a proxy for connectivity**, other aspects that could define connectivity could be effect of neighborhood, shape, and size of attributes in a matrix, and distances in relation to species. In terms of movement, the level of connectivity could also be assessed by an interpretation of sources, sinks, and net balances of resource displacement (Taylor et al., 1993). On the other hand, **neighborhood effects are linked to the community behavior**, in terms of the elements of which a matrix is composed, and with the surrounding population's interactions.

2.1.2.1 Urban Connectivity

Urban areas are often patchy zones defined by multiple land uses where the mean patch size as well as the distance to patches is low compared to other type of landscapes (Marsh, 2010b). This relationship between patches makes interactions between neighbors very different than those in other landscapes which are more open and land use patches of the same type are greater in size (i.e., forests, agricultural lands, etc.). Independently of the size or distance, patches need a high connectivity setting to have an effect on a close or distant neighbor, this has more to do with the capacity of a site to facilitate or not movement through its medium (Taylor et al., 1993).

Within the urban landscapes the effect of patchiness creates major connectivity limitations for the impacted species. **To alleviate this effect, urban planners suggest not only the reduction of concrete and asphalt but the increment of vegetation and open water as a tool to restore these areas,** these are achieved by effective landscape planning and the inclusion of green infrastructure elements into the city's design (Marsh, 2010a). On the other hand, **the increments of green infrastructure elements should not be aleatory and should underline some network and connectivity analysis**, to properly function as a unit of open spaces with ecological and social functions (Abunnasr, 2013).

2.1.2.2 GR for Urban Ecological Connectivity

Urban ecology is the study of the complex interactions in the human made environment that are cities and that constitute one of the most desired areas for human settlement in the last 50 years, the Journal of Urban Ecology defines this discipline as *"…the study of ecosystems that include humans living in cities and urbanizing landscapes."* (Indiana University, 2019). On the other hand, urban connectivity deals with the spatial-temporal layout of elements in the urban matrix (Abunnasr, 2013). In a broader scope **urban ecological**

connectivity then tries to identify the ecological components that define ecological interactions and dynamics of the natural elements within urban sites.

GR aim to act as **stepping-stones in an otherwise disconnected matrix** (Taylor et al., 1993; Madre et al., 2014). Studies have shown that the inclusion of this ecosystems (GR) in the urban setting has being beneficial for **species conservation** (Williams et al., 2014), that they have **shaped the plant and animal communities** of cities (Berardi et al., 2014), and that GR contribute in **migratory and non-migratory animal dispersal** (Narigon, 2013; Lugo y Rullán, 2015). Green roof connectivity needs to be addressed from a vertical perspective as well, since studies have highlighted that even under a good placement strategy, a limiting factor for GR functioning is building height (Bozorg Chenani et al., 2014; Olsen, 2015).

2.2 JUSTIFICATION AND OBJECTIVES

2.2.1 Justification

Most studies on GR have focused on the thermal effects of buildings and local microclimate, runoff quality and quantity and other hydrological aspects (Li and Babcock 2014). However, **very few studies have evaluated ecological features of GR and almost none have evaluated the connectivity at a larger scale level provided by GR in urban environments**. Therefore, research is needed to address the environmental benefits of GR at larger spatial scales and particularly their efficacy to connect the urban matrix.

2.2.2 Objectives

The objective of this study is to **evaluate the current ecological connectivity in the city of Chicago, U.S.A. to assess how the implementation of GR along with previous and constantly developing green infrastructures enhances connectivity** among elements. Our final goal is to **point out sensible distances that maximize connectivity of isolated elements within the sites** for future restoration purposes, developers, and policy makers. In order to evaluate their effectiveness in the mitigation of environmental impacts, GR need to be analyzed from different possibilities, that include the magnitude of the services they provide, the areas that they have direct and indirect effects, the possible problems that could arise from the construction, development and use stages and the way to manage them; lastly they should consider the connectivity of these structures to their surroundings to increase functionality and maximize resource allocation.

2.2.3 Research questions

1. *What is the proportion of area covered by green infrastructure in the totality of the city and what does it represent in terms of connectivity?*
2. *What elements of the urban landscape contribute to present urban ecological connectivity, and which ones have the most potential for connectivity enhancement?*
3. *What is the level of interconnection between* Green Roofs *and other green elements within the urban zone (i.e.,* Parks*, Urban Forests, and Conservation Areas)?*
4. *What are the most suitable areas to conserve and restore to maintain or increase the urban connectivity?*

3 METHODOLOGY

3.1 SUDY SITE

Most countries with a tradition of green roof implementation are located within the north hemisphere and in temperate climate cities; this is linked to economic reasons and has driven the design process towards specific components that are often standardized in the designs. **The site selected for the evaluation of the green roof connectivity was based on a literature review in which the selected city was commonly referenced for green roof description, evaluation, or exemplification.** Development of the connectivity analysis was done in the city of Chicago, located in Illinois, the United States of America (Annex I & II). The city comprises an **area of 606.1 km^2** divided in 76 districts (Annex III) (US Department of Commerce 2018, Figure 6) with a growing population that has been spreading in urban and suburban environments since early 1970s, with an exponential and steady increase from 6.0 million to 7.0 million people in only 4 decades, and to accommodate the growing population the city area also increased exponentially doubling its size in only 20 years (1970-1990) and with smaller increases in the following years (Smith and Roebber 2011) Chicago has undergone major climatic and environmental events that have led to the development of adaptation tools that face the global changing scenarios; one of **the major events was the heat wave of 1995 that got intensified by the high abundance of heat-retaining materials** (Smith y Roebber, 2011). The event caused the city to put in place an **urban green infrastructure plan that is still under development and revision given the changing scenarios of the projected global climate changes** (Sandor, 2008). Chicago is one of the **most common sites found in the literature for green roof implementation analysis because of its rapid development through public policies and corporative initiatives**. The most common topics found in the literature regarding GR in Chicago are vegetation assessments (ecology), air quality, runoff quality, implementation strategies and incentives effectiveness, ecological diversity, habitat provision, among others.

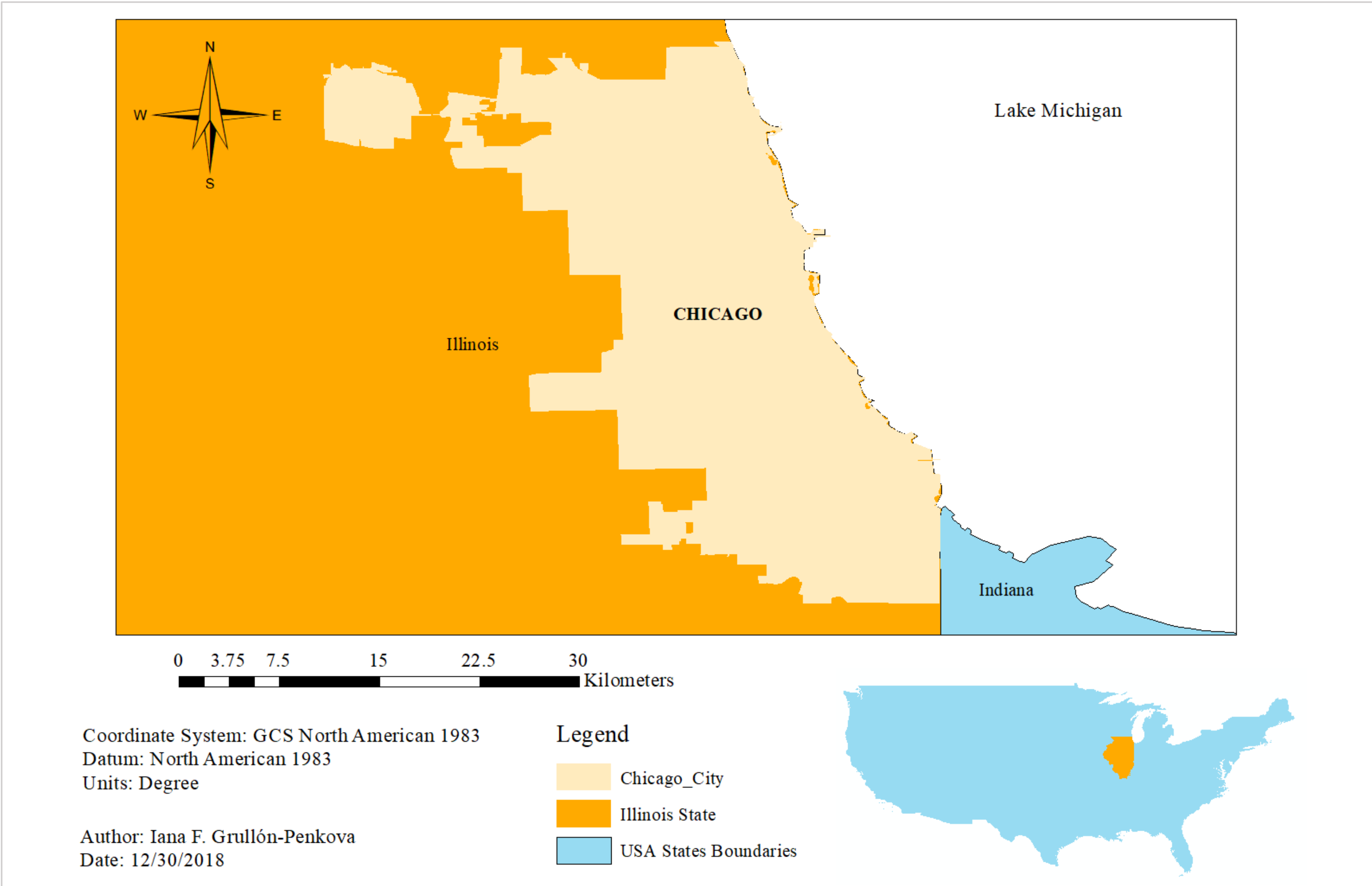

Figure 6. *Chicago's city boundaries map. Figure by Author*

Literature suggests that GR in the ecoregion of Chicago (Southwestern Great Lakes Moraine Plain) have incorporated a **mix of succulent and herbaceous species in an average substrate medium of 8.8-15 cm depth.** Most common herbaceous plants found effective by location are: *Allium cernuum*, *Amorpha canescen*, *Bouteloua curtipendula*, *Cassia fasciculata*, *Dodecatheon meadia*, *Eupatorium altissimum*, *Geum triflorum*, and *Verbena hastata* (Dvorak y Volder, 2010b, Figure 7).

Figure 7. *Most common herbaceous plants found effective by allocation in the City of Chicago, Illinois. Figure by Author, photos extracted from Google Images.*

Irrigation is recommended but not mandatory for most designs placed in this city, this is because Chicago is the second city in rank reported by the National Oceanic and Atmospheric Administration (NOAA) in terms of rainfall quantity in the United States 99.28 cm yr-1) (Olsen, 2015). This information along with connectivity analysis could provide valuable management bases for the implementation plans of green infrastructure in Chicago. The climate of the city is classified as **humid continental (Köppen Dfa)** (McPherson et al., 1994) with a humid season from March to September, with a peak during August, temperatures behave in a similar pattern as precipitation (Figure 8), these information is of great value to GR design in terms of its maintenance to ensure endurance, stability, and functionality.

