Ecological Connectivity Assessment and Urban Dimensions:

A Case of Phoenix Metropolitan Landscape

by

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ABSTRACT

This study addresses the landscape connectivity pattern at two different scales. The county-level analysis aims to understand how urban ecosystem structure is likely to evolve in response to the proposed development plans in Maricopa County, Arizona. To identify the spatio-temporal land pattern change, six key landscape metrics were quantified in relative to the urban development scenarios based on the certainty of the proposed urban plans with different level of urban footprints. The effects of future development plans from municipalities on landscape connectivity were then analyzed in the scaled temporal and spatial frame to identify in which urban condition the connectivity value would most likely to decrease. The results demonstrated that tremendous amount of lands will be dedicated to future urbanization, and especially urban agricultural lands will be likely to be vulnerable.

The metro-level analysis focuses on a group of species that represent urban desert landscape and have different degrees of fragmentation sensitivity and habitat type requirement. It hypothesizes that the urban habitat patch connectivity is impacted upon by urban density. Two underlying propositions were set: first, lower connectivity is predominant in areas with high urbanization cover; second, landscape connectivity will be impacted largely on the interfaces between urban, suburban, and rural areas. To test this, a GIS-based connectivity modeling was employed. The resultant change in connectivity values was examined for exploring the spatial relation to predefined spatial frames, such as urban, suburban, and rural zones of which boundaries were delineated by buffering method with two criteria of human population density and urban cover proportion. The study outcomes provide a practical guidance to minimize connectivity loss and degradation by informing planners with more optimal alternatives among various policy decisions and implementation. It also gives an inspiration for ecological landscape planning in urbanized or urbanizing regions which can ultimately leads urban landscape sustainability.

DEDICATION

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CHAPTER 1

INTRODUCTION

1.1 Purpose and Need of Research

This study aims to understand urban ecosystem pattern and landscape ecological connectivity in the Phoenix urban region. In order to effectively investigate the respective goal, the study has two different spatial scales: one is Maricopa County landscape and the other is urbanized metropolitan Phoenix landscape. Adopting the ideas and methodologies in landscape ecology, the study provides a prognosis regarding the effect of urbanization on ecosystem loss and fragmentation and landscape ecological connectivity. In addition to the research goals for county and metropolitan levels of analyses, this study fundamentally intends to construct an interdisciplinary model surrounding ecology and planning, science and application, and theory and practice especially viable in heterogonous urban landscapes.

1.2 Uniqueness of Research

Although the significance of ecological connectivity in fragmented urban areas has increasingly been emphasized (Forman, 2008), the current body of literature puts a lot of weight on wildlands or natural areas, leaving us ignorant about causes and consequences related to urban ecological connectivity. It is ironic, however, that loss and destruction of landscape and ecological connectivity is mostly occurring in urban regions and its conservation and restoration in urban settings is essentially in need of human attention. The reasons for the phenomenon can be summarized in several ways. To begin with, the majority of ecologists in the North America have viewed urban areas, which are subject to disturbances and other anthropogenic activities, differently from the ecosystems that they have traditionally perceived, and thus they don't view urban areas as the proper place for landscape connectivity analysis. Second, it is partly due to the lack of accumulated information on various latent benefits that can be drawn from physically and functionally connected landscapes in an urban condition. Therefore, the use of urban landscape connectivity for maintaining and enhancing sustainability remains an unexplored research area.

This study is one of the few investigations focusing primarily on the spatial pattern of landscape connectivity and its potential function at such a broad scale as metropolitan region. Since metropolitan areas are normally composed of three different layers of urban modification (i.e. urban, suburban, and rural areas), the study attempts to link the ecological aspects of landscape connectivity to the urban dimensions of population density and urban land cover ratio. These spatial relationships help understand in which condition of urbanization the ecological connectivity is the most likely to be influenced and what spatial planning measures are needed to conserve the landscape connectivity. The methodology and approaches employed in this study could be used as a means to gauge landscape sustainability and as a spatial tool to develop a spatially explicit ecological network.

1.3 Outline of The Study

The study consists of two main analysis parts (Chapter 5 and Chapter 6) each of which has its own research framework, including problem statement, site description, methodology, study results, planning implications, and conclusions. The two-tiered approach makes it possible to address site-specific issues and to apply as appropriate datasets and methods as possible in the target areas. Under the umbrella goals of quantifying landscape connectivity and understanding various dimensions around the relationship between urbanization and physio-ecological processes, Chapter 5 addresses the spatiotemporal landscape change in response to different schemes of proposed urban development plans at the county scale. Chapter 6 explores species-based ecological connectivity in urbanized Phoenix metropolitan areas. As theoretical foundations that support the underlying ideas in this study, Chapter 2 provides key concepts and theories in the mainstreams of landscape ecology and landscape planning, and then examines the evolving trend toward the integration for conceptualizing landscape sustainability. Chapter 3 critically reviews the contemporary landscape connectivity literature in varied perspectives, ranging from concept, method, and application, and uncovers how this study can fit in, and contribute to, the existing body of knowledge. Chapter 4 outlines overall research methods and presents a rationale to why a certain methodology and approach was used for a particular scale of study. Chapter 7 discusses how the two-scaled approach is relevant to each another and proposes some significant implications generated from the whole course of the study. Lastly, Chapter 8 summarizes and concludes general research outcomes and suggests key players' roles for landscape connectivity conservation in urban setting. For future research direction, new research ideas relevant to the topic of this study were included in this chapter.

1.4 Limitations

Despite the research's significance, the study has several constraints in the aspect of analysis. First, species-habitat association was not based on empirical evidence but rather on simplified assumptions with identified knowledge and the associated best data available. Although riparian areas and wetlands are undoubtedly crucial to both habitat protection and flood damage control in urban landscapes (Benedict et al. 2005), those components were not counted due to the extreme scarcity in amount and seasonal fluctuation in aridity in the Phoenix metropolitan area. Likewise, water bodies (streams or lakes) and canals were excluded. Second, a certain level of uncertainty exists relating to various kinds of data, especially for future circumstances, which can result in spatial and temporal inconsistency. Third, quantitative study results can have a scale effect. In other words, the numeric values derived from the landscape pattern metrics and ecological connectivity modeling can be contingent upon the different grain size of spatial data used, even if the overall pattern will not likely to be much influenced. Fourth, in addition to habitat type and patch size, other factors such as habitat quality can be a determinant of ecological connectivity. For example, North Mountain in metropolitan-Phoenix is one of the largest natural patches in the urbanized area, but desert vegetation therein has converted to exotic species due to recurrent fires, resulting in large areas of disturbance patches (communication with John Gunn). Explicably, this kind of issue was not taken into account in this study because of the broad extent of the study area and the lack of reliable data.

CHAPTER 2

THEORETICAL FOUNDATION

2.1 Landscape Ecology as Scientific Underpinnings

2.1.1 Pattern, Process, Dynamics, and Scale

Understanding the relationships between spatial pattern and ecological processes across a range of scales is the central part that landscape ecologists have emphasized (Turner et al., 2001). Since Carl Troll, a German biogeographer, coined the term landscape ecology in 1939, many landscape ecologists have developed its definitions to effectively reflect the key issues to be stressed (Risser et al., 1984; Turner, 1989; Forman and Godron, 1986; Pickett and Cadenasso, 1995; Nassauer, 1997; Wiens, 1999; Wu and Hobbs, 2007) and to guide the direction toward which the emerging approach should proceed with a rigorous theoretical baseline.

By simply looking at the various definitions made in the evolutionary course of landscape ecology, two characteristics can be commonly found. One is the constant concerns on pattern (structure), process (function), dynamics (change) and scale, which were already conceived in the original definition (Troll 1968; cited in Troll 1971) and epitomized by Turner and her colleagues (Turner et al. 2001). The other aspect relates to slow but sure attempts to embrace application realms into the boundary of landscape ecology (Nassauer 1997; Naveh and Liberman 1994; Wu and Hobbs 2007). The most recent definition

(Wu and Hobbs, 2007) articulates the term "art", denoting landscape design and planning, and highlights its integration with ecological science to deal with more optimal solutions to place-based issues.

As such, active interaction between the science and practical sectors has been encouraged as one of the key topics of landscape ecology (Wu and Hobbs 2002; 2007). One might say that landscape ecology is a branch or a part of ecology, but three main characteristics have distinguished it from other sub-disciplines of ecology (e.g., ecosystem ecology, population ecology, behavior ecology), or ecology-driven application disciplines (e.g., urban ecology, human ecology, and restoration ecology).

First, it deals with a broad, heterogeneous areas rather than small, relatively homogeneous areas (a.k.a. individual patches or sampling sites), and shift from spatially implicit (thus, mechanistic) to spatially explicit study. Second, it stresses the importance of identifying a proper scale at which to address the problem of interest. Third, in many cases it relies on indirect observation due to the difficulties in using traditional methods such as field sampling, laboratory and plot experiment. New analysis techniques, including Geographical Information System (GIS), remote sensing (RS), spatial statistics, and modeling methods, has made it possible to study spatial pattern over large areas and its change through time. These are also the reasons why landscape ecology had to emerge (Turner et al. 2001).

Surprisingly enough, these issues intersect with the concepts that characterize landscape planning: landscape planning literally addresses the issues occurring at such a large scale as landscape; scale approach, particularly spatial or organization scale, is inherent in planning systems; and planners have routinely used quantitative analysis for the last half a century, since Ian McHarg introduced the overlay method that influenced the introduction of GIS. The emergence of landscape ecology provides a turning point for landscape planning, which has struggled with putting the underscored importance of ecology into practice; in addition, it plays a crucial role that the previous ecology couldn't. Relevant theories of landscape ecology are described below.

2.1.2 Theoretical Models and Principles

The patch-corridor-matrix model – This model was developed by Forman and Godron (1986), and provided the first systematic conceptual framework for studying landscape pattern and process. As this concept is a clear form of landscape elements classification, it was readily adopted for main components of planning strategy such as ecological networks. It is still used as a communicative spatial language, but accumulated functions of each of the elements in the overall landscape context may need to be revealed. Blaschke (2006) argues that the patch-matrix-corridor model of Forman (1995) still offers much that is of value to landscape ecology. The model provides the key to understanding land use systems and land use changes through the development of structural or spatial indicators that can sit alongside other sustainability measures addressing the economic, social and cultural aspects of sustainability.

According to the patch-corridor-matrix model, core areas and corridors are surrounded by ‘matrix’ habitat, which favors or inhibits the functions of core areas and corridors to a greater or lesser extent. If species are to cross the matrix to behave as meta-populations or to satisfy their life cycle processes, then either the matrix must be ‘permeable’ in terms of being reasonably conductive to traversal and survival, or ‘porous’ in terms of having smaller areas of suitable habitat which serve as ‘stepping stones’. The matrix is further enhanced if network connections are present; it is generally considered desirable to join core areas by corridors, which may serve to increase the areas’ connectedness (extent to which features are physically joined up) and connectivity (degree to which corridors actually assist functions such as foraging and migration). While there is very limited evidence that corridors per se demonstrably and uniquely assist life cycle processes, especially in heterogeneous fine-grained landscapes where movement is relatively easy for mobile species, they do appear to perform several valuable roles. In practice, a key value of ‘corridors’ is that they frequently comprise relics of formerly widespread habitat types, which can be used as nuclei for landscape restoration and biodiversity recovery.

System theory - System theory provides a holistic philosophy by which the order of nature or other systems can be understood (Cook 2000). It is usually related to the nature of complexity of the systems in nature and society. In landscape ecology the idea of system theory was developed to understand the landscape as the total spatial and functional entity (Naveh 1991). The notion of the "Total Human Ecosystem" introduced by Naveh and Liberman (1994) emphasizes such a holistic landscape perspective. This view is particularly predominant in much European and Mediterranean landscape ecology literatures The Gestalt concept being used in psychology was borrowed to describe the landscape as an integrated system with self-organizing tendencies, and configured in a way that the whole is different than merely the sum of its parts. The strength of this approach is gained through analysis of the essential functional interrelationships of the system.

Hierarchy theory – Hierarchy theory (O'Neil et al. 1989) is a general theoretic framework within complex system theory developed in the 1960s and 1970s. With hierarchy theory, the complex system can be more or less simplified by taking things to pieces. It can solve a problem of how a system of discrete functional elements or units is linked at two or more scales (Forman 1995). The landscape system is a nested hierarchy, with each level containing the levels below it. In a hierarchically structured system, the speed of process tends to be determined by the level the process occurs in. For example, there are slow processes at higher levels, and fast processes at lower levels, while the higher levels to some extent control the dynamics at the lower levels. The scale issues occur when a process cut across different levels in a hierarchy. Wu et al. (2006) systematically presents dimensions (time, space, and organization), and kinds of scales to be considered. The scale consideration is also essential to find proper grain and extent in analysis.

Island biogeography theory – The Island biogeography theory developed by Robert MacArther & Edward Wilson (1967) investigates the geographic location of species. The main observation was that island area, isolation, and age are, respectively, control colonization-extinction rate and hence the number of species. It may be the earliest attempts to identify the relationship between pattern and process. These simple principles were applicable in landscape planning studies on patch size and its effect on biodiversity. Additional concepts derived from this theory such as stepping stones conceptually contributed to basic ecological system and MAB (the Man and the Biosphere program), an intergovernmental scientific program launched in the early 1970s by UNESCO (United Nations Educational, Scientific and Cultural Organization). However, many critiques exist in using it as a primary model for land planning, as it does not consider significant characteristics of landscape such as landscape heterogeneity, edge effect, and disturbances.

2.2 Landscape Planning

2.2.1 Historical Perspectives

Landscape planning is considered a branch of landscape architecture on the simplest idea or sometimes compatible with the extended urban planning. However, the most reasonable description relevant to planning practice is the study of investigating the land and associated environmental and socioeconomic issues occurring at a broad geographical scale and implemented over a long period of time. A number of books and journal articles provide the historical context and evolution of U.S. landscape planning. This literature can be grouped into historical accounts, policy/legislation discussions, and environmental applications. A brief summary of the historical development of landscape planning can be provided within the framework of four periods of transformation to establish a knowledge baseline: awakening, formative, consolidation, and acceptance.

During the emergence and awakening era from the mid-19th century, there was an actively growing environmental movement that was a precursor to landscape planning. Philosophical thoughts from pioneering naturalists such as Ralph Waldo Emerson (1803-1882) and Henry David Thoreau arguably formed a fundamental basis of modern landscape planning. The use of nature is illustrated in the literature of that time (e.g., Poems of Nature (Thoreau 1895), and Nature (Emerson 1836), reprinted in MacIver (2006) and Emerson and Ziff (2003), irrespectively). Urban park systems (e.g., the 'Emerald necklace' open space planning in Boston) and greenways of the type planned by Frederick Law Olmsted (the 'father of landscape architecture'), are key examples of initial urban landscape planning. Olmsted tried to bring significant landscape elements such as marshes, wetlands, and open spaces into city.

In addition, the intrinsic characteristics of landscape such as vegetation, hydrology, habitat, and human activity, beyond garden-scale landscape planning, started to be considered in cities. During this period, the values of, and respect to, nature particularly motivated people to long-term preservation of wildlife. John Muir (1892), the founder of the Sierra Club, established the initial form of the national park system that was later systematized in the early 20th Century, resulting in the park service of today. Entering into the early 20 century, Gifford Pincho, who instituted the US Forest Service, emphasized nature conservation for the greatest good and the greatest number of people for the longest time. Overall, all these modes of thinking laid groundwork for the development of landscape planning, particularly in terms of multiple use and landscape sustainability.

The formative era can be characterized by much broader planning approaches and more ecological in theories. Patrick Geddes, as a biologist but later an innovative planner, emphasized the broader pattern where people and landscape interact with each other. Based on Darwin's theory of evolution, he developed the new city planning theory that explains society and environment, as a whole, in the framework of a 'region'. The notion of regionalism is also developed along this line. Another focus was the importance of scientific survey and analysis. The overlay mapping that became a major analytic tool in modern landscape planning was introduced. The issues of the critical components are in a region, how they can be mapped differently, and how to use them for decision making are all critical to analytical planning. The benefit was to bring together natural and cultural components in the region. This is grounded on Geddes' argument that as cities become incomparably huge and complex, unless an exact analysis is accomplished, urban problems may not correctly be identified or resolved. Therefore, principal characteristics of modern landscape planning use the large scale and holistic approach, and Chicago urban ecology traditions are rooted in these early planning ideas. Early efforts in open space planning are shown in this period, meshed with enactment of the National Park Act.

A couple of issues in this stage of consolidation include consideration of geographic characteristics such as soil and vegetation, and reinforcement of social value such as participation. In this regard, contribution of Lewis Mumford to the modern urban and regional planning is enormous. His key words are totality, balance, ecology, and regeneration, all of which focus on ecological harmony and natural resources conservation in regional planning. These concepts offered a starting point from which ecological planning developed. He also paid attention to the nature of boundary bounded to landscape, from which modern edge studies are generated, and helped to establish regional cities as an important area of research. Along this line, an example of comprehensive river basin planning occurred in this era. The Tennessee Valley Authority (TVA) is related to building a dam to produce electricity as a means to economic resurgence, but it was also an experimental place where the comprehensive strategy of natural resource characteristics of watershed was used.

During the mid-twentieth century, many landscape planning efforts were widely accepted and used for various purposes. While being influenced by preceding urban theories, landscape planning started embracing justified ethical value system. Silent Spring, the book written by Rachel Carson (1962) is widely credited with helping launch the environmental movement around 1960s. The misuse of technology, as a newly emerged urban problem, was analyzed since it wasn't always going to be best answered only being possible answers, while the responsibility for the society and environment is much gained the public awareness.

As the modern sense of landscape planning was used in the book first titled Landscape Planning (Hackett 1971), numerous landscape planning books and studies have published. Among them, there are some distinguishing books related to landscape planning. McHarg's book Design with Nature (McHarg 1992), was by far the most important landscape planning book of the twentieth century. His land suitability analysis based on the overlay technique has been a significant tool to identify and evaluate the landscape. Arnold Weddle, founding editor of the journal Landscape Planning, wrote of an activity that landscape planning distinguished from related professions by looking beyond their 'closely drawn technical limits' and 'narrowly drawn territorial boundaries'. On the other hand, the majority of environmental laws including the NEPA (National Environmental Policy Act) have also been enacted to reflect more diverse and complex demands on preservation of specific landscape elements (e.g., riparian corridor) or for specific purposes (e.g., National Scenic Act, Clean Water Act). Some principles of landscape planning are incorporated into various types of legislation and policy documents (e.g., the National Environmental Policy Act and Environmental Impact Assessment influenced by the work of Ian McHarg). On the other hand, whole ideas of landscape degradation have surfaced, generating the necessity of the role of planning for landscape restoration.

In conclusion, the early landscape planning was developed in a form of town planning with the idea of incorporating public open space into towns. However, it became larger in scale and concerned with place. Historically, many planning activities and designs have been initiated, mainly meshed with environmental problems and events that arose in the corresponding epoch. Although early planning theories are quite idealistic, few were practiced in the real world. While the traditional foci of landscape planning are aesthetics and economics, the explicit inclusion of ecological principles in landscape planning is quite a recent advancement (Opdam et al. 2006). This should be examined for landscape connectivity, which puts a theoretical foundation on ecological planning and design.

2.2.2 Landscape Planning Theory

A bulk of literature exists that may be relevant to the subject areas of this study. For the general framework, many substantial and procedural theories have been developed and well documented in Ahern's work (2005). He suggests a typology for sustainable landscape planning, including a theoretical orientation; resource or goal orientations; interdisciplinary versus transdisciplinary; strategic orientation and spatial concepts. This seems to be adaptable to many derivative planning approaches as well, such as ecological planning (Thompson and Steiner, 1997; Mcharg, 1969; Steiner 2000), and landscape ecological planning (Musacchio, 2001). They have established their own theories, principles and methods often with a shared conceptual root, and which have been used distinctively or compatibly. The framework approach of Steiner (2000) and the seven steps of the LEP process (Musacchio, 2001) have a similarity to this study in building a theoretical framework, and thus adaptation to this study is possible.

The sustainable principles in the city context have been portrayed in publications relating to the ecological city (Platt et.al, 1994; Register, 2006), green city (Beatley, 2000), and sustainable city (Walter, 1992). In a narrow sense, such endeavors relate to make amenity cities function in balance with nature to the extent of humans' pleasures. The concepts of an environment-friendly city and healthy city are slightly beyond this, and attempt to create far much sound environment. In a broader sense, it views a city as an organic complex where urban activities and spatial structure should achieve the properties of ecosystems such as diversity, self-support, circulation, and stability. The conservation and restoration of urban biodiversity and ecosystems, and material circulation is intensified within an existing urban system. Sometimes, it is encouraged as a way of obtaining ecological advancement for a wide range of issues dealt with in every sectoral planning. It even suggests sustainable economic structure and incorporates human activities to help make the desired city picture. This extensive body of literature does not too much focus on current or alternative spatial pattern and processes therein, but some critical relationship at the city scale can be inferred.

On the other hand, quantitative scientific findings are often handy and applicable in planning and managing lands of human-dominated areas. In certain cases, it helped to establish wise use of lands otherwise doomed as empty landscapes. The Environmental Law Institute developed a series of conservation thresholds intended to inform biodiversity planning (2003).The thresholds present specific recommendations regarding key conservation planning parameters, including: minimum patch area by species type, proportions of suitable habitat, size of edge effects, and riparian buffer width. While this level of generalization may be unacceptable to scientists, it provides a starting point where it could be applied and tested in planning, thus potentially yielding new knowledge that could inform science.

The specific topics related to landscape connectivity in planning literature include the studies on open space networks, greenways, and ecological networks.

Some network studies focus only on a single purpose such as quality of life (Shafer et al. 2000), which is often based on the human ecosystem perspective (Bubolz et al. 1980; Force and Machlis, 1997). Others emphasize its multifunctional capacity for nature corridors, cultural and recreational accessibility, alternative transportation route, and useful educational resources (Tan 2006). But specific literature for passive linear recreational activities is not as common (Cook 2000). Networking under-utilized lands along linear elements may not be relevant to the study, but considering implications to increasing connectivity through site restoration is possible. Ecological networks emphasize the network coherence that is based on ecological processes (Opdam et al. 2006).

While fes studies use ecological networks for practical reasons such as identifying a linked reserve system or conservation area prioritization (Weber, 2006), the most significant role played in landscape planning has been the use of ecological networks as a spatial concept (Cook and Lier 1994; Vuilleumier and Prelaz-Droux 2002). However, linking this promising tool to implementation is relatively weak in the United States, which does not require the preparation of landscape plans like countries with a federal land use planning system such as many European countries and Canada. Vasarhelyi and Thomas (2006) argue, particularly focusing on ecological network, that legislation that enables ecological networks and is harmonized across the different jurisdictions involved is needed to promote network creation at large geographic scales (Vasarhelyi and

Thomas 2006). This literature may be relevant as a scientific prerequisite to conceive the next step of this study.

2.3 Landscape Sustainability

2.3.1 Sustainability for Urban Environment

Acknowledged as a powerful but somewhat difficult-to-define concept being addressed in many disciplines, sustainability aims to assure the viability of ecological, social, and economic systems (Munier 2005). However, the term “sustainability” has been primarily applied to a variety of nonurban contexts (Platt et al. 1994). Applying an ecological definition of sustainability to urban communities tends to be viewed as an oxymoron, because urbanization in the traditional view destroys natural phenomena and process, demanding inputs (e.g., food, timber, clean air and water, energy) drawn from elsewhere to replace and augment local resources. Urban sustainability thus may be viewed in two senses. The first concerns the protection and restoration of the remaining biological phenomena and processes within the urban community itself – “the greening of the city.” In the second sense, urban sustainability refers to the impact of cities upon the larger terrestrial, aquatic, and atmospheric resources of the biosphere from which they draw sustenance and upon which they inflict harmful effects.

Many planning efforts have made to reach urban sustainability. While the ecological, economic, and social dimensions of sustainability are equally important in principle (Wu 2007), the ecological dimension has relatively been undervalued in the planning framework, and is not yet well developed to be an effective input in urban planning practice.

2.3.2 Debates on Sustainable Landscapes

With regard to the question whether or not landscape can be sustainable, whole notion of a sustainable landscape development has involved in a contradiction, because landscapes continuously evolve in a more or less chaotic way, demanding social and economic needs (Antrop, 2006). This view represents that landscape may contribute to sustainability, but they are not sustainable in themselves (Potschin and Haines-Young, 2006). Landscapes in which people are dominant certainly mirror social and economic needs and priorities, and as these changes it is likely that these cultural landscapes will also be transformed. Thus, there is a sense in which it is unlikely that landscapes can even sustainable, except where an attempt to adopt an overtly conservationist approach is made.

On the one hand, landscape agenda and new research issues have highlighted that more equal emphasis should be given to the environmental, economic and social pillars of sustainability. Natural capital paradigm reflects the wider shifts in thinking about sustainability, with emphases on biophysical process and human values. The concepts of natural capital and sustainable landscapes fit squarely with the 'ecological' as opposed to the 'semiotic' discourses recognized by Cosgrove (2002) insofar as they deal with landscape in terms of the interactions between nature and society, rather than with landscape in terms of its cultural meanings (Antrop, 2006).

On the other hand, there is a view that landscape sustainability can be achieved when cultural aspects are added to the traditional three pillars of sustainability. With an emphasis on both ecology and culture of landscape sustainability, Musacchio (2009a, b) argues that there are six Es consisting of landscape sustainability, including environment, economy, equity, aesthetics, experience and ethics. This approach may be useful when a landscape research needs to be operationalized for planning and design problems (Musacchio, 2011). However, the purpose of planning for sustainable landscapes will vary according to setting, and will lie somewhere on a continuum from strong protection to creative development and regeneration depending on current landscape condition (Selman, 2006).

2.3.3 Definition of Landscape Sustainability in this Study

With an understanding that sustainability is best understood in an ecological frame of reference, this study reinterprets the definition of landscape sustainability as “a regenerative capacity of landscape to effectively maintain ecological functions invested in nature and society.” As an operational definition in the context of this study, landscape sustainability refers to landscape properties that support not only ecological processes (such as biodiversity) without any outstanding harms but also facilitate other associated environmental and human benefits by conserving natural land attributes as maximum as possible and by minimizing negative effects of urbanization processes. This definition is based on the standpoint that sustainability of landscape can be involved in the maintenance of spatial patterns of land cover types that are ecologically beneficial (Leitão et al. 2006). By implication, therefore, planning in the context of landscape sustainability must not only take account of the outputs of landscape functions, but also the nature of landscape patterns as an issue in its own right.