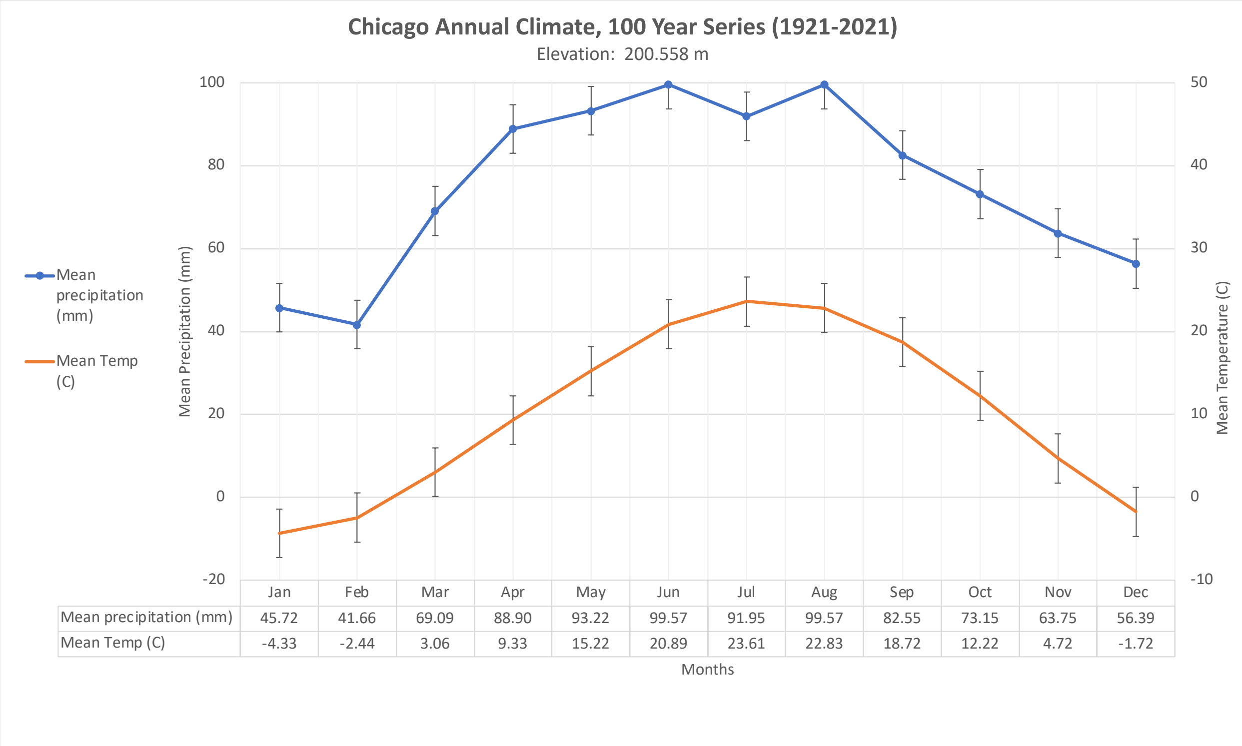

Figure 8. *Chicago's climate graph. Data source:* (National Oceanic and Atmospheric Administration, 2021)*, Figure by Author.*

Chicago's green roof implementation strategy is remarkable, the city is one of the **major precursors in North America to spread in a great way GR across the city center and the surrounding areas**. It is through the incorporation of economic incentives of different classes that the city has achieve multiple certifications and awards. At the individual scale buildings obtain certifications as well, and this serves as one type of incentive for corporations or constructors to highlight structures sustainability marks. One of the most popular certifications is the Leadership in Energy and Environmental Design (LEED). This certification serves as a rating system for buildings and "provides a framework to create healthy, highly efficient and cost-saving green buildings." (U.S. Green Building Council, 2018). The points for this certification are spread into different categories and those depend on the type of project and the certification class; **GR can account for almost 15 points in the point system depending on the case and are strictly related to the beneficial aspects of the green roof design** (Carter y Fowler, 2008).

3.2 METHODS

The evaluation of ecological connectivity was performed through a **Geographical Information System (GIS) analysis**. Using the ArcGIS Program (ArcGIS, 2015), we created georeferenced layers for the different green infrastructure elements, some extracted from the city zoning plan (Annex IV), the GR layer from the city data base, and the ArcGIS base map. The green roof layer was acquired from the Chicago Data Portal here all registered GR are identified, and area estimates are given; the second layer contains Parks and was extracted from the city zoning classification this data captures all land uses under the city ordinance; a third layer is composed by Urban Forests from the city's inventory. Maps for each individual component of the green infrastructure can be found on Annexes I-VI. For this work, superficial and linear elements were analyzed**; superficial elements were defined by the land use and cover and classified in** Table 2. The combination of all mentioned layers resulted in a map of the city's green infrastructure considered under this analysis. Superficial elements constituted homogeneous surfaces with similar characteristics or classifications, such as: Parks, *Conservation Areas*, forests, and the most recent incorporation into modern cities green infrastructures, Green Roofs. On the punctual elements we accounted street trees of the major Chicago streets; extracted from the lineal element of the analysis: roads. All the beforementioned constituted patches of the landscape, all remaining elements were considered the surrounding matrix o the urban site dedicated to other uses or covers.

3.2.1 Landscape characterization

As part of the urban landscape characterization, we performed a quantification of the **structure through the calculation of composition and configuration indexes computed for the TUC classes** (

Table **3**) with the use of Patch Analyst as an extension of ArcGIS. The analysis was performed at the class level, using the type of use and coverings as said class. This component constituted a comparative analysis between the City with the presence of GR and without to establish a base framework to compare with.

Table 2. *Land Use and Land Cover (LULC) type, its abbreviation, and data source description.*

Types of Use and Coverings (TUC)	***Code***	***Description***
Green Roofs	GR	GR were defined by an inventory layer from the city of Chicago.
Parks	P	Parks were defined by an inventory layer from the City of Chicago.
Conservation Areas	CA	Open spaces were extracted from the City of Chicago Database
Urban Forests	UF	Urban forests were defined by an inventory layer from the city of Chicago.
Street Trees	ST	Street trees were defined by the Major Roads of Chicago Layer and a buffer of 20 m from the center. Trees in that area were marked.
Urban Matrix	UM	All remaining space in the City of Chicago that did not fall in any of the remaining categories.

Table 3. *Landscape composition and configuration indexes applied in the analysis.*

Index name	***Abbreviation***	***Type***
Total Area	TA	Composition
Patch richness	PR	Composition – Richness
Patch richness density	PRD	Composition – Richness
Number of patches	NUMP	Configuration – Subdivision
Mean patch size	MPS	Configuration – Subdivision
Total edge	TE	Configuration – Complexity
Edge density	ED	Configuration – Complexity
Area Weighted Mean Shape Index	AWMSI	Configuration – Complexity
Mean perimeter/Area Ratio	MPAR	Configuration – Complexity
Patch size standard deviation	PSSD	Configuration – Complexity

Description and formulas of the calculated landscape composition and configuration indexes:

Composition Indexes:

- Richness
  - **Patch richness** (PR)

    Number of types (classes) of patches present in the landscape.

- **Patch richness density** (PRD)

  Ratio between patch richness (PR) and the total area of the studied landscape (TA). [km^2]

Configuration Indexes:

- Subdivision
  - **Number of patches** (NUMP)

    Number of patches identified in the landscape.

$$NUMP = \sum_{k=1}^{M} n_k$$

  - **Mean patch size** (MPS)

    Ratio between total number of patches and total area of studied landscape.

$$MPS = \frac{TA}{NP}$$

- Complexity
  - **Total Edge** (TE)

    Sum of all the perimeters of all patches identified in the landscape.

$$TE = \sum_{i=1}^{NUMP} e_i$$

3.2.2 Connectivity Analysis

A third stage of the process consisted of the connectivity analysis performed using Conefor Sensinode 2.6, which "*is a software package that allows quantifying the importance of habitat areas and links for the maintenance or improvement of connectivity, as well as evaluating the impacts on connectivity of habitat and landscape changes*" (Saura y Torné, 2009). The program evaluates the ecological connectivity based on chosen dispersal characteristics and ranges. For that dispersal information a selection of species must be incorporated into the program. **Conefor uses a *node – connection* approach, in which the nodes are the spatial units and the connections in this case were evaluated through a probabilistic model to indicate if the nodes are connected or not**. The authors of Conefor use "*the existence of a link between a pair of nodes*" as a direct implication of "*the potential ability of an organism to directly disperse between these two nodes*" (Saura y Pascual-Hortal, 2007). Nodes and distances files were created using the Conefor ArcGIS extension; for nodes the identifiers were unique values assigned to each patch represented in the landscape that was characterized by each Type of Use and Coverings (TUC) and the attribute assigned to each one was its corresponding area. The connections were established by Euclidean distances *("straight-line from edge to edge"* (Saura y Pascual-Hortal, 2007)*,).*

Two functional groups of bird species were defined to evaluate how GR contribute to the city's wildlife connectivity. A wide range of organisms could be considered under this evaluation, but avian organisms are not affected by the vertical limitation some of the elements (Green Roofs) of the analysis have. **To account for species mobility and dispersal ranges, bird functional groups were defined considering the season of the year (spring and autumn)** Table 4**.** Also, a species description is provided for conservation/restoration information availability convenience in terms of habitat design and inventories of species of interest. Functional groups species were derived from migration and visiting lists of bird species created by the City of Chicago for conservation works during a year-round scheme (Pollock, 2018). The radius of the home range distances was used as the median dispersal distance (probability of 0.5) for the Conefor platform. The program was executed for the calculation of probabilistic connections which computes "*an estimation of the strength, frequency or feasibility of that direct movement by the analyzed organisms*" (Saura y Pascual-Hortal, 2007). **The Probability of Connectivity index (PC) was calculated to evaluate the input of each type of use and cover to the urban ecological connectivity.** The nodes to add function was utilized to incorporate the 25% increase of potential patches for green roof implementation in the City of Chicago to the analysis. Same attributes and characteristics were applied to the creation of this random patches throughout the city; drawn at a 1:2,000 scale using the ArcGIS satellite imagery base map as reference to identify structures like buildings suitable for green roof placement.