CHAPTER 3

LITERATURE REVIEWS

3.1 Land Fragmentation

3.1.1 Causes of Fragmentation

Early fragmentation was originated by continent-scale land clearing in around the twentieth century and then brought about by human processes such as agricultural clearing and industrial resource extraction. However, recent fragmentation has been attributed to human settlement itself. The fragmentation effects of urban and suburban sprawl fundamentally differ from that of land clearing, which has more resiliency in habitat restoration.

Some literature views increased human population as a cause of fragmentation, but human-induced sprawl is a more direct cause. The trends in demographic and urbanization are often not linear. In many part of the urbanized or urbanizing regions in the world, the pace of land transformation by the cultural landscapes outgrows the speed of adding people into the cities. For example, in Massachusetts, a 28 percent population increase during the past 50 years has resulted in a 200 percent increase of developed land. This acceleration of land consumption is occurring even in areas experiencing a population decrease. Nevertheless, human population increase has been a fundamental agent for initiating major and minor land alteration.

Evidently, human land use and development are quickly fragmenting and decreasing the amount of available open space suitable for habitat (Ahern, 2006). In many areas with increasing sprawl, fragmentation has turned out to be virtually inevitable. Intensively exploited landscapes often display fragmentation, where patches of semi-natural habitat become progressively diminished and isolated (Selman, 2006). In the next section, the impacts and cost of land fragmentation are discussed.

3.1.2 Cost and Impact of Fragmentation

Fragmentation of the landscape affects habitat size and shape, and distance from other areas of suitable habitat. Organisms dependent on a particular habitat size or distance (or both) from the edge of their habitat are pressured by the increase of "edge" environment that accompanies fragmentation. This, in turn, affects species diversity directly and indirectly, as many biologists argue that habitat fragmentation is the single greatest threat to the biological diversity of native species (Noss, 1991; Mac et al., 1998).

The fragmentation effects include changes in predator-prey relationships, alteration of seed dispersal mechanisms, and nest parasitism. Small, isolated populations in fragmented systems are particularly vulnerable to extirpation through a combination of demographic, environmental, and genetic factors that interact to create a "vortex" of extinction (Gilpin and Soulé, 1986).

Habitat destruction caused by fragmentation affects not only the quantity of species, but also the quality of those species that survive. Generalists or edge species, which are able to survive in a variety of habitats, are less likely to suffer from habitat loss and fragmentation than specialist species, which require unique pockets of habitat. Likewise, all species have a minimum area point – how large a given habitat area must be for a viable population to survive. Different species groups will have different minimum area requirements and thus will be affected differently by habitat fragmentation and loss (Forman, 1995).

More important, fragmentation isolates once-contiguous landscapes, thereby impeding movement between previously intermixing plant and animal populations. In such case, it may be difficult for species to migrate to locations more suited to their ‘range’ or encounter some ‘elbow room’ in which to perform local coping strategies (Selman, 2006). In addition to biotic elements, fragmentation also affects abiotic factors, such as hydrologic regimes, mineral nutrient cycles, radiation balance, wind patterns, disturbance regions, and soil movement.

Efforts to mitigate fragmentation effects require a remarkable amount of financial investment, time, and human resources. Many wildlife corridors or linkage plans are difficult to implement due to such problems. In this regard, potential effects and prohibitive costs of actually connecting fragmented landscapes is unparallel to any benefits gained by means of land fragmentation.

3.2 Urban Biodiversity

3.2.1 Changing Definitions of Biodiversity

A wide range of definitions of biodiversity have been articulated in the literature. The differences among the definitions emphasize the complexity of the issue. Keystone Center (1991) describes biodiversity broadly as “the variety of life and its processes.” Biologist B. A. Wilcox (1985) calls it “the variety of life forms, the ecological roles they perform, and the genetic diversity they contain.” These simple definitions recognize that both the quantity of species and the ecological processes that affect those species are important. Noss and Cooperrider (1994) extend the previous definitions to understand more complex processes in nature, referring to biodiversity as “the variety of living organisms, the genetic differences among them, the communities and ecosystems in which they occur, and the ecological and evolutionary processes that keep them functioning, yet ever changing and adapting.” Subsequent definitions adopted by national or international organizations (U.S. National Biological Information Infrastructure, World Conservation Union, UNEP: Global Biodiversity Strategy), all have three components in common: species, genetic, and ecosystem. With consideration of a certain kind of scale, Sheila Peck (1998) defines biodiversity at biological organization scales, including landscape, community, population, and genetic: whereas Robert Whittaker (1975) categorizes it depending on the spatial scale: alpha diversity (species in a small, well-defined area), beta diversity (diversity of species between habitats, such as along a gradient), and gamma diversity (the number of species over landscapes or vast geographic areas).

Recently, temporal and evolutionary scales have been added to the biodiversity definition to understand and appreciate the precious heritage of biodiversity. Jack Ahern et al. (2006) extracted several important principles out of the existing definitions of biodiversity: (1) biodiversity exists and needs to be understood at multiple scales; (2) biodiversity is inseparable from its physical environment; and (3) biodiversity is integral with ecological processes. Ahern et al. integrated these principles into their own definition of biodiversity: “biodiversity is the totality, over time, of genes, species, and ecosystems in an ecosystem or region, including the ecosystem structure and function that supports and sustains life” (Ahern et al. 2006).

3.2.2 Sprawl and Urban Biodiversity

Generally, biodiversity tends to decline with increasing urbanization. The centers of metropolitan cities will have fewer species than less-developed areas on the urban-suburban-rural-natural gradient. Species diversity may actually be greater, however, in highly developed suburban areas than in less-disturbed environments. According to the intermediate disturbance hypothesis (Connell 1978), species richness or diversity will be greater in moderately disturbed environments than in either heavily disturbed areas (such as city centers) or lightly disturbed habitats (such as intake forestland outside the city limits). Thus it is not urbanization per se that causes an increase in biodiversity, but the moderate increase in disturbance that creates wider array of vegetative cover types. In this case, the increase in biodiversity often comes about because more habitat generalist species occupy the area (Johnson and Clemens, 2005). Some synanthropic species benefit from sprawl. On the contrary, species that specialize in interior habitats are usually very sensitive to fragmentation and thus decline or are extirpated. Research on several taxa support the intermediate disturbance theory as it relates to suburban development, but the type and level of development is critical (Johnson and Clemens, 2005).

Patterns of development associated with sprawl relate directly to habitat loss and fragmentation, with a concomitant reduction in biodiversity. In addition, sprawl plays a significant role in amplifying other threats to biodiversity, such as invasive species, pollution, overexploitation, and global climate change (Wilcove et al. 1998). Nevertheless, various types of natural features in cities still can contribute to biodiversity. Parks, golf courses, greenways, and other open spaces create habitat for some species. Almost any assemblage of vegetation can provide shelter, nest sites, and food in the midst of towns and cities. Lawns can provide food and resting sites for geese and prey in the form of earthworms and other invertebrates. Increased availability of water and food (for animals) and nutrients (for plants) are among the chief factors that draw some species to urban and suburban environments. Vacant lots, although usually unintended by city or town planners, are another form of open space. Mortberg (2000) supports this by showing that the presence of red-listed forest birds is still possible in urban environments with such green space features and properties.

3.2.3 Regional Biodiversity Planning and Design

Although every scale of biodiversity efforts is important, conserving regional biodiversity is a critical and at the same time challenging task because it requires an enormous volume of information on the mechanisms behind regional ecology and human geography. However, if habitat loss is the leading cause of biodiversity decline as noted earlier, it follows that planning and design will be essential in any viable solution by directly conserving, protecting, or managing landscapes and habitats. As the significance of regional biodiversity and associated land use is widely perceived, novel efforts for integrating ecological information with planning and design processes began to emerge. A considerable body of literature about planning and applied design research has the same goal of regional biodiversity, but the terminology often varies depending on planning intention. For example, "ecological network" focuses on ecological core areas surrounded by buffer areas, and corridors connecting the core areas (Forman, 2001). The conceptual model was originally developed by Man and Biosphere program (MAB) and thereafter widely used with adjustment. Although ecological networks highlight diversity conservation, other landscape functions are facilitated in the network.

Most European countries have adopted this concept as a national land conservation strategy and have used it as a spatial concept for multi-actor planning (Opdam et al., 2005). For this reason, the implementation of ecological network design is viably supported within the landscape planning framework (Vuilleumier and Prelaz-Droux, 2002). In the context of North America, it is difficult to plan ecological networks due partially to the lack of legitimate planning and political support. Vásá rhelyi and Thomas (2006) evaluated the capacity of Canadian and American legislation to implement terrestrial protected areas networks and concluded that neither American federal law nor New York State law showed any capacity to enable development of a protected area network. In contrast, the authors found, Canada has some provisions such as the Canada National Parks Act and the Species at Risk Act, where coarse- or fine-scale ecological criteria are incorporated into network conservation. Such a large-scale network creation becomes especially difficult in urban landscapes that encompass partitioned jurisdictions. As Cook (2002) suggests, however, planning an ecological network is a viable and necessary approach to respond to fragmentation and deterioration of quality of natural systems.

Similarly, "green infrastructure" is used with an emphasis on a system of natural areas as a backbone of landscape. Based on the literature, the notion of green infrastructure is more frequently used in the United States, while the ecological network concept is more popular in Europe. The important examples of planning and designing of green infrastructure originated in Maryland (Weber et al. 2006) and Florida (Hoctor et al. 2000); while in Boston a green infrastructure project is underway. Regional biodiversity is often addressed as a means of justifying green infrastructure development. At times green intervention and engineering efforts are combined with green infrastructure practice. As a more human side term, “greenways” is a concept for networking linear landscape elements for the purpose as either “trails (Shafer et al. 2000) ” or “wildlife corridors (Tan, 2004)”. Even though greenway planning can convey multiple functions, including biodiversity conservation, it tends to be perceived as relating to quality of life and transferred over to recreation purposes.

While having much potential, the aforementioned diversity planning concepts have are challenged when they are put in practice in real landscapes, because ecologically important areas often traverse lands desirable to and thus highly valued by humans. Similarly, conserving connectivity in urban systems entails political and social trade-offs, because protecting connectivity through developed landscapes necessarily compels humans to alter land-use patterns.

In addition, whether or not such planning and design interventions resulted in success from multiple perspectives is not clear in contemporary literature. For example, there is a certain level of criticism about wildlife corridors and whether they are actually used by species and provide enough security or resources. Beier and Noss (1998) confirmed these issues to some degree in a review of 17 empirical studies, but also counteracted some of this skepticism through their research verifying corridor functionality (Beier and Noss, 1998).

Nonetheless, much literature has supported that the planning and design endeavors contribute to not only understanding complex landscapes in theory, but also increasing public awareness of biodiversity's value to humans in practice. There are obvious propositions in landscape architecture that biodiversity planning, regardless of specific terms, is in demand in urban, suburban, and rural areas, as non-degraded habitat becomes increasingly scarce: thus, biodiversity goals become an explicit part of a project's goal or design process (Ahern et al. 2006).

3.3 Landscape Connectivity

3.3.1 Multiple Perspectives of Landscape Connectivity

The Webster dictionary (Webster online, 2010) defines connectivity as the quality, state, or capability of being connective or connected; while continuity refers to uninterrupted connection, succession, union or uninterrupted duration of continuation, especially without essential change. When applying either of these terms to landscape, what to connect, why to connect, and which way to connect become key questions. Forman (1995) describes landscape connectivity as a degree of spatial connectedness among landscape elements such as patches, corridors, and matrix (Forman, 1995). Patch connectivity focuses on amount and arrangement of habitat patches, and thus Euclidean or effective distance between the patches becomes an important issue (Broquet et al. 2006). Corridor connectivity identifies linear features to promote dispersal through connectivity restoration (Beier et al. 2005; Davies &Pullin 2007; Graves et al. 2007). Matrix connectivity evaluates overall landscape mosaic, including landscape matrix to maintain maximum landscape continuity of non-built areas (Levin et al. 2007). This study takes the matrix connectivity approach with an understanding that overall landscape mosaic is important, not just binary landscape (Andersson, 2006).

Another definition widely accepted in ecological science is describing it as the degree to which landscapes enhance or impede animal or plant movement and spatially sensitive ecological processes (Taylor et al. 1993; Tischendorf and Fahring 2000; Moilanen and Hanski 2001). According to Fry et al. (2007), connectivity relates to the functional linkages in a landscape and differs from connctedness, which refers to the physical connection between landscape elements. Connectivity is much more than being physically connected and may include the resistance to movement caused by barriers or by land use types.

Some researchers maintain that the quality and effect of the landscape matrix is critical to conserve connectivity (Joly et al. 2003; Stevens et al. 2004; Umetsu and Pardini 2007). In contrast, Levin et al. (2007) do not discern these spatial structures. Instead, they evaluate the overall landscape mosaic to maintain maximum landscape continuity of non-built areas (Levin et al. 2007).