Table 4. *Functional groups description and bird species characterization.* (The Cornell Lab of Ornithology, 2020). *Information on this table was extracted from Birds of the World and All About Birds, from The Cornell Lab of Ornithology.*

Group 1: Spring		
Mean dispersal Distances (m)		**270 – 500 m**
Blue Jay 	**Scientific Name**	***Cyanocitta cristata***
	ID Info	Order: Passeriformes Family: Corvidae *"Common, large songbird is familiar to many people, with its perky crest; blue, white, and black plumage; and noisy calls."*
	Habitat	*"Blue Jays are found in all kinds of forests but especially near oak trees; they're more abundant near forest edges than in deep forest. They're common in urban and suburban areas, especially where oaks or bird feeders are found."*
	Home range	0.23 Km^2
Chimney Swift 	**Scientific Name**	***Chaetura pelagica***
	ID Info	Order: Caprimulgiformes Family: Apodidae *"A bird best identified by silhouette, the smudge-gray Chimney Swift nimbly maneuvers over rooftops, fields, and rivers to catch insects."*
	Habitat	*"Chimney Swifts breed in urban and suburban habitats across the eastern half of the United States and southern Canada. They are most common in areas with a large concentration of chimneys for nest sites and roosts."*
	Home range	0.79 Km^2

Group 2: Autumn		
Dispersal range (m)		**100 – 400 m**
Chipping Sparrow 	**Scientific Name**	***Spizella passerina***
	ID Info	Order: Passeriformes Family: Passerellidae *“Slender, long-tailed, with a medium-sized bill. Depending on the time of year color brightness varies, being summer birds brighter and winter ones darker. With a distinctive black line through the eye and red-brown cap.”*
	Habitat	*“Found in woodlands and forests,* Parks, *along roadside, and in backyards.”*
	Home range	0.03 Km^2
Tree sparrow 	**Scientific Name**	***Passer montanus***
	ID Info	Order: Passerformes Family: Passeridae *“A small, rounded songbird. Chestnut cap and black face. Normally brown to dark-brown bodies, with white and gray bellies.”*
	Habitat	*“Normally found in town areas, farmlands,* Parks, *and lightly wooded areas.”*
	Home range	0.50 Km^2

4 RESULTS

4.1 CHICAGO'S LANDSCAPE STRUCTURE

4.1.1 Elements of the landscape

The presence of multiple and varied elements within the study area enabled the construction of the green infrastructure layer of the City of Chicago. We took in consideration Chicago City Ordinance (City of Chicago 2018; 2007) as well as some other City inventories and resources to build a catalog of layers from which to extract the green infrastructure information within the city. A Land cover and land use map was built from punctual, superficial, and linear elements of the landscape, Figure 9. Areas per type of use and covering are presented in Table 5 **Urban Forest were the largest green infrastructure with more than 65% of the area.** GR represented less than 0.5% of the green infrastructure of Chicago while *Conservation Areas* and Parks contributed similarly and more than 15% each to total area of Chicago´s green infrastructure.

Table 5. Absolute and relative surface occupied by each type of land use and cover.

Type of land use/cover	Surface Area (Ha)	Relative surface of green infrastructure elements (%)
Conservation Areas	3,592	17.4
Green roofs	32.6	0.2
Parks	3,114	15.1
Urban Forests	13,948	67.4

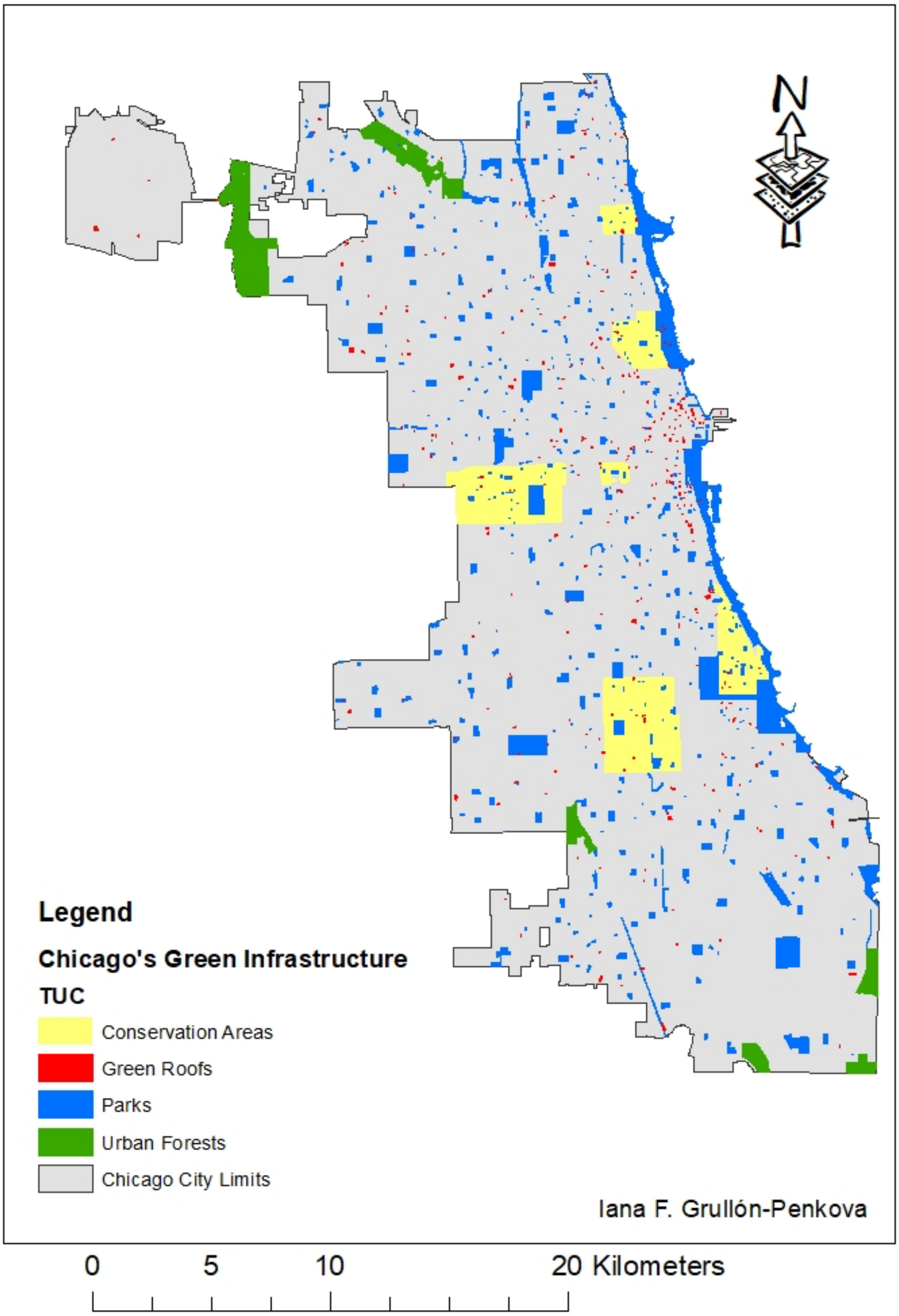

Figure 9. *Chicago's Green Infrastructure Map, composed of Green Roofs, Parks, Urban Forests, and Major Conservation Areas. Note that Green Roofs are not visible in this map due to their small size. See Annex VI for detailed information on the location and sizes of Green Roofs.*

4.1.2 Quantification of the Landscape

4.1.2.1 Composition Indexes

This section describes the composition of the Chicago City landscape in terms of the analyzed types of land use and covers. The composition index denominated "richness" describes the number of types (classes) of patches that exist within the studied area. **In the City of Chicago, we have analyzed four different classes that comprise a total area of 20, 688.9 Ha (206.9 Km^2).** The landscape without the existence of Green Roofs is a less fragmented one, with only 3 different classes covering an area of 20,656.3 Ha (206.7 Km^2).

4.1.2.2 Configuration Indexes

Configuration indexes describe the spatial arrangement and the attributes patches in the landscape have in contrast with each other or reference values from similar habitats. The subdivision indexes summarized in Table 6 describe how many patches correspond to each class and the mean patch size of each of the studied types of coverings. This information combined with other indexes related to the complexity of the forms, as shown in Table 7, helps to understand how patches act in connection with similar class patches and the rest of the network based on their spatial attributes.

- **Configuration Indexes – Subdivision**

Table 6. *Configuration indexes - Subdivision: for the City of Chicago*

Type of land use/cover (k)	***Number of Patches (#)***	***Mean patch size (Ha)***
Conservation Areas	7	513
Green Roofs	428	0.12
Parks	583	5.34
Urban Forests	19	68.2
Landscape	**1,037**	**184**

- **Configuration Indexes – Complexity**

Table 7. *Configuration indexes - complexity: for the City of Chicago.*

Type of land use/cover	*Total Edge (Ha)*	*Edge density (m/Ha)*	*Area weighted mean shape index*	*Mean perimeter/ area ratio (m/Ha)*	*Patch size standard deviation (Ha)*
Conservation Areas	70,267	8.7	1.36	29.8	429
Green Roofs	72,322	8.9	1.40	3,047	0.25
Parks	660,541	81.9	4.44	793	23.9
Urban Forests	105,690	13.1	2.17	116	62.5

4.2 HABITAT CONNECTIVITY ANALYSIS

This section describes the type of class that contributes in a more significant way to the ecological connectivity of the Chicago green infrastructure network. The most suitable seasons for avian species to be present in the area were Spring and Autumn because of the temperature and humidity conditions. Therefore, species selection was based upon seasonality sightings.

4.2.1 Probability of connectivity (PC)

The PC values represent the direct probability of a species, within the specified dispersal distances, to move from one patch to other. PC values for the landscape showed that probability of connectivity increased with distance. The Equivalent Connected Area (ECA) index "*defined as the size of a single habitat patch (maximally connected) that would provide the same value of the IIC and PC metric (respectively) as the actual habitat pattern in the landscape"* (Saura y Pascual-Hortal, 2007) also increased with distance (Table 8).

Table 8. *ECA values at four median dispersal distances for the studied species of the City of Chicago.*

Distance (m)	***ECA without GR (Ha)***	***ECA with GR (Ha)***	***Difference (ΔHa)***
100	7765.99	7770.00	4.01
270	8101.26	8100.00	-1.26
400	8248.50	8250.00	1.50
500	8360.25	8360.00	-0.25

We also calculated the importance of individual nodes for the connectivity of the landscape, in other words the dPC, which indicates the reduction of connectivity that the removal of each node would cause. Urban Forests (UF) being the largest land unit had the highest dPC values at all dispersal distances. The second most important set of nodes were Conservation Areas, followed by Parks, and finally Green Roofs; as shown in Figure 10. Detailed percentile values (25, 50, 75%) can be found in Annex VII.