To a lesser extent, landscape connectivity is related to population dynamics in examining behavioral properties (e.g., movement direction, (Belisle 2005; Baguette & Van Dyck 2007) and the colonization process by which a set of populations are Interconnected into a metapopulation (van Langevelde 2000; Wimberly 2006). All these body of research are often applied to landscape biodiversity (Estrada-Peña, 2002) in general, and habitat network of a single or multiple species (Bani et al. 2002), or reserve design and planning (Carlos et al. 2003; Rothley & Rae 2005; Bodin & Norberg 2007) in particular.

Generally, high connectivity and a well-designed network is assumed to better facilitate flows of energy, materials, and species, and so are important for conservation in developing landscapes (Sanjayan and Crooks, 2005). However, high connectivity may also facilitate disease or undesired species. However the relationship between landscape connectivity and its negative feedback is not well documented. Additionally, scale concerns tend to be ignored, although connectivity is dependent upon the scale of observation and ecological process (Wu et al. 2006). For example, Bunn et al. (2000) found that the same landscape in the Coastal Plain of North Carolina is connected for mink but unconnected for warblers (Bunn et al. 2000).

3.3.2 Structural Connectivity versus Functional Connectivity

Since the concept was formalized in landscape ecology about three decades ago (Taylor et al. 1993), the meaning of the term “landscape connectivity” has become rather diffuse and ambiguous. The generally used definition of landscape connectivity emphasizes not only spatial properties of the landscape (structural connectivity), but also ecological processes and organisms' mobility (functional connectivity). Nevertheless, it seems true that current connectivity literature has clearly divergent approaches on this subject. While structural connectivity measures how connected or spatially continuous landscape elements are, functional or behavioral connectivity refers to how connected an area is for an ecological process, such as dispersal of plants and animals, and energy and nutrient flows.

In the planning field, the structural connectivity, albeit not overtly used as a planning term per se, has often been applied as a baseline spatial strategy with regard to open space planning in cites (Erickson, 2006; Parker, 2008), since it can be readily visualized and thus possibly implemented within a short-term planning period. Conversely, exploring functional connectivity is fairly underestimated despite its acknowledged importance, partly due to the challenges in making it operational in planning process. Consequently, certain areas are assumed functional (e.g., species persistence or movement) but actually are not, which may result in "unrealistic or impractical" circumstances (e.g., unlikely pathways). For example, "ecological network" (Cook and Lier, 1994; Cook, 2000; Cook, 2002; Vuilleumier and Prelaz-Droux, 2002; Opdam et al. 2006) theoretically provides a spatially explicit landscape framework on which ecological function can be well performed.

However, it tends to focus more on how landscape structure is spatially organized simply by mapping them out, rather than delving into what is, and would be, going on in the real landscape. A challenge to implementation is an insufficient understanding of ecological knowledge in planning applications: thus, ecological effects of networks are rather implicit. This may be overcome by linking scientific properties of ‘functional connectivity’ to planning concepts to create sustainable landscapes.

This study attempted to combine structural and functional connectivity into landscape connectivity analysis by incorporating habitat specificity of indicator species, such as habitat types and habitat range. However, this study has its limitations to be an application of functional connectivity, due to the lack of empirical knowledge on dispersal distances for the indicator species.

3.3.3 Benefits and Disadvantages

The most important advantage of landscape ecological connectivity lies in its capacity to enhance biodiversity and facilitate animal movement. Although there are few studies directly dealing with explicit cause-effect relation between landscape connectivity and ecological and environmental benefits, virtually all research in landscape ecology assume that connectivity is the most essential gain.

There is also a new view of not constraining the benefits of connectivity within biological diversity but extending them to the human dimension. For example, Fry et al. (2007) suggest that landscape connectivity is an important determinant of the ways in which animals or humans alike can navigate and move around in the landscape. In that case, connectivity will have significance for resource availability and the frequency of cultural interaction, and also affects visual aspects by indicating accessibility (Fry et al. 2003). Thus, landscape connectivity can result in great gains in recreational, cultural and aesthetic aspects, in addition to biophysical benefits.

On the other hand, there are negative consequences as well due to the physical connectedness of natural landscapes. One of them is that landscape may be a passage for ecological disturbance such as disease or fire. Corridors facilitate unintended transmission of disease, weedy species, ecological disturbances, or genetic material (Sanjayan and Crooks, 2005). Species composition can be affected by connected landscapes, often introducing more exotic invasive species outcompeting native species, which in turn can lead to disruption of populations and communities, ecosystem structure and function (Vitousek, 1988) and potentially to a monoculture.

3.3.4 Trends in Landscape Connectivity Research and Application

Wildlife corridors and linkages are connectivity design products. As a region-wide effort, Southern California has planned, designed, and implemented large-scale corridor and habitat linkages at the regional level across the urbanizing landscape of California. Florida (Hoctor et al. 2000) adopted a regional landscape approach to help guide the design of the Florida reserve network identifying ecological priority and landscape linkages necessary for functional connectivity. Their models incorporated land-use data on important ecological areas in the states. The corridor or linkage studies pay particular attention to linear features to promote dispersal through connectivity restoration (Beier et al. 2005; Davies and Pullin 2007; Graves et al. 2007), while patch connectivity studies accentuate habitat arrangement and Euclidean or effective distance depending on species (Broquet et al. 2006).

In Europe, ideas and methodologies of landscape connectivity are often translated and dissolved into ecological network concepts. The ecological network has substantial strengths in the sense that it is very feasible and viable in planning practice and that it provides a framework in which more adaptive management strategies can be developed (Opdam et al, 2006).

Unlike the way of applying landscape connectivity in the planning area (e.g., multiple species approach, landscape-based spatial cohesion, etc.), the connectivity application in the ecology field often turns up for conservation biological objectives, such as reserve network selection (Kati et al. 2004), habitat network only for a particular species (Graves et al. 2007), corridor and linkages for multiple species (Beier, 2005; Hepcan et al. 2010; Hepcan and Ozkan, 2010; Davies and Pullin, 2007), most of which are targeted to natural areas. One of the components distinguishing such divergence is the consideration of landscape matrix. More recently, there is an important shift in landscape connectivity research to understand landscape connectivity as a bridging concept to urban morphology and environmental goods and benefits. Bierwagen (2007) investigated the relationship between urban models and landscape connectivity and concluded that smart-growth types of compact cities are more desirable for connectivity conservation than low-density urban and suburban sprawl. Similarly, Park et al. (manuscript in progress) attempts to compare two different metropolitan landscapes, one in Izmir, Turkey and the other in Phoenix, Arizona, U.S.A. to unveil the relationship between urban ecosystem structure and landscape connectivity as a predictor for biodiversity and urban sustainability.

Figure 3.1 illustrates that contemporary literature on landscape connectivity research has strongly concentrated on natural landscapes at local level. This study attempts to complement the landscape connectivity studies for an urban region at landscape scale, adding another case to the first quadrant of the chart below.

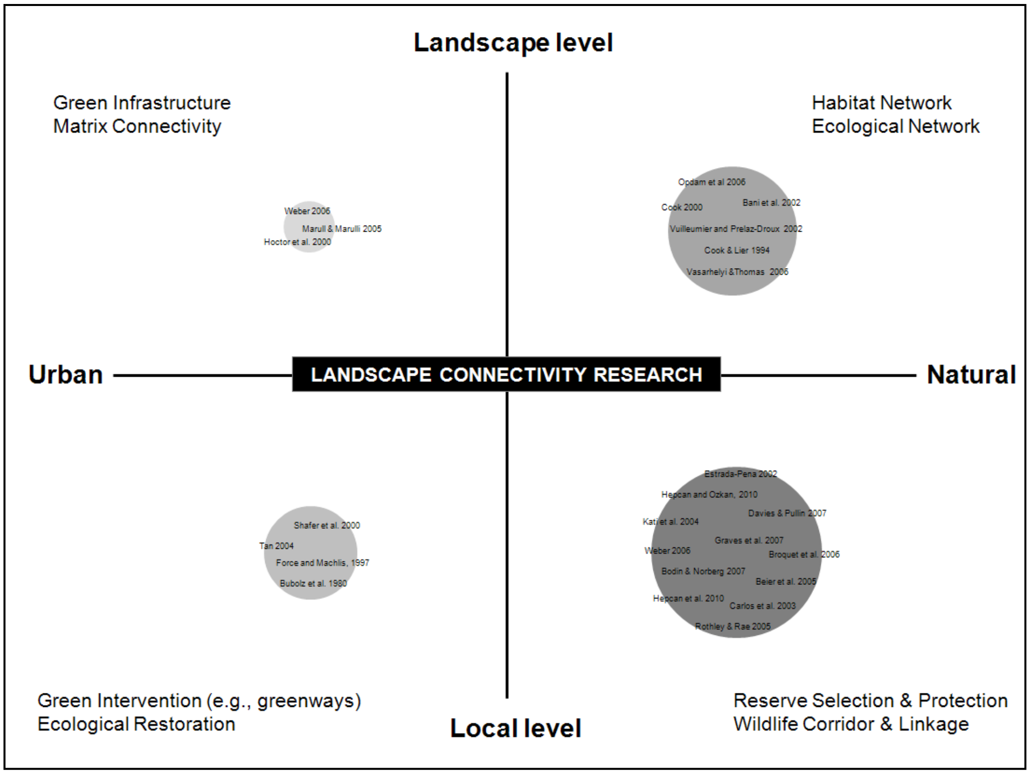


Figure 3.1 Concentrated areas of landscape connectivity research

3.3.5 Landscape Connectivity Quantification Approach

Numerous methods and approaches have been developed from general landscape ecological principles to measure landscape connectivity. Although there are a wide range of proposed connectivity measures and geometric analyses from very simple to highly sophisticated (Selman, 2006), categorizing the methodological approaches into four groups is possible: 1) connectivity metrics; 2) least-cost analysis; 3) empirical ecological models; and 4) graph-based approach. Below is a brief description of each method.

The connectivity metrics method is, in many cases, spatial data-driven analysis. While some research capitalizes on existing landscape pattern metrics, such as the ones in FRAGSTATS, new landscape metrics have been developed. A couple of specific metrics in FRAGSTATS calculate the connectivity, such as connectance (CONNECT), contagion (CONTAG), and contiguity (CONTIG) as direct measures. Other composition and configuration metrics are also indirectly associated with connectivity values (for details, see Schumaker (1996) and Pacific Northwest Research Station (1995)). With the technical advancements, such measures have been widely utilized in the landscape ecology literature. Some authors argue that simple measures are inferior in predicting ecological process to complex measures (Atte and Marko, 2002), and develop new metrics with performance tests for identifying the effectiveness of the metrics.

The use of least-cost analysis has been growing in recent landscape and ecological connectivity studies because it calculates `effective distance', a measure for distance modified with the cost (landscape resistance). This method is used as a flexible tool to model functional connectivity and a straightforward way to include landscape and behavioral aspects (Adriaensen et al. 2003). Unlike landscape metrics that often are calculated at distinct analysis levels such as an individual patch, class (the same kind of patch), and entire landscapes, least-cost modeling assesses a series of values on the overall landscape. The application of least-cost methods is shown in urban research (Marull and Marulli, 2005) as well as ecological studies as a useful tool to quantify the connectivity values of each cell location across the landscape matrix.

Ecological models developed by scientists provide an exclusive analysis platform for calculating functional ecological connectivity (e.g., PATCH, FUNCONN). Many of the empirical models are based on spatially explicit population or meta- population information and are associated with complex patch delineation processes. Population viability and persistence are the key aims of the connectivity (Carlos et al. 2003). There are critical issues of setting thresholds as a function of the level of fragmentation, which influences the ultimate connectivity values. The neutral landscape model (Gardner et al. 1987) motivated by the classic percolation theory, provided the earlier discussion on the threshold effects in connectivity.

Lastly, graph-theoretical approach is another emerging method to measure landscape connectivity. Graph theory was originally developed in geography and computer science but has been applied to landscape ecological issues. Compared to normal typical data structures of vector and raster, the graph represents the landscape, consisting of a set of nodes connected to some degree by edges that join pairs of nodes functionally (Urban and Keitt 2001). Up until now, its usage has been increasing in the connectivity literature with several foci, including simple graph construct development such as minimum spanning tree (see Dean and Timothy, 2001, p.1206-1207), optimal path selection among habitats at various scales (Fall et al. 2007), and decision support for conservation priority (Jordán, Báldi et al. 2003; 2007; Saura and Pascual-Hortal 2007). In addition to the studies using graphs as a visual representation of connectivity, there are modified applications of the graph method such as geographically referenced graphs (Fall et al., 2007) and graph-based landscape indices (Saura and Pascual-Hortal, 2006; 2007; 2008).

In sum, a large variety of methods have been proposed to effectively quantify landscape connectivity as a vital element of landscape structure (Taylor et al. 1993). In theory, the different approaches can be organized in four types as described above, or two or more combined approaches are used in practice. For example, Ferrari et al. (2007) adopts the graph theory metrics along with the percolation theory, and Bunn et al. (2000) use a mixture of different landscape indices for their case areas.