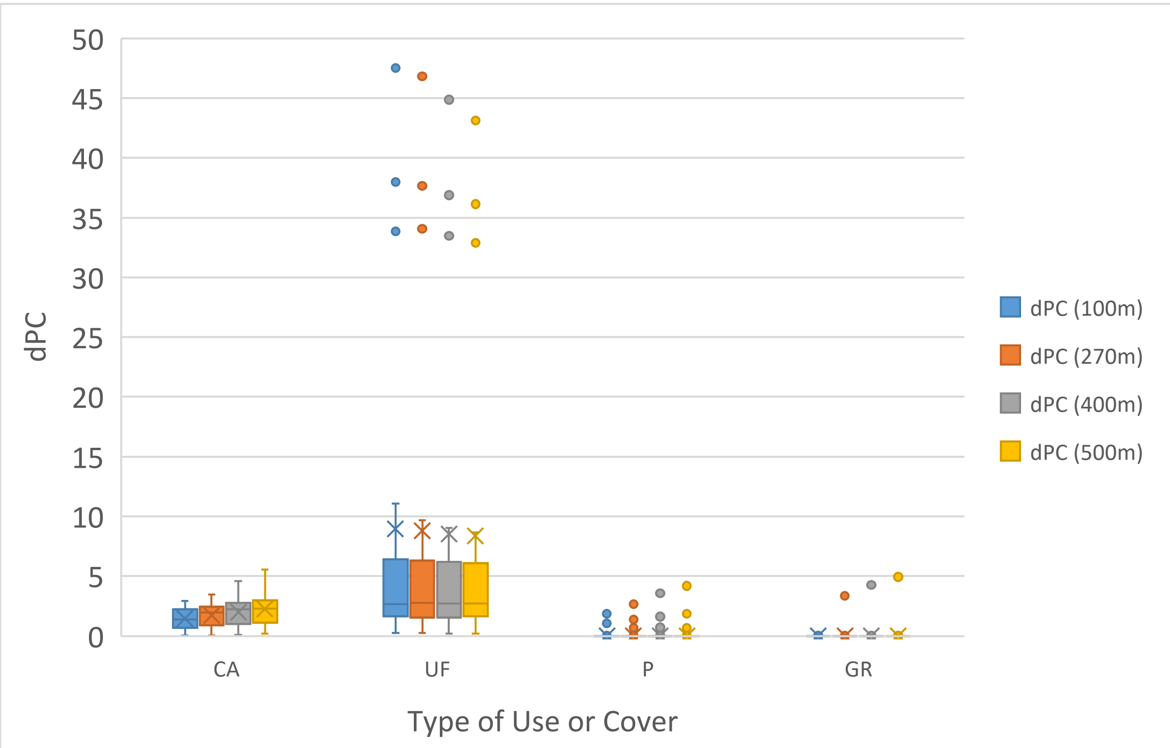

Figure 10. *Distribution of dPC values per type of use and cover of the city of Chicago at four median dispersal distances.*

A rank of the top 10% nodes of the Green Roof covering was performed to establish which of the current Green Roof nodes contribute the most respective to the analyzed dispersal distances, Annex VIII shows the nodes with their respective dPC values for the most influential green roof patches for the ecological connectivity; patches position within the network is captured in Figure 11. This analysis can help in the decision making for green roof maintenance, improvement, and or implementation.

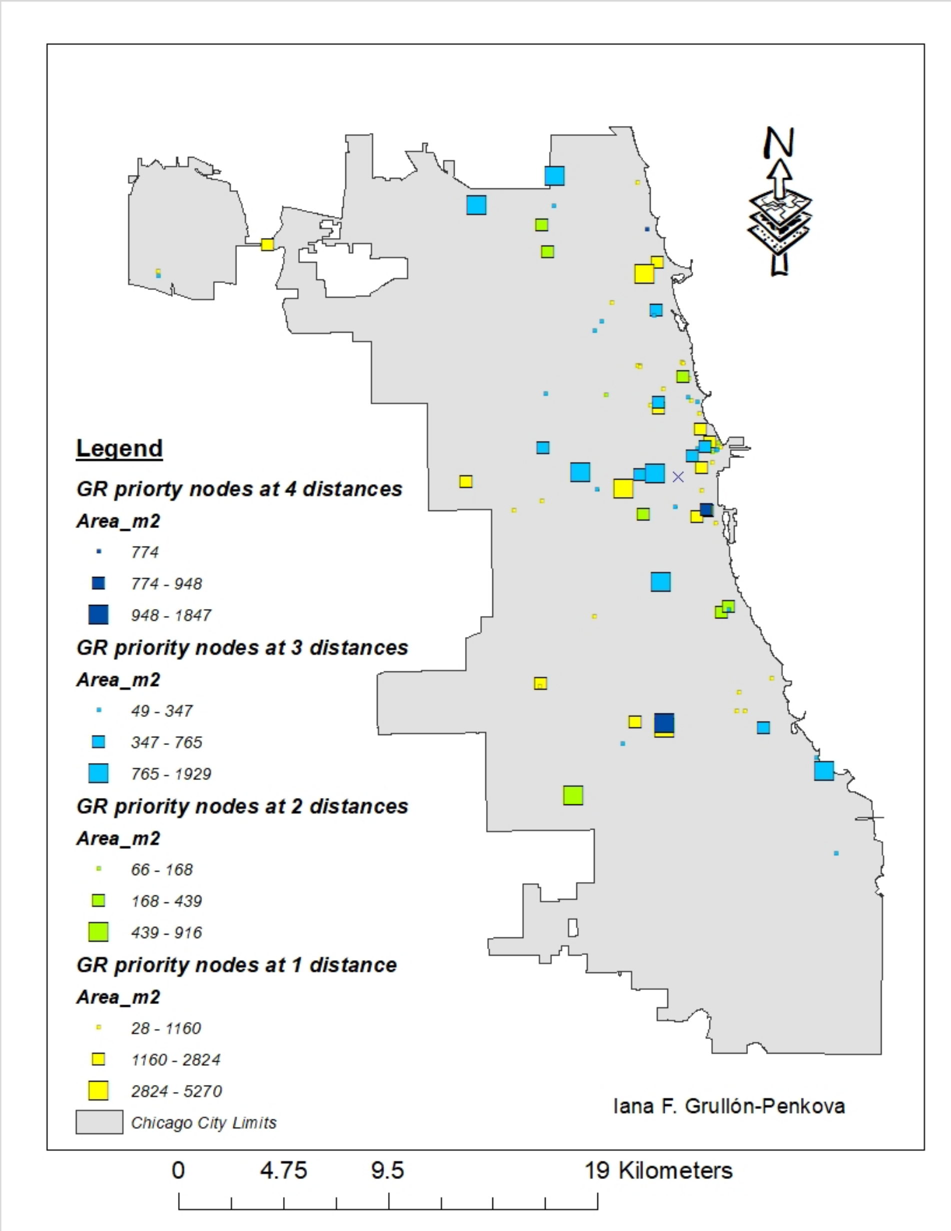

Figure 11. *Priority nodes from the currently available Green Roof patches of the Chicago City green infrastructure network at 4 different distances.*

4.2.1.1 Green Roof potential placement

After incrementing in a 25% the number of Green Roof patches and calculating the contribution of the randomly added Green Roof nodes we propose the following patches as the top priority areas to implement Green Roofs if economic incentives were available. Annex

IX references the nodes, with their respective dPC by analyzed distance. Position within the Green Roof network is shown in Figure 12.

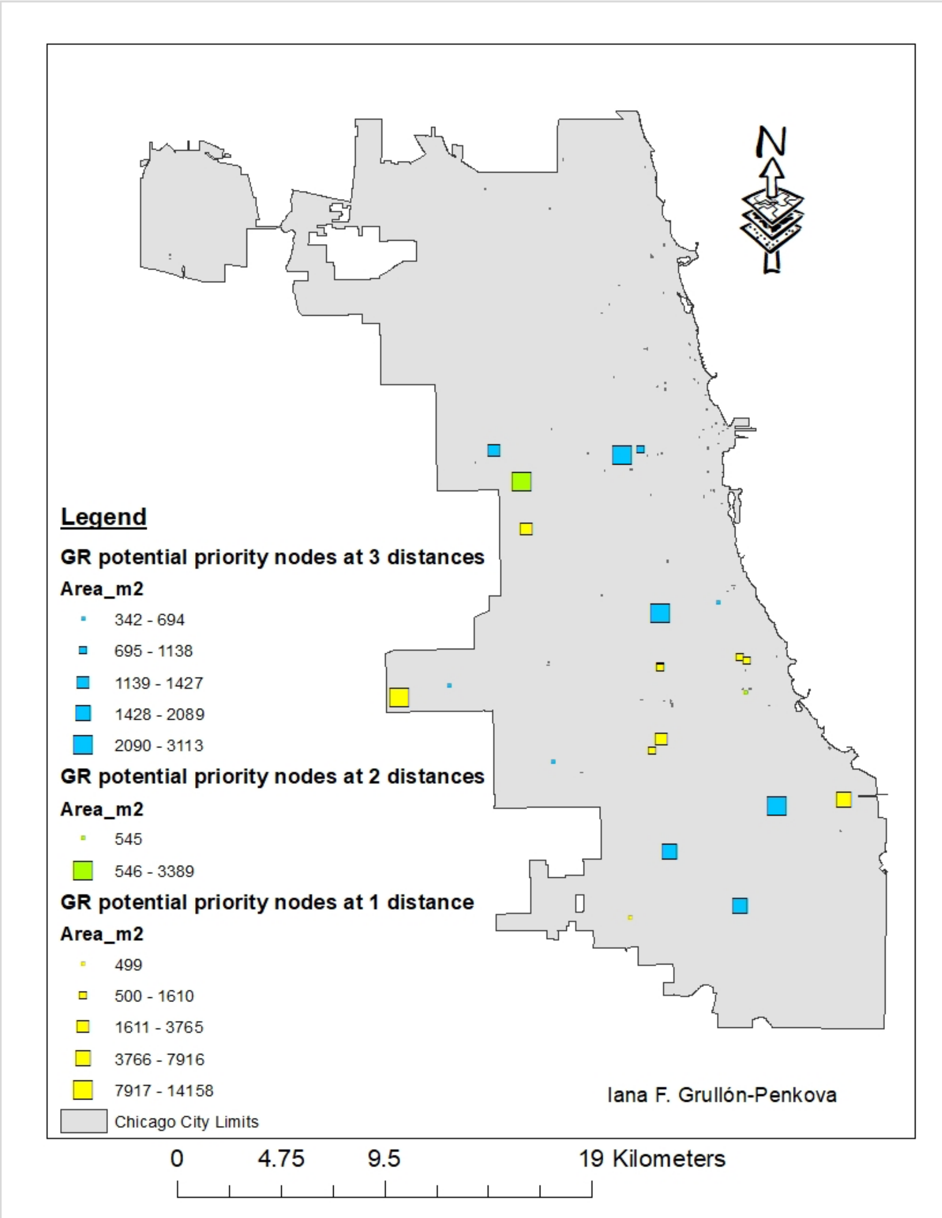

Figure 12. Priority nodes to add from the potential Green Roof patches of the Chicago City green infrastructure network at 4 different distances.

4.2.1.2 Green Roofs PC fractions

The computation of the three different components of the PC index were performed to evaluate the way each of the patched designated by the Green Roof type of covering contribute to the local connectivity. PC Intra, Flux, and Connector, represent the type of connection that can exist between patches, whether they are intra connected, allow flow through them, or serve as steppingstones between adjacent patches (Table 9). As expected, the GR mainly contribute as connectors. The limited size of GR prevents a significant contribution to intrapatch connectivity.

Table 9. PC fractioning contribution of the Green Roof nodes.

Distance	***PC Intra (%)***	***PC Flux (%)***	***PC Connector (%)***
100	0.00	0.00	98.95
270	0.05	49.98	49.98
400	0.00	0.61	99.39
500	0.00	0.56	99.44

5 DISCUSION

Urban spaces in contrast to other landscapes are very fragmented habitats (Fernández-Juricic y Jokimäki, 2001), the different uses of the land in these areas constitutes a high patch-class diversity. Not only that, but **the different land uses or covers differ from each other greatly**, ranging from completely artificial (human-made) spaces like parking lots, buildings, shopping centers, roads, etc.; to natural lands like Urban Forests and prairies, but passing through what could be classified as intermediate areas that encompass some degree of naturalness and human-made habitats, like Parks, gardens, cemeteries, etc. **Green roofs would fit into what we have classified as the intermediate type;** they are human-made systems design with the aim to resemble natural (ground level) ecosystems to the highest degree possible (Berardi et al., 2014).

Chicago is not an exception to the fragmentation trend of urban areas. Zoning captures all land uses and divides the space into different patches that together compose the urban matrix. **The analysis performed in this work focused on four major green infrastructure elements: Urban Forests, Parks, Green Roofs, and Conservation Areas.** Other elements, such as street trees, that could be part of the urban green infrastructure were excluded because of their spatial distribution was irrelevant for our analysis. **Green infrastructure elements occupied 34% (206.889 km^2) of the area of Chicago.** Most of the space is occupied by Urban Forests while Green Roofs only represented a tiny fraction, this distribution reflects historical urban land use and cover trends. Urban forests have been an important part of the landscape since longer times than Green Roofs, which are relatively new. The fact most of the land in the area is covered by forests in contrast to other elements of the green infrastructure indicates a policy towards the promotion of this types of areas within the city. If other elements are to gain importance in this network, they must be equally relevant for the city's public policy agendas, this way areas for their establishment can be located and designated to improve the city's green infrastructure network. Also, forests have been studied for longer periods of time than their novel counterparts (Green Roofs), therefore more information of the benefits, population dynamics, habitat quality, and ecological services is available (McPherson et al., 1994).

Another reason for Green Roofs not to dominate the green infrastructure area is the spatial arrangement of the different elements in the landscape which facilitates or hinders the occupancy of elements within the network. For instance, the size of Green Roofs depends on the size of the buildings or other infrastructures that can be used for implementing these elements, and the total occupied area they cover can only be increased by incrementing the number of patches of this class. The implementation of Green Roofs has increased in pace during the last decades and economic incentives have played an important role in this (Carter y Fowler, 2008; Karteris et al., 2016), but bigger efforts are needed to cover larger areas than the ones present to this date.

The size and number of patches of the different element's determines greatly the quality of the patch (Kang et al., 2015)**.** Patches smaller in size and with higher edge ratios will be affected by the surrounding habitats in a greater way than patches with the opposite trend (large patch size and small perimeter/area ratio). In this regard, *Conservation Areas* had the largest mean patch size and smallest mean perimeter/area ratio, followed by Urban Forests, Parks, and Green Roofs. Being the smallest in size and having the highest mean perimeter/area ratio, **Green Roofs are low quality habitat patches compared to the rest of the elements of the Chicago green infrastructure.** This means that Green Roofs are highly influenced by their surrounding and the boarder effect is greater in these elements than in the rest of the green infrastructure. In terms of wildlife habitat provision, this could translate into a low diversity area due to the lack of high-quality spaces and resources. The border effect on these ecosystems could alter temperature conditions of the habitat, food availability, and genetic flux due to the lack of species interactions, among other ecological attributes, but these effects may become irrelevant if studies of specific species needs are performed to evaluate the habitat characteristics or niches necessary to enhance said habitats (Gardiner et al., 2018).

When considering spatial analysis of this kind, not only the size and edge density are important. **The spatial positioning of elements within the network also determines their value for the entire system, and their influence in it**. Conservation Areas and Urban Forests while being the largest in size, the number of patches (7 and 19 respectively) is relatively small, and their position is limited to the periphery of the city. Other elements like Parks and Green Roofs, instead are distributed throughout the city area or concentrated in the central site where tall buildings prevail. Regardless of this Urban Forests and Conservation areas proved to be the most important elements for the City's connectivity, relegating Green Roofs to a minimal contribution that serves no greater purpose than the addition of steppingstones in the land. The land use and cover with the highest influence on the city's connectivity is Urban Forests, it had the largest number of nodes and area exerting influence over the network. In other words, **Urban Forests are the most important elements for maintaining or increasing the current urban ecological connectivity of Chicago.** The second most important set of nodes are Conservation Areas, Parks, and Green Roofs come last in terms of their contribution to present ecological connectivity**. Notably, Conservation Areas, despite occupying larger patches of land do not particularly contribute to the connectivity of Chicago within the analyzed mean dispersal distances.** It is important to highlight that this analysis took in consideration avian species with relatively small home ranges, and that for other species the mobility or dispersal between different types of area (land uses and covers) difficulted by patch size and placement may not be consistent with our findings.

Prioritization of nodes of the green roof's classification showed that current patches have a small contribution to the city's connectivity. As stated before, green roof placement is often driven by external non-ecological elements and factors, their positioning within the landscape is often arbitrary and not intended for the landscape connectivity and functioning. **Added nodes (or patches) of green roof ranked among the most important nodes of this class in maintaining or improving the ecological connectivity of the site in contrast with the current ones.** Specifically, patches 1053, 1057, and 1039 are the three most contributing areas of Green Roofs with potential of increasing the city's connectivity. Enthought the contribution to connectivity of the Green Roof patches is minimal, it is important to highlight that these systems can provide other ecological benefits within urban sites, therefore performing a prioritization analysis can also provide management information to decide which Green Roofs are no longer needed for ecological connectivity and its contribution to the landscape is minimal or nonexistent because their low relevance in the network in relation to the rest of patches; these decisions will facilitate economic incentives allocation, and financing continuation, as well as design and maintenance of current and potential Green Roofs.

Finally, we found that when dissecting the fractions of the PC into the *intra*, *flux* and *connector* parts, Green Roofs have a strong connector component. In other words, **irrespective of their size Green Roofs contribute to the connection of other patches in the landscape by acting as steppingstones.** This is an important finding and highlights the role of Green Roofs as connectors despite the small area occupied by these structures in addition to their additional ecological benefits. The dPC connector is a metric independent of the size of the patch, and it is the topological positioning what determines the value of the node in the network (Saura and Rubio 2010). Therefore, if Green Roofs are limited by size, they act as stepping stones, and the habitat island effect has a strong influence on the quality of the habitat, using an ecological connectivity approach can be a suitable tool for prioritizing the placement of Green Roofs and maximize their connectivity capacity within a largely fragmented area like urban landscapes as conservation and restoration measures for these ecosystems. A careful place selection must be made to allocate resources and funding in the most effective way using ecological functioning as a framework for green roof implementation.

6 CONCLUSIONS

1. Within the very fragmented area of urban sites, Green Roofs are not one of the highest contributors to their connectivity with the area they currently cover; other elements like Urban Forests and Parks play a more important role in providing high quality spaces for different wildlife species and plants within cities. Green Roofs do contribute to increasing total green infrastructure area, especially in places that have other designated uses and covers and that can be difficult to "naturalize", like city centers.

2. Green Roofs are spread within the matrix in small patches with a high border effect, acting as islands, therefore providing relatively low-quality habitats for different species. They do not contribute in significant ways to the urban landscape ecological connectivity but encompass many other ecological benefits therefore increasing the area covered by these novel ecosystems can enhance ecological functioning of urban sites.

3. Placement of Green Roofs has been limited to city centers and in concentrated spots of land, making difficult for these systems to contribute in an ecologically valuable way to the green infrastructure network. Technological measures could be approached in targeting problems related to green roof implementation in non-flat buildings and other types of structures to increase space availability for their implementation.

4. Given Urban Forests and Parks are among the highest contributors to the urban ecological connectivity, Green Roofs should be placed in areas that facilitate species movement between all elements in ecologically valuable topological places. Since Green Roofs are steppingstones within the urban landscape, restoration plans should carefully select their implementation places to enhance ecological connectivity and not be left to aleatory or stochastic decisions driven by economic factors.

7 ACKNOWLEDGEMENTS

This work was prepared as part of the graduation requirements for the Ecosystem Restoration master’s degree, I would like to thank my professors and classmates for the wonderful experience that it was attending a collaborative Master in which not only 4 different institutions were involved, but also the range of nationalities, levels of expertise, and backgrounds was very rich and diverse that it allowed for constant learning and development. I thank my tutors Professor Pedro Villar and Aitor Gastón for their support during the process; the Program Coordinator at my home institution María Dolores Jiménez, and the rest of people who at some point helped me through different processes.