In the aspect of planning application, the simple metrics seem to be practical in that they allow relatively quick assessment for the demand of immediate solutions in planning process, while the least-cost modeling methods may be particularly useful for scenario-based connectivity analysis because of its predictable capability. The classic ecological models and landscape graphs heavily focus on ecological flow (such as dispersal) and its application has been limited to a small number of conservation scenarios. Calabrese and Fagan (2004) compared the existing connectivity quantification methods using the criteria of data-dependency, spatial scales, and outputs. The authors suggested that empirical modeling has a greater data requirement, whereas graph structures are relatively effective in relation to input data required. In relation to the problem of which method the most useful is, however, no consensus has been arrived at yet.

CHAPTER 4

RESEARCH METHODS

This chapter describes the methods used for county and metropolitan scales and provides the reasons why certain methods were considered for scales.

Fundamentally, both county- and metropolitan-level studies are based on quantitative methods in dealing with landscape pattern and process. The major difference is that the former enumerates a suite of landscape metrics describing ecosystem pattern change in response to future urbanization, while the latter is used to generate GIS-based landscape ecological connectivity modeling which ultimately generates a series of connectivity maps as research outcomes. Even if both methods can be switched over to apply the reverse purposes of each study, the landscape metrics quantification is more useful to the higher spatial levels of understanding the overall landscape pattern. Conversely, the modeling approach gives more specific information on a cell-by-cell basis, and thus is more appropriate for understanding spatially explicit urban impacts.

Another difference is that the county-scale study is dependent on the physical arrangement of natural lands, while the metropolitan-scale study takes the multiple indicator species approach. The main reason that the species approach was not considered in the county-level is because it may not sensitively disclose the ecologically important areas especially in urbanized parts of the region. Additionally, the research inquires of the county-scale study are not directly relevant to species-habitat relations, even if such an approach would be meaningful if the study objectives are related to more species-driven questions or regional biodiversity.

Third, both studies attempt to couple landscape ecological pattern and process with urban dimensions. In doing so, the county-scale study takes a vertical approach, using urbanization scenarios that anticipate the temporal changes caused by a realistic implementation of different magnitudes of proposed urban plans. On the other hand, the metropolitan-scale study examines horizontal variation in association with landscape ecological connectivity and urban development. To address the horizontal variation, the study used landscape gradient analysis. There are a variety of ways to do the gradient analysis. For example, Forman and Godron (1986) categorized the landscapes gradient into natural-managed-cultivated-suburban-urban, depending on the degrees of human modification. Based on the same concept, this study focused more on urban modifications taking place across the urban landscape, and developed a whole process to make the contextual concepts of urban, suburban, and rural areas more spatially explicit. The boundaries of each area served as a spatial framework compatible to landscape ecological connectivity assessment. The landscape modification gradient approach is especially useful when facilitating the integration between nature and culture and uniting people with place in that it reflects the increasing human influences on the structure and function of landscape (Wu, 2010; Forman and Godron, 1986). To be consistent to the spatial scales, the county-scale study examined the general magnitude of urban development, while the metropolitan-scale study delved into population densities and urban land cover proportions to tie the ecological information to urban dimensions.

The two-tiered approach provides appropriate methodologies for each research design. The results from the county-level study can be incorporated into the metropolitan-level study to understand the approximate landscape alteration in temporal and spatial scales and horizontal and vertical scales caused by the urban plans proposed by local municipalities.

Both approaches present a variation in addressing landscape pattern and urban dimensions. Therefore, it would be possible to apply part of or the entire methodological process to other metropolitan areas or urban regions experiencing rapid urbanization. However, it should be noted that Maricopa County is comparatively larger than other counties in the United States, being equivalent to almost two or three counties, so that the methodologies and approaches should be carefully selected for application in other areas. In addition, the methodologies in this study is fairly data-driven, therefore, it is very important to suit the most appropriate level of scale to the scales of analysis and data to avoid tremendous amount of data processing time.

Table 4.1 summarizes key approaches in research methods addressed in the two studies. The full description related to the approaches is discussed in detail in the methodology sections in chapter 5 and chapter 6.

Table 4.1 Principal methodological approaches used in county- and metropolitan-scale studies

Category	County-scale study	Metropolitan-scale study
Spatial scale	Relatively high	Relatively low
Key quantitative method	Landscape metrics	GIS-based landscape connectivity modeling
Study outputs	Numeric/ aspatial	Spatially explicit connectivity maps
Data properties	Natural land-based	Multiple indicator species approach
Framework for urban component analysis	Urbanization scenarios (Temporal variance)	Urban modification gradient (Spatial variance)
Urban components	Magnitude and certainty of proposed urban plans	Human population and urbanized land cover ratio

CHAPTER 5

COUNTY-LEVEL ANALYSIS

5.1 Issues and Problems

5.1.1 Urban and Suburban Sprawl

Ecosystems in urban regions can significantly and instantaneously be influenced by urbanization, altering their pattern and function in the landscape mosaic. As the second fastest growing region in North America (U.S. Census Bureau, 2009), Greater Phoenix has undergone an enormous amount of urbanization over the past years. In particular, continuous and accelerating urban and suburban developments have concentrated in Maricopa County, which was ranked top in the gain of population between 2007 and 2008 (U.S. Census Bureau, 2009).

These circumstances, inevitably, have led to a dynamic change in landscape composition and configuration, resulting in ecological processes changing at various spatiotemporal scales (Wu et al. 2011a; Wu et al. 2011b). As shown in a series of maps below (Figure 5.1), the land use pattern over the last century in Maricopa County illustrates a gradual shift from open deserts to agriculture during the early 1900s and then a remarkable conversion of deserts and agricultural lands into urban areas since 1970s. While the spatial pattern of initial urbanization appeared in a spatially intensified form centered on the core of Phoenix, a tendency of spatial leaping and remoteness from urban centers is conspicuous in the latter period. More recently, there is a tendency to conurbation between the detached cities, which began to fill up the holes of undeveloped remnant natural patches at a faster pace. According to the Greater Phoenix Regional Atlas (2003), future population could increase up to approximately 30 million by 2050 requiring 10,467 square miles of urban lands to accommodate these populations. Nevertheless, all urban development plans proposed and conceived from municipalities will not provide sufficient urban areas even to the lowest level of population growth projection (Redman, 2003). In the short run, more than two million additional people will likely inhabit this area in the next two decades (Maricopa Association of Governments, 2007).

Certainly, all these figures signify that additional natural lands would be replaced by a varied multitude of urbanization processes, and significant ecological consequences might be drawn by cutting off the function-supporting areas. In contrast to the frequent reviews on future socio-economic projection, however, nearly no efforts have been made to anticipate the future status of natural landscape patterns at the county scale.

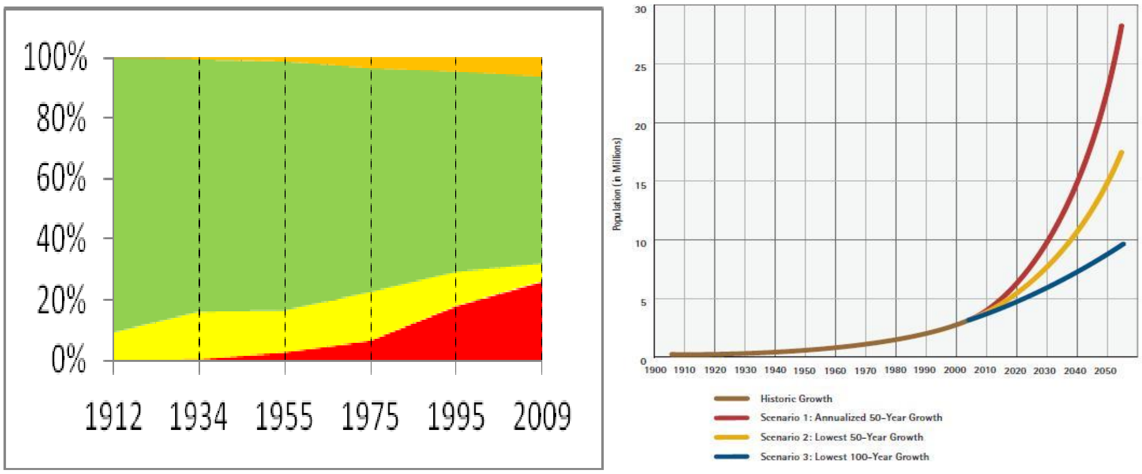
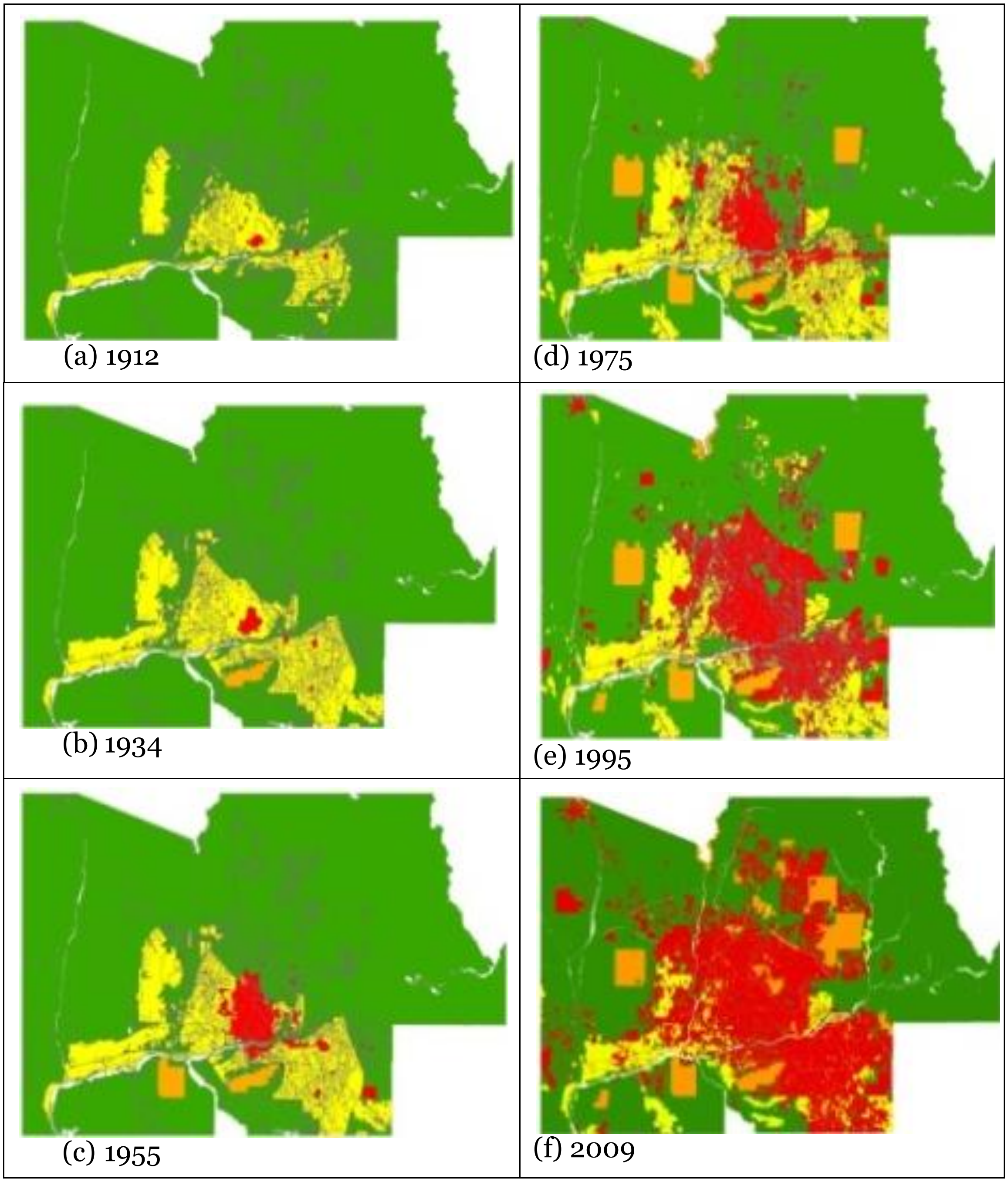


Figure 5.1 Historical land use change (left) and population growth projection (right) of Maricopa County, Arizona
Source: GIS data obtained from ISSI (left) and Greater Phoenix Regional Atlas, 2005 (right)



(a) 1912

(d) 1975

(b) 1934

(e) 1995

(c) 1955

(f) 2009

Figure 5.2 Urban expansions from 1912 to 2009 in Maricopa County
Note: Red-urban; Orange-recreation; Yellow-agriculture; Green-desert (Data source: Maricopa Association of Governments)

5.1.2 Urban Ecosystems Loss and Fragmentation

Urban ecosystems have distinct characteristics in terms of both pattern and process. As complex, dynamic biological-physical-social entities in which spatial heterogeneity and spatially localized feedbacks play a large role (Pickett et al. 2008), urban ecosystems provide multifunctional services that are critical to wildlife communities and human well-being (Andersson, 2006). For instance, well-functioning ecosystems regulate the environment (e.g., noise reduction, modulation of temperature, removal of air pollution, protection of water quality), supply resources (e.g., food, water, fuel), support ecological processes (e.g., increased biodiversity, habitat, soil formation, ecological memory, seed dispersal, pollination, and storage and cycling of nutrients) and even gratify people (e.g., recreation, enhancement of property value, community cohesion). Particularly, in regions under heavy urban development pressure like Maricopa County, the inherent existence of ecosystems can serve as a shock absorber by buffering urbanization influences or obstructing urban development paths.