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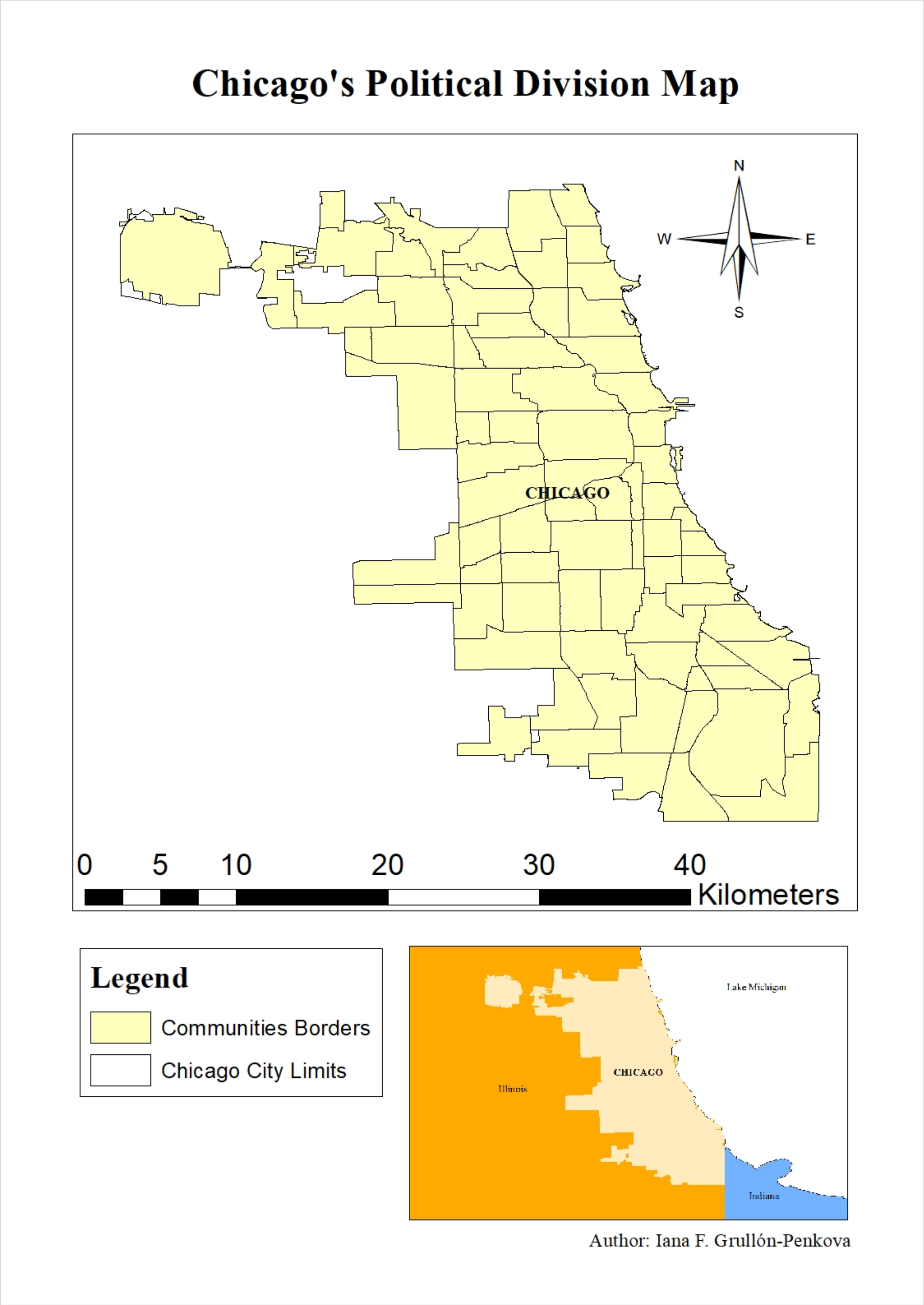
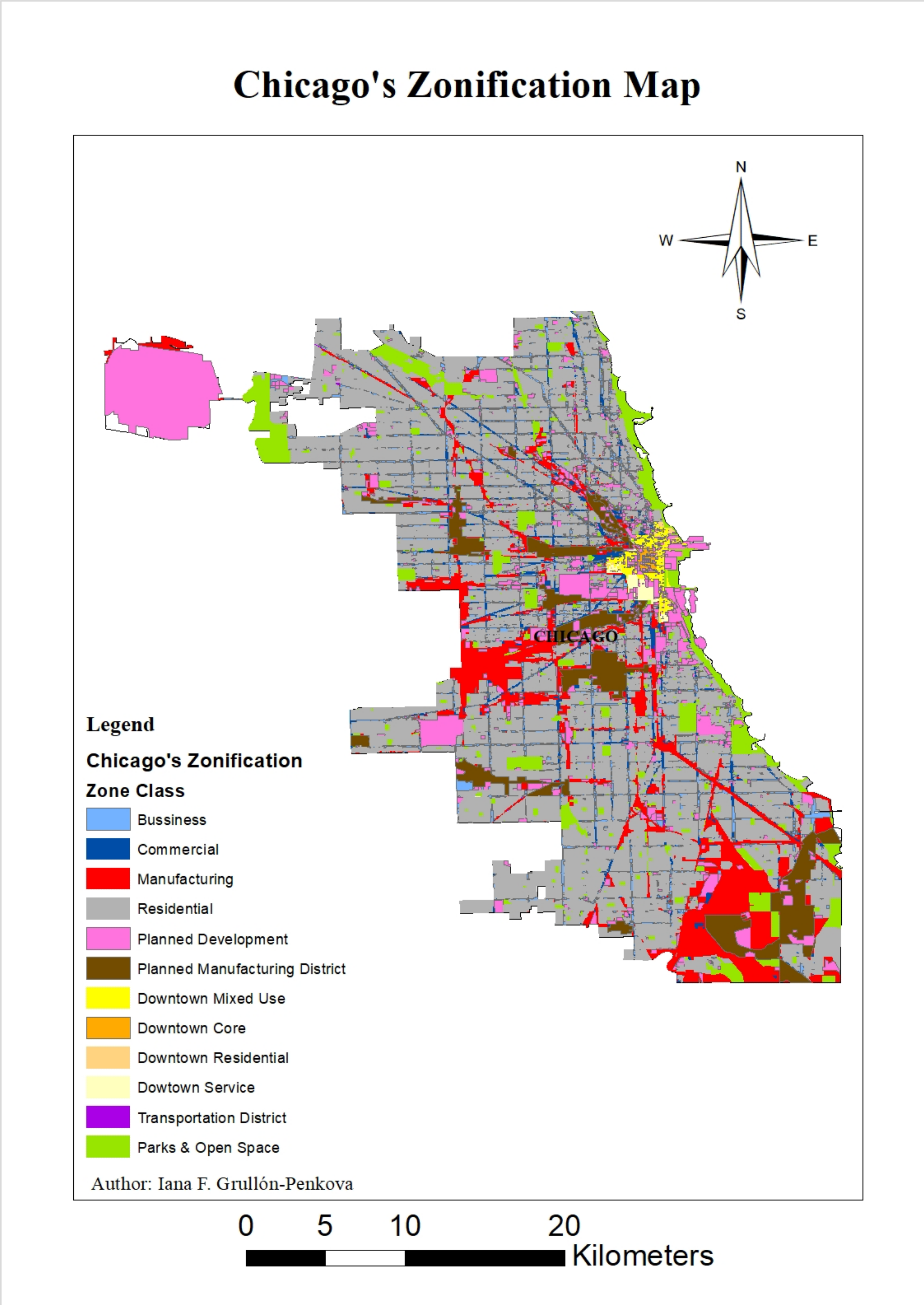
9 ANNEXES

ANNEX I. Chicago's Community Planning Map. Source: (City of Chicago 2018).
This figure contains the City of Chicago, Illinois USA, with the political subdivision of all 76 districts. This division may help identify zoning plans and development strategies on a local scale.

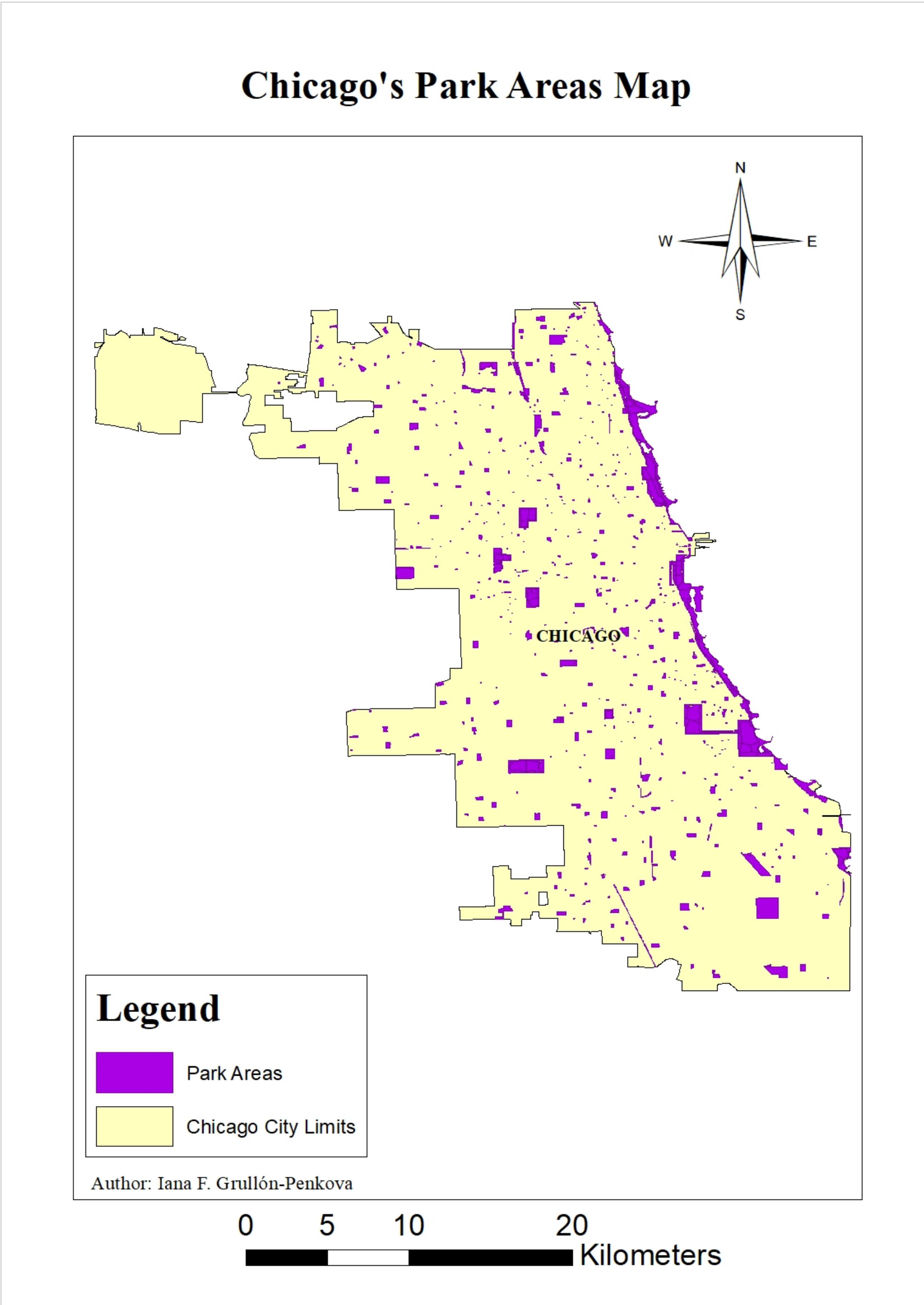


ANNEX II Chicago's Zoning Map, categories were extracted from Chicago City Ordinance. Source: (City of Chicago, 2007)
This figure contains the current zoning classification of the City of Chicago, in which there are 12 classes (see legend). Class 12 – Parks and Open Spaces was extracted and used for the buildup of the green infrastructure analysis.

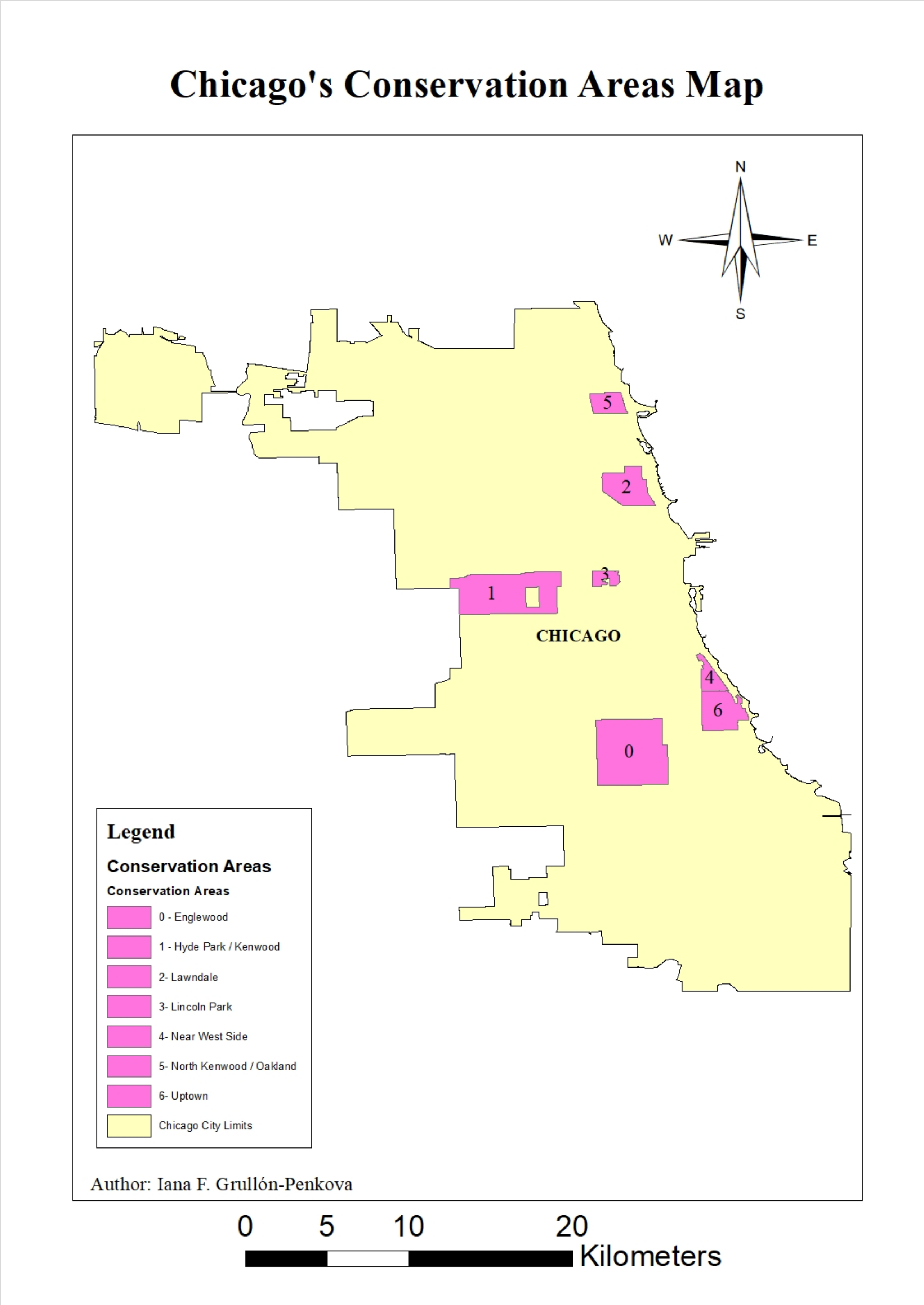


ANNEX III. Chicago's Parks Map. Source: (City of Chicago 2018)

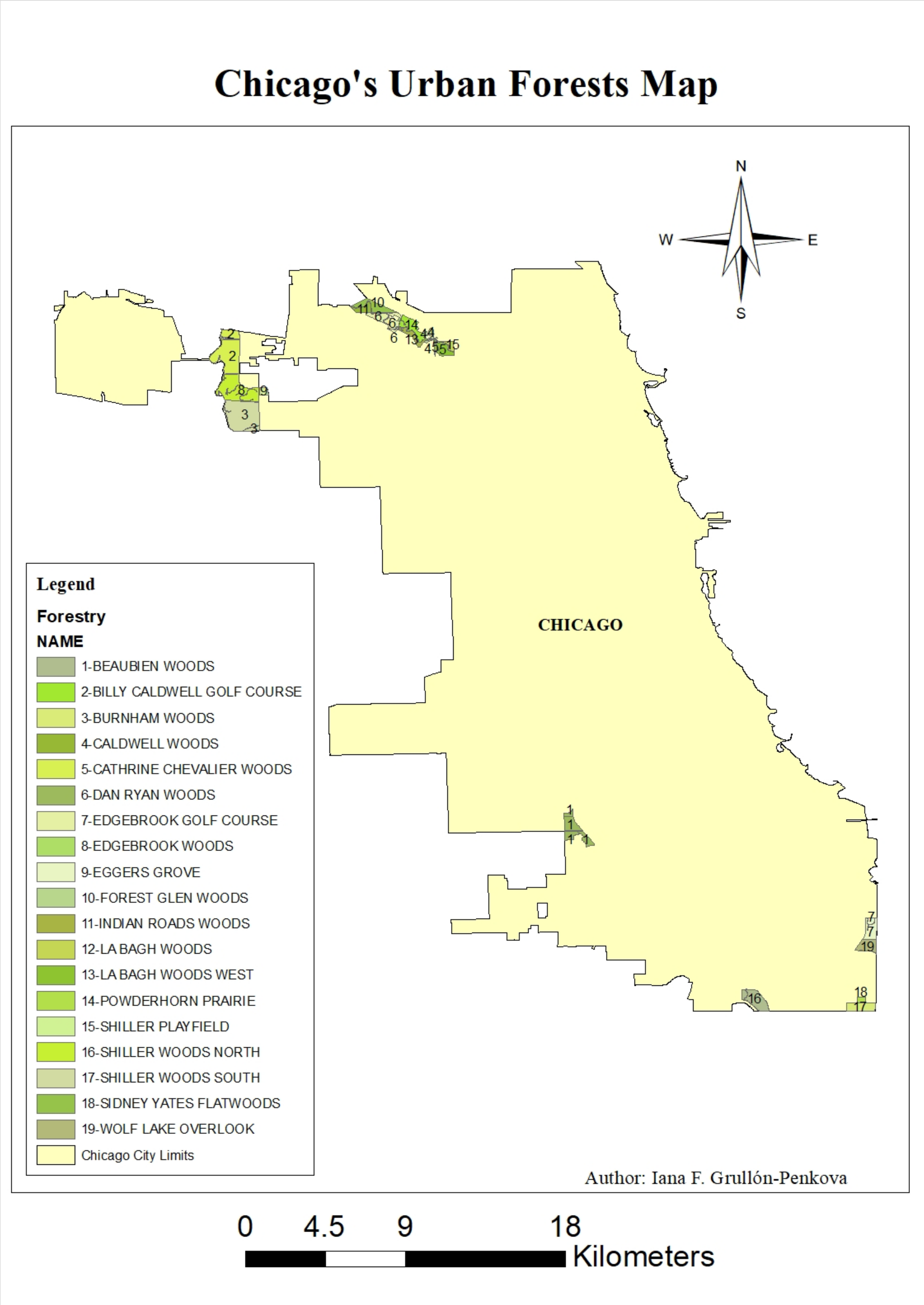
This figure contains the designated park areas in the City of Chicago, in which there are 583 polygons that cover a total area of: 33.48 km^2.



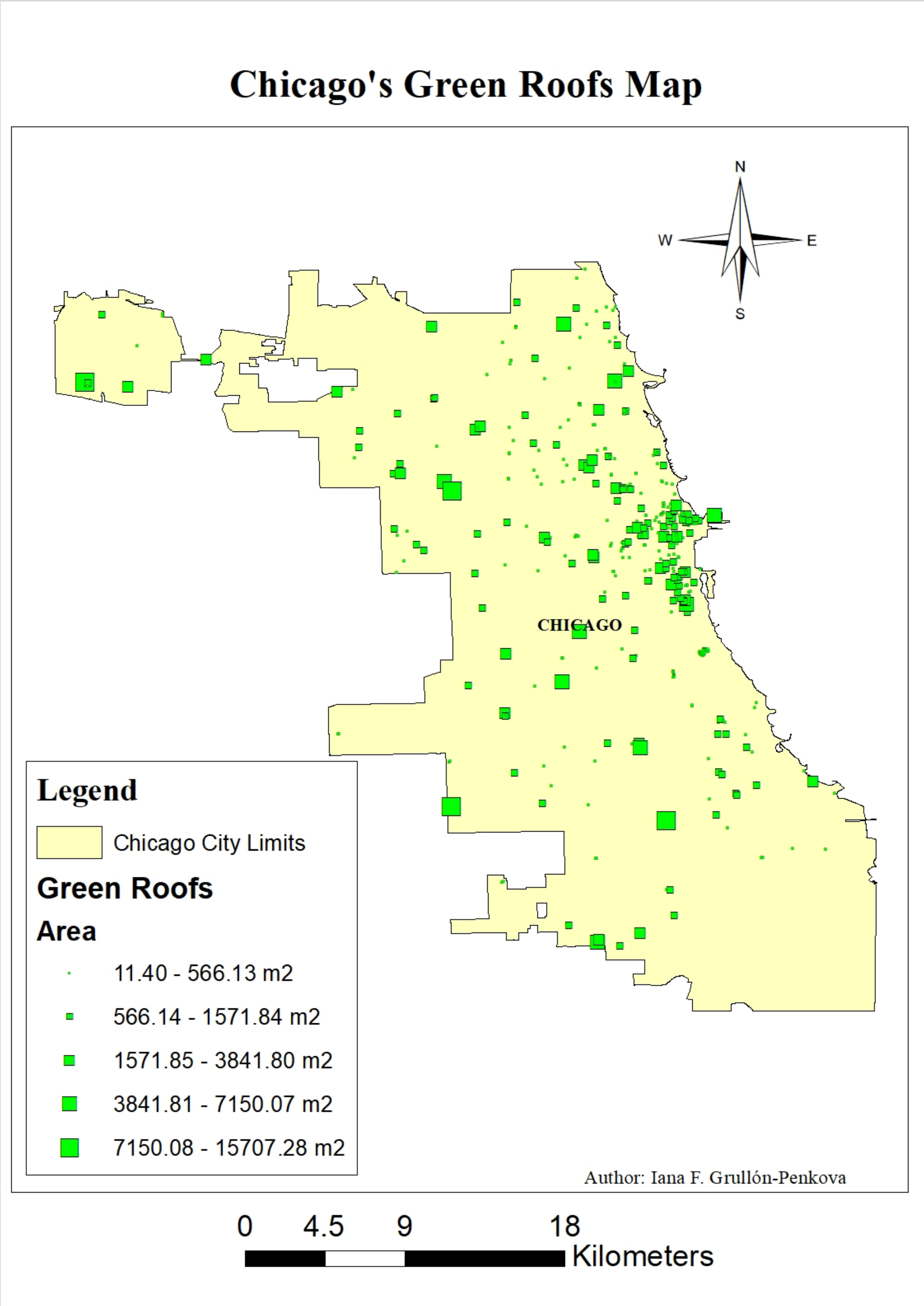
ANNEX IV. Chicago's Conservation Areas Map. Source: (City of Chicago 2018)
This figure contains the current *Conservation Areas* in the City of Chicago, in which there are 7 polygons that cover a total area of: 35.95 km^2.