Since ecosystem services are determined by ecosystem structures and processes (Andersson, 2006), it is an important first step to recognize changing patterns of ecosystems and maintain alternative ecosystem functions the change would deliver. Of various measures to understand ecosystem pattern change, habitat loss and fragmentation are the most useful. As a main driver of ecosystem loss and fragmentation, urban development is essentially interleaved into, and thus modifies, the existing landscape structure. The new insertion of heterogeneous urban patches can also make a drastic change in spatial arrangement by creating more contrasting edges between nature and urban areas. Consequently, the predominance of anthropogenic disturbances such as human settlement and other urban activities results in a partial loss of habitat and longer distances between ecosystem patches. In this sense, habitat loss and fragmentation need to be addressed as key components of ecosystem pattern change due to urbanization.

Based on author's quick assessment, desert shrubs and agricultural lands which have been vital ecosystems in Maricopa County demonstrate a decaying pattern in structural connectivity during the same time frame. Figure 5.3 illustrates that the degree of connectivity for both desert shrubs and agricultural lands is almost exactly in inverse proportion to the percent urban land cover through time and more abruptly decreases in relative to the total amount of ecosystems does. Given the fact that the lands to be converted to urban use are expected to increase in the future landscape, more careful consideration is needed regarding the spatial distribution of ecosystems contingent upon future urbanization activities in order to reduce the likelihood of the removal of ecologically important areas and destruction of ecosystem functions.

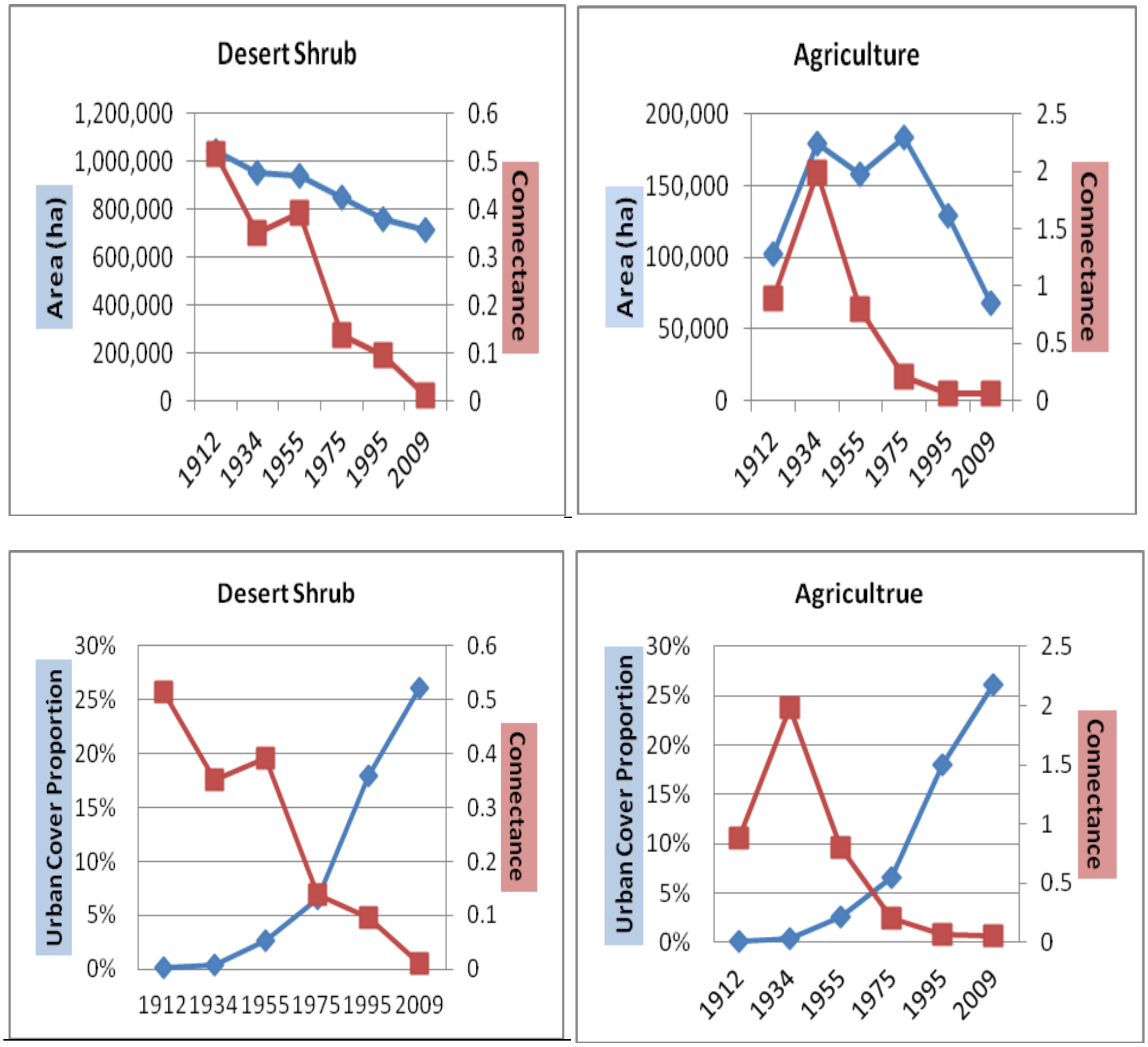


Figure 5.3 Structural connectivity changes of desert shrubs and agricultural lands relative to total ecosystem amount (top) and urban cover proportion (bottom)

5.1.3 Regional Open Space Planning

Landscape planning traditionally has involved the designation and protection of exceptional countryside. However, while this still remains important, there is a growing recognition of the multifunctionality of rural areas, and the need to encourage sustainable use of whole territories rather than just their hotspots (Selman 2006). There are many practical ways to deal with connectivity in landscape planning. In most European countries, the notion of connectivity has been understood in the context of ecological networks for the whole landscape of interest. Conversely, landscape connectivity efforts in North America have primarily focused on conserving or restoring ecological corridors or wildlife linkages between isolated wildland blocks. The former stresses landscape-driven processes, at times including cultural aspects of connected landscapes. In contrast, the latter relies heavily on animal movement and habitat security attempting to delineate actual habitat areas to be used by an individual, or a group of, species. Although both approaches may be equally important to their own conservation objectives, there is an important distinction with regard to landscape planning. In many cases, the European connectivity approach is supported within the legal planning framework and so has more room to integrate with planning sectors.

On the other hand, the United States does not have legitimate devices for, and seldom develops, landscape planning or regional open space planning, though there are some exceptions at an individual state level. The lack of landscape planning systems often hampers the ability to use large-scale connectivity as a spatial strategy in urban regions. Although some municipalities have their own open space plans as a part of a general plan, the inconsistency between cities and extensive unincorporated areas with no formal plans can be problematic to landscape connectivity. Therefore, to ensure regional-scale open space connectivity conservation, it is necessary either to have a self-regulating planning apparatus or to incorporate the connectivity concept into existing urban planning system.

In Maricopa County, some discrete efforts pertaining to regional open space have been made. For example, the County's Comprehensive Plan places important natural lands in three different open space categories: Dedicated; Proposed; and Potential Open Space. Dedicated Open Space areas are mostly in public ownership and correspond to unique environmental and physical qualities, including mountains and foothills, rivers and washes, canals, significant desert vegetation, wildlife habitat, and cultural resources.

Nearly 2,000 square miles of dedicated open space exists in the region in the form of regional parks, wilderness areas, wildlife areas and the Tonto National Forest. Proposed Open Space is mostly located in the unincorporated areas of the County, including significant mountainous areas, major rivers and washes, upland Sonoran Desert vegetation, canals, trails, and archeological sites, which either serve as unique open space or complement the services of Dedicated Open Space areas. More than half (55 %) of the areas are in public domain and 90 square mile (15%) belongs to state trust land and the remaining 30 percent is in private sectors for the 100-year floodplain or slopes over 15 percent (Source: Maricopa County, 2020).

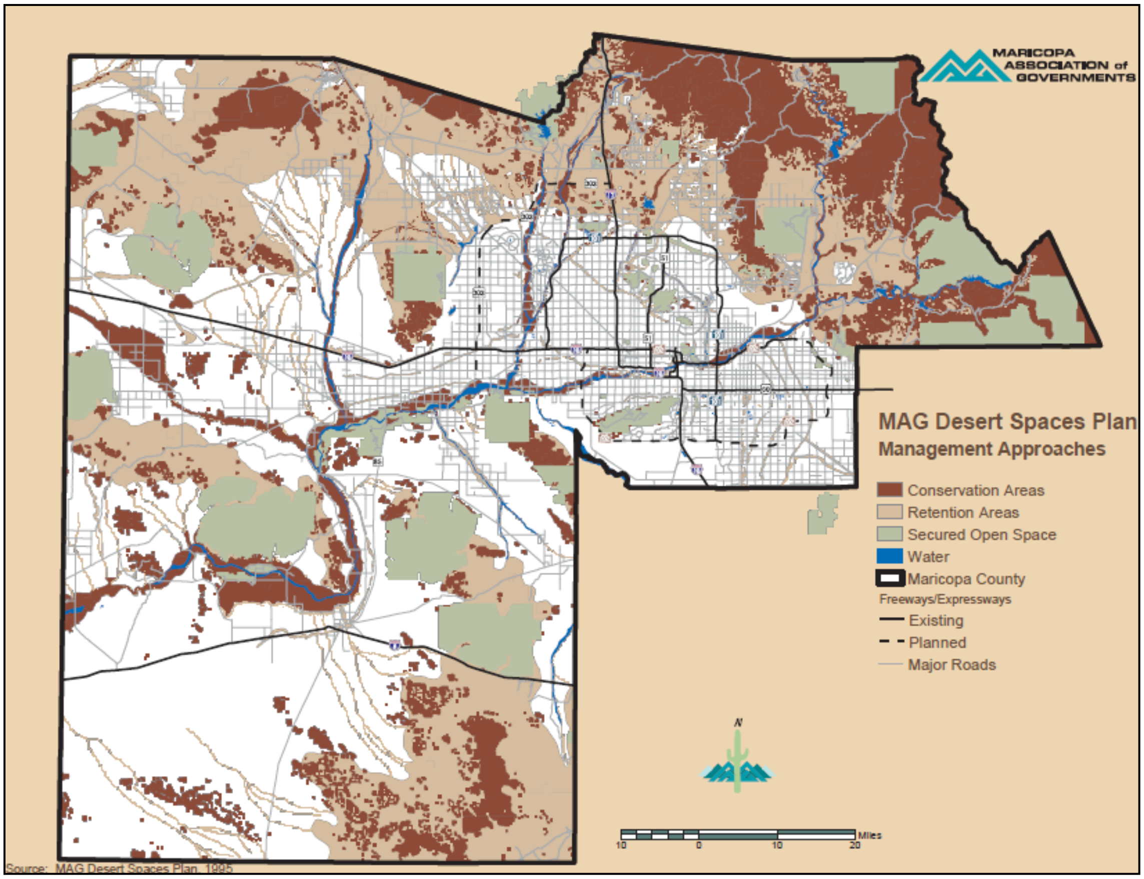
Table 5.1 Dedicated Open Space areas on Maricopa Comprehensive Plan 2020 (tabulated based on the text of the plan report)

Category	Size (acres)	Primary location	Management Agency
Regional Parks	115,200	Throughout the County	
Wilderness Areas	320,000	Rural Development Area and approximately 235 mi^2 of Tonto National Forest	BLM
Wildlife Areas	1,881	3 locations: Robbin's Butte; Base and Meridian; Three Bar	US Fish & Wildlife Service
Tonto National Forest	640,000	Northeastern corner of the County	US Department of Agriculture, Forest Service

In 1995, an official regional open space plan, called "Desert Spaces" was developed by the Maricopa Association of Governments. The Desert Spaces Plan has three management approaches, identifying Conservation Areas, Retention Areas, and Secured Open Spaces. While Conservation Areas include forest and mountain areas and Sonoran Uplands with higher slope, Secured Open Spaces only encompass regional park boundaries in this region. The Retention Areas (later renamed Environmentally Sensitive Areas) are relatively less developed lands due to present landscape values but also allow careful urban development.

More recently, an initiative on and interconnecting trail system is under way to link protected natural open spaces throughout the Phoenix metropolitan region. It is particularly inspiring in the sense that it will increase the accessibility to nature by building linear green pathways in human-dominant areas and that various stakeholders are getting involved in the participatory process. Despite these promising efforts, there are still some challenges to conserving regional open spaces. First, the designated preserves are principally under the corresponding management agency's supervision and authorization. The current regional open space planning system has no converging point at which separated decision-making process can be synthesized and at which accumulated influences of any urban activities can be anticipated regionally.

Second, the endeavors take a passive rather than proactive approach in protecting, maintaining, and enhancing the intrinsic values of regional open spaces. Indeed, both the Desert Spaces Plan and Regional Trails System put more emphasis on anthropogenic aspects such as recreation, landscape aesthetic, and human quality of life than potential ecological functions. Third, the County programs don't have a defensive instrument for controlling or guiding future urbanization. For instance, since current Arizona law allows the Proposed Open Space to be developed at a minimum of one dwelling unit per acre, a lot of privately-owned and state trust lands that are targeted for Proposed and Potential Open Space are vulnerable to future development. Although there are a variety of techniques to acquire and conserve open space such as easement or preservation initiatives, bringing a specific parcel into the public domain to preserve is practically difficult.



Source: MAG Desert Spaces Plan, 1995

Figure 5.4 Open space classification in the Desert Spaces Plan (MAG, 2004)

5.2 Research Objectives

This study was motivated by the necessity of understanding existing and future ecosystem loss and fragmentation. The main purpose of the study is to investigate how urban ecosystem structure is likely to evolve in response to different urbanization schemes in Maricopa County, Arizona, by calculating a selected set of landscape pattern metrics. The a priori hypothesis of the research is that there should be an extensive loss of landscape connectivity along with urbanization processes. The operational prepositions are set as following: (1)

both the amount of ecosystems and connectivity values will decrease as more urban development come into play; (2) connectivity gradients will be different depending on the ecosystem type and urbanization phase. Throughout the study, a high degree of connectedness is assumed to be beneficial to wildlife movement and biodiversity and ultimately to improve ecological landscape sustainability.

5.3 Research Questions

Because the intent of this study was to diagnose the current landscape pattern and predict the amount of urban ecosystems loss and the degree of fragmentation in Maricopa County in response to proposed urban developments, the following questions needed to be answered during the course of the study:

(1) What is the existing condition in spatial pattern of key ecosystems representing the Maricopa County landscape?

(2) Is there any significant variation in landscape structure of the selected type of ecosystems?

(3) Which type of urban ecosystems would be more likely vulnerable than others in Maricopa County in the context of landscape connectivity?

(4) How does urbanization alter the pattern of urban ecosystems and modify landscape configurations?

(5) How do landscape pattern metrics behave in different urbanization scenarios?

(6) Which kind of ecosystem would be the most influenced by urbanization process in this region?

(7) Can the landscape connectivity concept be better understood in the planning context and in human-dominated urban environment?

5.4 Research Setting: Maricopa County, Arizona, USA

The coexistence of distinctive natural landscape and ever-increasing urban lands represents the unique characteristics of Maricopa County. As a part of the northeastern Sonoran Desert Ecoregion (Figure 5.6), this area consists of the Lower Colorado Sonoran Desert Zone that is positioned in the central part of the area and the Upland Sonoran Desert Zone in the Phoenix urban outskirt. While the Lower Colorado Sonoran Desert Zone, from 1000 to 4000 feet, contain vegetation such as ironwood, mesquite trees and other mixed cactus plant communities that can be less susceptible to human settlements dominated in this area, the Upland Sonoran Desert Zone is characterized by desert plants such as rich saguaro, creosote bush, palo verde, and ocotillo (MAG, 2003). The more important wildlife habitats are found at higher elevations from 4000 to 6000 feet where juniper and pinyon pine trees, scrub oak and Manzanita bushes (chaparral), and grasslands occur, and as the type of vegetation changes into ponderosa pine, Gambel's oak trees, and a small amount of Douglas fir trees in the colder north-facing canyons above 6000 feet (Witzeman et al. 1997)

The nine desert mountain parks located in the Phoenix urban outskirts are known as the largest regional park system in the country and consist of designated open spaces along with other conservation areas such as wildlife areas. The agricultural lands provided extremely important sources of Arizona's economy (e.g., cotton, cattle, citrus, copper, and climate), particularly during the early 20th century. The extensive canal system built by Hohokam residents who needed water for their crop activities promoted agricultural land use (Musacchio et al. 2003). At present, the majority of the croplands are being threatened by suburban development, but the remaining areas still have great potential as nesting sites for a variety of birds, foraging sources for particular wildlife species, or open space corridors for animal movement between riparian areas and desert parks (Musacchio et al. 2003). In addition, desert washes and riparian areas play a pivotal role in increasing biodiversity in this arid region. These natural landscapes have been relatively well preserved and deliver multifunctional ecosystem services to human communities, such as urban biodiversity, wildlife habitat, urban climate mitigation, storm-water management, food production, landscape aesthetics, and recreation.

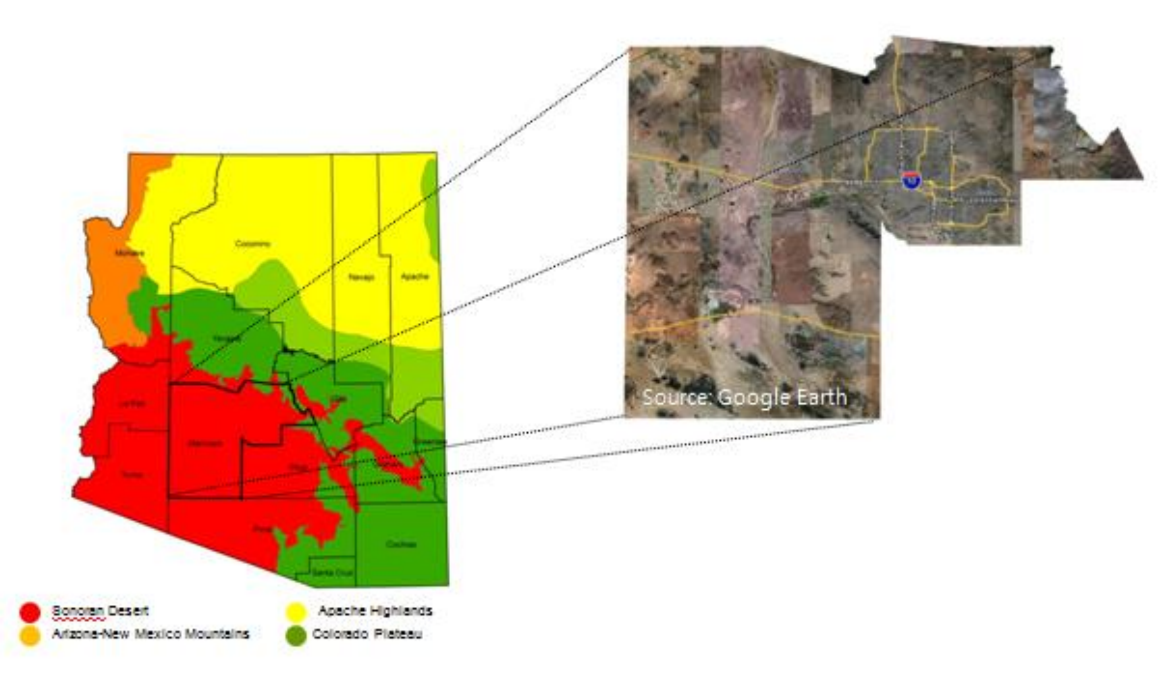


Figure 5.5 Eco-regional context of study area

As of 2009, the total population in this county increased to 3,397,000. Currently, approximately three quarter of all lands is owned by federal and state government and private land holdings are aggregated around the already urbanized area. The large portion of public lands is possessed by the Bureau of Land Management (BLM) and dominate the western part of the region. State Trust Lands that are most likely to covert to urban use are scattered in the grid road systems throughout the county.

Table 5.2 Land ownership in Maricopa County

Land ownership category	Areas (hectares)	Percentage (%)
State Trust Land	555,800	6.5%
BLM	2,619,716	30.7%
Private Land	1,767,759	20.7%
Forest	1,161,970	13.6%
Indian Reserves	1,301,556	15.3%
Military	709,369	8.3%
Local and State Parks	40,700	0.5%
Wildlife Areas	348,848	4.1%
Other	15,331	0.2%

The study area is bounded by a 213.8km×170.1 km Maricopa County boundary which serves as a spatial scope for the ecosystem pattern analysis. With elevations ranging from under 700 feet to over 7000 feet, there is a great variety of habitat found – from the low elevation creosote flats up to the pines and Douglas firs of the higher elevations, and including both we t and dry areas (Witzeman et al. 1997). The main reason for selecting this area is that it still has decently preserved ecosystems which at the same time have been, and will be, under a great development pressure necessitating optimal arrangement of existing landscapes. The adequacy of available data sets pertaining to urbanization scenario building also made it possible to analyze this region.

5.5 Methods

5.5.1 Data

5.5.1.1 Ecosystem Layer

Two main GIS layers were created with relevant data sets: an ecosystem layer and an urbanization layer. For the former, a National Land Cover 2001 Dataset (NLCD) was obtained from the United States Geological Survey with a 30m cell size. Among 14 land classes originally available for the study area, only four classes were selected as an essential type of ecosystem that represents Maricopa County: (1) Desert Shrub; (2) Grassland; (3) Agricultural land; and (4) Maintained Open Space. While desert shrubs and grasslands are assumed as typical ecosystems being worth protecting, conservation of agricultural lands is often a controversial subject contingent on people's perceptions. Nevertheless, agricultural lands were considered for this study because of their biological, environmental, and cultural importance in the regional context. The maintained open spaces were included since much recent literature in urban ecology stresses that even small-scale green patches can be a habitat for urban species that succeed in adapting to the urban environment, or at least serve as ecological stepping stones in the landscape matrix mosaic.

To validate the data accuracy on land classification, the NLCD dataset was compared with the local Land Use 2000 dataset (source: Maricopa Association of Governments). As a result, the single coverage of maintained open space turned out to be used for neighborhood parks, golf courses, street trees, residential gardens, and temporary green fields in vacant lots. The desert shrubs appeared in a diverse form ranging from a big chunk of patches along the outlying deserts which were mostly used for passive open spaces and vacant areas to urban parks and tiny spotted pieces in the built environment such as residential, educational or institutional facilities. Although a part of the Tonto National Park belongs to the study area, forest-related classes were excluded from the ecosystem layer due mostly to the marginalized location and undersized amount that together make the regional pattern analysis pointless. As secondary datasets, Arizona GAP vegetation was gained from the Central Arizona-Phoenix Long-Term Ecological Research (CAP-LTER) project. However, the GAP vegetation was not used as direct input for the analysis, but merely for backing up the primary datasets. All data sets were adjusted to have the same spatial reference using NAD 1983 Albers coordinate system, and all the vector-based input and intermediate data were converted to the raster format to quantify landscape metrics.

5.5.1.2 Urbanization Layer

A variety of datasets from multiple sources constituted the urbanization layer. First, the Major Development Database was gained from MAG that compiled the known development data at the municipality-level from MAG member agencies along with some unincorporated areas. The data initially had five categories for urban projects according to their development status. The data set was reclassified into two classes, established and potential development to be incorporated into urbanization scenarios. To capture the most recent trend and annual variance in development supply, the same datasets for the latest three consecutive years from 2007 to 2009 were obtained. This data is especially useful for estimating the short-term impact of urbanization. In addition, to include existing and proposed plans at a long-term scale to the study, the Future Land Use dataset (released October 2010) was obtained which combines three databases of Existing Land Use, Major Development, and local General Plan Land Use. The composite datasets were prepared by MAG through diverse information sources such as individual municipalities, aerial imagery, and other outside sources including newspaper articles, and developer information. Lastly, land ownership was used to identify the spatial distribution of lands in public and private sectors in building urbanization scenarios.

5.5.2 Landscape Pattern Metrics

Landscape metrics have been a central method to quantify landscape pattern and to analyze landscape change through time and space. Although uncovering the pattern-process relationship still remains a challenging area of research, the quantification of pattern has received considerable attention on the premise that ecological processes are linked to and can be predicted from some broad-scale spatial patterns (Turner et al. 2001).

Of the numerous landscape metrics developed to date, this study focused on what Botequilha-Leitão and Ahern (2006) suggests is the most useful in identifying loss of landscape diversity, fragmentation, and disturbances, and in comparing the consequences of alternative planning options. Since landscape structure is often characterized by both composition (i.e. shape, size, diversity, etc.) and configuration (spatially explicit characteristics of land cover, associated with patch geometry or with the spatial distribution of patches), the selection of landscape metrics was made to have a balance between the two components. Furthermore, to avoid redundancy in outcome pattern, only one of the highly correlated metrics (e.g., NP vs. PD; LSI vs. PAFRAC) was taken into account. As a consequence, six landscape metrics directly or indirectly associated with land fragmentation were chosen: NP (Number of Patches), LPI (Largest Patch Index), CONTIG_MN (Contiguity Index), PAFRAC (Perimeter-Area Fractal Dimension), ENN_MN (Euclidean Nearest Neighbor Distance), and CONNECT (Connectance). The selected landscape metrics were computed at class (different ecosystem types) and landscape scales (i.e., Maricopa County) with the aid of FRAGSTATS (version 3.3), a widely used pattern analysis software (McGarigal, 1995).

Number of Patches (NP) was considered as a simple measure of the extent of subdivision or fragmentation of a particular patch type that may be fundamentally important to a number of ecological processes. Although it has limited interpretive value by itself, it is probably most valuable as the basis for computing other more interpretable metrics (McGarigal, 1995). In calculation of patch number, the 8-neighbor rule was used for determining the delineation of patches, because it generates the gravitated patches rather than scattered tiny patches with such a small size as a single grid pixel. The reduction in patch size seems not reasonable because it calculates any two cells of the same class that are diagonally touching as separate patches (Figure 5.6). It may cause the increase in patch number and thus may capture incorrectly extreme information.