ANNEX V. Chicago's Urban Forest Map. Source: (City of Chicago 2018)
This figure contains the current forest areas in the City of Chicago, in which there are 19 polygons that cover a total area of: 12.95 km^2.



ANNEX VI. Chicago's Green Roofs Map. Source: (City of Chicago 2018)
This figure contains the current Green Roofs in the City of Chicago. Circles represent locations and circle size correspond to coverage area intervals.



ANNEX VII. Percentiles of the dPC at four median dispersal distances of the City of Chicago Green Infrastructure.

	dPC (100m)			
Percentile	**Conservation Areas**	**Green Roofs**	**Parks**	**Urban Forests**
25%	0.6845981	0	0	1.637855
50%	1.358062	0	0.0000267	2.642654
75%	2.256174	0.0000089	0.0003738	6.397058
Min	0.0194557	0	0	0.2220583
Max	2.913556	0.0028569	1.982851	47.50455

	dPC (270m)			
Percentile	**Conservation Areas**	**Green Roofs**	**Parks**	**Urban Forests**
25%	0.9013856	0	0.0000082	1.548043
50%	1.937462	0.0000327	0.0001145	2.765762
75%	2.455594	0.0002249	0.0008668	6.286983
Min	0.0395928	0	0	0.2211945
Max	3.441406	3.499479	2.669707	46.81788

	dPC (400m)			
Percentile	**Conservation Areas**	**Green Roofs**	**Parks**	**Urban Forests**
25%	1.011628	0.0000079	0.0000315	1.55981
50%	2.266386	0.0000789	0.0002366	2.735801
75%	33.46631	0.00041593	0.0015692	6.181371
Min	0.100081	0	0	0.2179276
Max	4.562436	4.350903	3.56512	44.87196

	dPC (500m)			
Percentile	**Conservation Areas**	**Green Roofs**	**Parks**	**Urban Forests**
25%	1.088755	0.000021075	0.0000691	1.615453
50%	2.500893	0.0001381	0.00033	2.69286
75%	32.87434	0.0005659	0.0025092	6.114836
Min	0.1806791	0	0	0.215624
Max	5.535045	4.978735	4.180282	43.13225

ANNEX VIII. 10% most contributing Green Roof nodes from the current patches of the Chicago green infrastructure network at four different dispersal distances.

Node	***TUC***	***dPC (100m)***	***dPC (270m)***	***dPC (400m)***	***dPC (500m)***
614	Green Roofs	0	0.0002944	0.0010724	0.0025399
615	Green Roofs	0	0.002265	0.0024997	0.0026704
619	Green Roofs	0.0028569	0.0001308	0.0002839	0.0003683
637	Green Roofs	0	0.0015046	0.0050703	0.0091391
642	Green Roofs	0.0000178	0.002543	0.0028703	0.0031001
643	Green Roofs	0.0000178	0.0010303	0.0033434	0.0056477
650	Green Roofs	0	0.0015209	0.0016086	0.0016498
656	Green Roofs	0.0000178	0.0090437	0.0244131	0.0436543
663	Green Roofs	0.0000178	0.0288973	0.0329371	0.0358427
664	Green Roofs	0.0005696	0	0.0000237	0.000046
665	Green Roofs	0.0001424	0.0010303	0.0012932	0.0013505
666	Green Roofs	0.000801	0.0159859	0.0196503	0.0219307
667	Green Roofs	0.0009078	0.0002126	0.0003312	0.000399
668	Green Roofs	0.001869	0.0000491	0.000071	0.0001151
669	Green Roofs	0.0002937	0.000278	0.0002681	0.0002609
670	Green Roofs	0.0001424	0.0000654	0.0001498	0.0002149
674	Green Roofs	0	0.000417	0.0010961	0.0021179
675	Green Roofs	0	0.0003107	0.0009857	0.00188
679	Green Roofs	0	0.0009158	0.0010566	0.001128
683	Green Roofs	0	0.0026575	0.0030437	0.0032996
698	Green Roofs	0.0005518	0	0.0000079	0.0000077
701	Green Roofs	0.0002314	0	0	0.0000077
706	Green Roofs	0	0.0008504	0.0013957	0.0017572
719	Green Roofs	0.0000623	0.00148	0.0039033	0.0067603
721	Green Roofs	0.0000979	0.0008177	0.0010172	0.0011587
722	Green Roofs	0.0000979	0.0005969	0.0008595	0.0010666
745	Green Roofs	0.0003827	0	0	0.0000153
758	Green Roofs	0.0007565	0.0000981	0.0001104	0.0001151
759	Green Roofs	0.0002403	0.0028047	0.0047076	0.0057858
760	Green Roofs	0.0002047	0	0	0.0000077
763	Green Roofs	0.0001691	0	0	0
778	Green Roofs	0	0.0007359	0.0008595	0.0008748
780	Green Roofs	0.0002759	0.0000654	0.0000631	0.0000614
781	Green Roofs	0.0002047	0	0	0.0000077
784	Green Roofs	0.0000356	0.0056993	0.0305242	0.0722839
804	Green Roofs	0	0.0014555	0.0038481	0.0058395
808	Green Roofs	0	0.0030991	0.0035878	0.0039135
810	Green Roofs	0.0001335	0	0	0
811	Green Roofs	0	0.2264278	0.3152014	0.4062172
828	Green Roofs	0	0.0091827	0.0103692	0.0110114
834	Green Roofs	0	0.4988918	0.4930004	0.4872181
836	Green Roofs	0	0.0004906	0.0014194	0.0021409
846	Green Roofs	0	0.0240647	0.0570269	0.0846382
850	Green Roofs	0	0.0021178	0.0080509	0.0146716
852	Green Roofs	0	3.499479	4.350903	4.978735
860	Green Roofs	0.0001246	0	0	0.000046
862	Green Roofs	0.0001246	0.0001063	0.0001341	0.0001458

867	Green Roofs	0	0.0009158	0.0010566	0.0011127
876	Green Roofs	0	0.0066642	0.0086975	0.0100676
878	Green Roofs	0	0.0001472	0.0008595	0.0019337
882	Green Roofs	0.000979	0.0011284	0.0013484	0.001458
883	Green Roofs	0	0.0011366	0.0018925	0.0025092
894	Green Roofs	0.0001335	0.0012184	0.0044631	0.0118401
897	Green Roofs	0	0.0010139	0.0011434	0.0012047
898	Green Roofs	0	0.0012184	0.0011828	0.001174
900	Green Roofs	0.0006942	0.0002617	0.0002681	0.0002916
901	Green Roofs	0.0004361	0	0.0000158	0.0001074
902	Green Roofs	0.0020203	0.0001308	0.0002129	0.0002456
907	Green Roofs	0	0.0001063	0.0008674	0.002233
911	Green Roofs	0	0.0028456	0.0069785	0.012032
913	Green Roofs	0	0.0007441	0.0030911	0.0061234
914	Green Roofs	0	0.0524878	0.0603782	0.0668434
917	Green Roofs	0.0002403	0.0000654	0.0000631	0.0000767
918	Green Roofs	0.0001335	0	0	0
919	Green Roofs	0	0.0003107	0.001443	0.0035144
923	Green Roofs	0.0000979	0	0.0000237	0.0000691
924	Green Roofs	0	0.0039331	0.0126087	0.0216315
925	Green Roofs	0.0000089	0.0025349	0.0038323	0.0046808
929	Green Roofs	0	0.0005724	0.0020265	0.0040132
932	Green Roofs	0	0.000556	0.0021448	0.0039288
937	Green Roofs	0	0.0009076	0.0036588	0.0077272
957	Green Roofs	0.0000356	0.2288645	0.2592075	0.30238
960	Green Roofs	0.0002136	0	0	0.0000077
961	Green Roofs	0.0003115	0.0000491	0.0000946	0.0001535
966	Green Roofs	0	0.0013901	0.0015534	0.0016651
991	Green Roofs	0.0004005	0	0	0.0000153
992	Green Roofs	0.000089	0.0000164	0.0000631	0.0001688
993	Green Roofs	0.0001335	0	0	0
995	Green Roofs	0.0002759	0.0001308	0.0001735	0.0002072
996	Green Roofs	0.0001869	0	0	0.0000077
999	Green Roofs	0.0000979	0.0003025	0.001033	0.0025476
1000	Green Roofs	0.0004361	0	0	0.0000153
1001	Green Roofs	0.0000356	0.0008177	0.0010724	0.001128
1004	Green Roofs	0.0000356	0.0245472	0.027993	0.0304252
1005	Green Roofs	0.000089	0.0000491	0.0000789	0.0000921
1006	Green Roofs	0.000089	0.0005806	0.0013957	0.0018416
1007	Green Roofs	0.0001602	0	0	0
1008	Green Roofs	0.0002403	0	0	0
1012	Green Roofs	0	0.0097714	0.0124273	0.0143724
1020	Green Roofs	0	0.0009731	0.0011039	0.0011971
1027	Green Roofs	0.0000979	0.0002944	0.0004337	0.0005218

ANNEX IX. 10% most contributing Green Roof nodes from the potential patches to add to the Chicago green infrastructure network at four different dispersal distances.

Node	***TUC***	***dPC100***	***dPC270***	***dPC400***	***dPC500***
1038	Green Roofs	0.0006052	0.0003434	0.0013247	0.0027317
1039	Green Roofs	0.0012994	0.0007359	0.0035169	0.0072514
1048	Green Roofs	0	0.0071221	0.0086029	0.0099371
1053	Green Roofs	0	3.343324	4.272972	4.938281
1057	Green Roofs	0	0.0024286	0.0063083	0.0096762
1065	Green Roofs	0	0.0048408	0.0071836	0.0087017
1067	Green Roofs	0	0.007441	0.0073176	0.0073128
1074	Green Roofs	0	0.1470542	0.1657502	0.1788451
1077	Green Roofs	0.0006942	0.0002453	0.001585	0.0034531
1078	Green Roofs	0.0006764	0.0004416	0.0022473	0.0046271
1081	Green Roofs	0.0000178	0.0026575	0.0052595	0.0068064
1086	Green Roofs	0.0009434	0.0004497	0.0005283	0.0005832
1087	Green Roofs	0.0004272	0.0000491	0.0001183	0.0001918
1091	Green Roofs	0	0.0153318	0.0211722	0.024179
1103	Green Roofs	0.0004094	0	0	0.0000077
1104	Green Roofs	0.0006052	0.0000899	0.0001498	0.0002149
1107	Green Roofs	0	0.0037205	0.0057405	0.0074202
1120	Green Roofs	0	0.0044237	0.0108818	0.0164672
1127	Green Roofs	0.0009523	0.0004334	0.0005125	0.0005602
1133	Green Roofs	0.0019491	0.000278	0.0003864	0.0004681
1134	Green Roofs	0.0004895	0	0.0000079	0.0000844
1147	Green Roofs	0	0.0841326	0.1221284	0.1710643