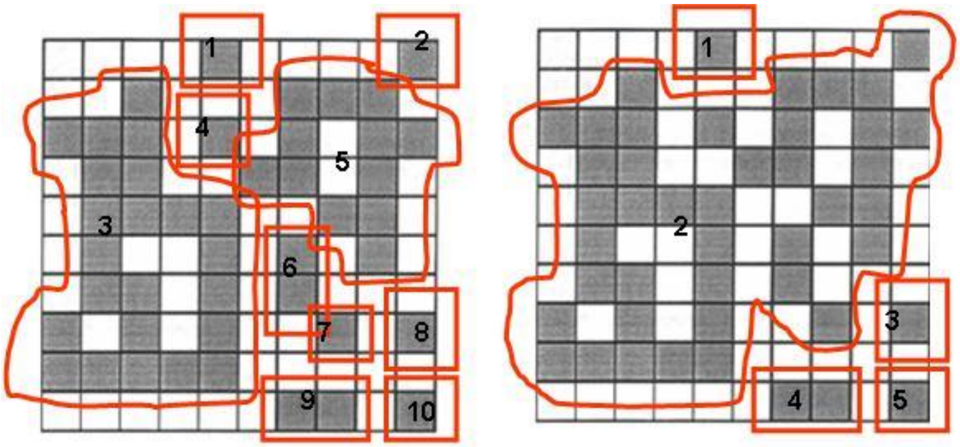


Figure 5.6 Diagram examples showing the difference in number of patches when using 4 cell (left) and 8 cell rules (right)

Largest Patch Index (LPI) at the class level was included to quantify the percentage of total landscape area comprised by the largest patch. This metric measured the dominance by each ecosystem type. LPI is affected by neighbor rule: if applied with 8-cell rule, it generally computes a patch larger than the largest patch quantified with the 4-cell rule, with some exception depending on the characteristics of a given landscape.

Contiguity Index (CONTIG) assesses the spatial connectedness of cells within a grid-cell patch which is computed in a manner of assigning binary values to a 3x3 moving pixel template with more weights on orthogonal relationship rather than diagonal contiguity. This index is a measure of patch boundary configuration (LaGro, 1991) and thus used for identifying the ecosystem types with different level of continuous patches.

Perimeter-Area Fractal Dimension (FRAC) was used as a landscape index for identifying shape complexity based on a log-log relationship between patch perimeter and patch size across a full range of patches in the class and landscape. The range of a fractal dimension measures is from 1 and 2: a fractal dimension greater than 1 indicates a departure from Euclidean geometry (i.e., an increase in shape complexity). This metric approaches 1 for shapes with very simple perimeters such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

Mean Euclidean Nearest Neighbor Distance (ENN_MN) was used to evaluate patch isolation using simple Euclidean geometry as the shortest straight-line distance between the focal patch and its nearest neighbor of the same class. Even though the neighboring patches may not be large enough to be considered as ecological focal patches and Euclidean distance can differ from functional distance, this index was used to provide overall pattern of land fragmentation.

Lastly, the Connectance Index (CONNECT) defined the number of functional joining within a specified threshold distance and represents a percentage of the maximum possible connectance given the number of patches. In this study, the threshold distance was commonly set as 30m Euclidean distance for the overall pattern analysis and then different ranges of 30m, 200m, 1 km, and 5 km were used for functional distances. All selected metrics were then computed using FRAGSTATS (version 3.3), a widely used pattern analysis software (McGarigal, 1995) at class and landscape levels.

Although the patch-level analysis is not impossible to execute, it was excluded from this study due to the following reasons. First, it requires huge volume of input data load resulting in tremendous computer processing time. Second, there is inconsistency in analysis scale, that is, the unit of analysis (i.e., individual patch) and the extent of data does not integrate well to draw meaningful outcomes. More importantly, the study highlights the overall pattern of individual and combined ecosystem types on a landscape mosaic rather than the characteristics of single patches. The summary of equations and brief descriptions for the selected landscape metrics are demonstrated in the table.

Table 5.3 Selected landscape pattern metrics (based on McGarigal, 1995)

	Landscape metrics		Description	Equations
Landscape Composition	NP	Number of Patches	Number of patches in the landscape of class type i.	$NP = n_i$
	LPI	Largest Patch Index	Percentage of the landscape comprised by the largest patch 0 ≤ LPI ≤ 100	$\frac{\max_{j=1}^{a} a_{ij}}{A(100)}$
Landscape Configuration	CONTIG_MN	Contiguity Index	Mean values on connectedness of cells within a grid-cell patch in each class type 0 ≤CONTIG_MN ≤ 1	$\mathrm{CONTIG}=\frac{\left[\frac{\sum_{r=1}^{z} c_{ijr}}{a_{ij}}\right]-1}{v-1}$
	PAFRAC	Perimeter-Area Fractal	Shape complexity from simple square to convoluted 1 ≤ PAFRAC ≤ 2	$\cfrac{2}{\cfrac{\left[n_i \sum_{j=1}^{n}\left(\ln p_{ij} * \ln a_{ij}\right)\right]-\left[\left(\sum_{j=1}^{n}\ln p_{ij}\right)\left(\sum_{j=1}^{n}\ln a_{ij}\right)\right]}{\left(n_i \sum_{j=1}^{n}\ln p_{ij}^{2}\right)-\left(\sum_{j=1}^{n}\ln p_{ij}\right)^{2}}}$
	ENN_MN	Euclidean Nearest Neighbor Distance	Mean values of distance (m) from patch ij to nearest neighboring patch of the same class type	$\frac{\sum_{j=1}^{n} h_{ij}}{n_1}$
	CONNECT	Connectance Index	Degree of connectedness between the patches of the focal class within user-specified threshold distance 0 ≤ CONNECT ≤ 100	$\left[\frac{\sum_{j=k}^{n} c_{ijk}}{\frac{n_i(n_i-1)}{2}}\right](100)$

a_{ij} area (m^2) of patch ij

A: total landscape area (m^2)

Cijr: contiguity value for pixel r in patch ij

V: sum of the values in a 3-by-3 cell template (13 in this case)

aij : area of patch ij in terms of number of cells

c_{ijk} : joining between patch j and k (0 = unjoined, 1 = joined) of the corresponding patch type (i), based on a user specified threshold distance

n_i : number of patches in the landscape of the corresponding patch class type

4.5.3 Scenario Building for Future Urban Development

One of the effective ways to predict the future condition of spatial pattern is to build a scenario with a basis on generally agreed upon assumptions. It is particularly useful when there is a certain level of uncertainty that could to some degree be resolved by demarcating a series of situations. In this study, three different urbanization phases were designed, including short-term, mid-term, and long-term development scenarios. The short-term scenario reflects officially confirmed urban projects that either were already completed or are under construction with the highest potential of actual “urban footprints.” This phase shows the stationary status of urbanization.

The mid-term scenario represents the potential development status when the proposed urban plans are materialized in real landscapes. Even if nothing is built yet in most urban projects in this category, and the conceptual plans may be canceled or rejected, it is assumed that all current plans would be executed in built-out form, taking the plan boundaries as unalterable and ruling out any natural or designed green leftovers that planned spaces will possibly have. Lastly, the long-term scenario supposes that all developable private natural lands will be converted into built-up areas. This scenario is grounded on a study where private lands will likely be converted to urban use. This is not unrealistic given the fact that all natural open space areas currently owned by private domain along with State Trust Lands have been, and will be, assigned a high priority for urban development. As such, urbanization options are added in a cumulative fashion with an increase in development intensity and decrease in development certainty. The scenarios are evaluated for future ecosystem patterns with reference to baseline status, where target ecosystem pattern is simply diagnosed for comparison with other scenarios. The selected set of landscape metrics is then quantified for each scenario to examine the important change in spatial pattern characteristics.

Table 5.4 Urbanization scenario description

Urbanization Scenarios	Development categories	Components included for future urbanization	Descriptions
Short-term	Established development	Completed plans	Urban developments that are already built out
		Active plans	Urban developments that are currently under construction
Mid-term	Potential development	Approved plans	Urban development projects of which entitlements are approved by local jurisdictions (i.e. zoning with or without conditions) or in the final plat process after approval
		Conceptualized plans	Urban development plans that have been submitted to local jurisdictions for review or have received approval
		Potential plans	Any potential development for which plans have not been formally submitted to planning authority
Long-term	Extreme development	Private lands	Lands owned by private sectors except already urbanized areas with private ownership holdings

5.6 Results

5.6.1 Spatial Characteristics of Urban Development

As of the year 2009, there is the total of 2,914 known urban projects proposed for residential, commercial, recreational developments, roads and other urban uses, which corresponds to approximately 664,100 acres of future urban land cover. Despite the worldwide economic recession in recent years, the increase in urbanization is remarkable in this region. Just for three consecutive years from 2007 to 2009, urban development last year increased by more than 100 percent over the previous year. It is also interesting that there is a contrast of vertical development with relatively large-scale urban projects and spatial dominance of small plans on a horizontal pattern.

As shown in Table 5.4, the number of projects was highest for confirmed development, followed by potential and anticipated projects. This makes sense because a number of actual plans are already in the development review process. The large number of confirmed projects shows an extremely low mean lot size, inferring they will mostly be built in a way that fills the void spaces or adds to uncompleted developments. On the contrary, the potential and anticipated plans are high in both total areas of property and mean lot size, which means that coming developments would require relatively huge tract of lands concentrating on new residential developments in outlying suburbs. Not surprisingly, the manifestation of urban development at different levels will bring further urbanization processes on and around the current development path.

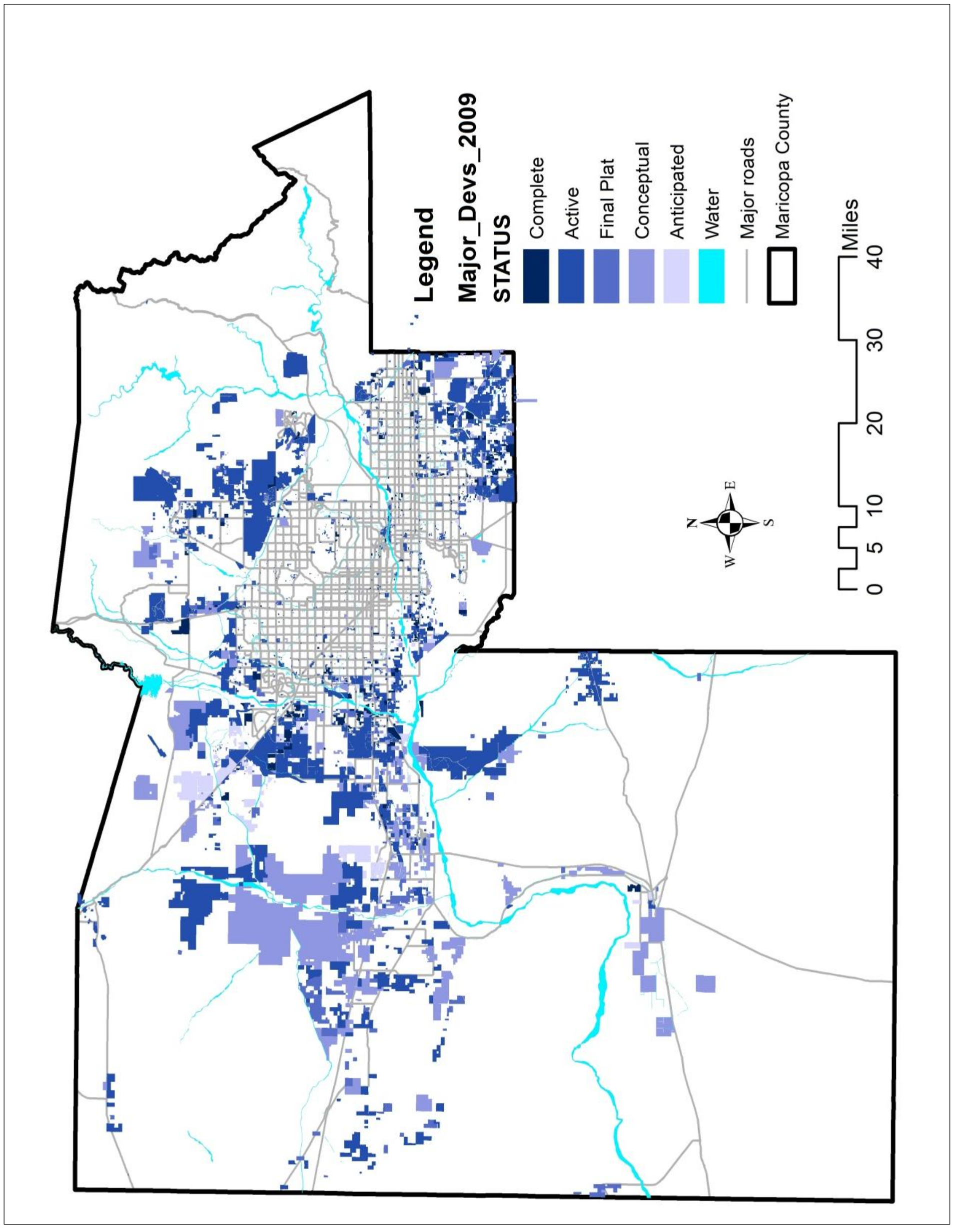


Figure 5.7 Location of proposed municipality development plans with different status of development

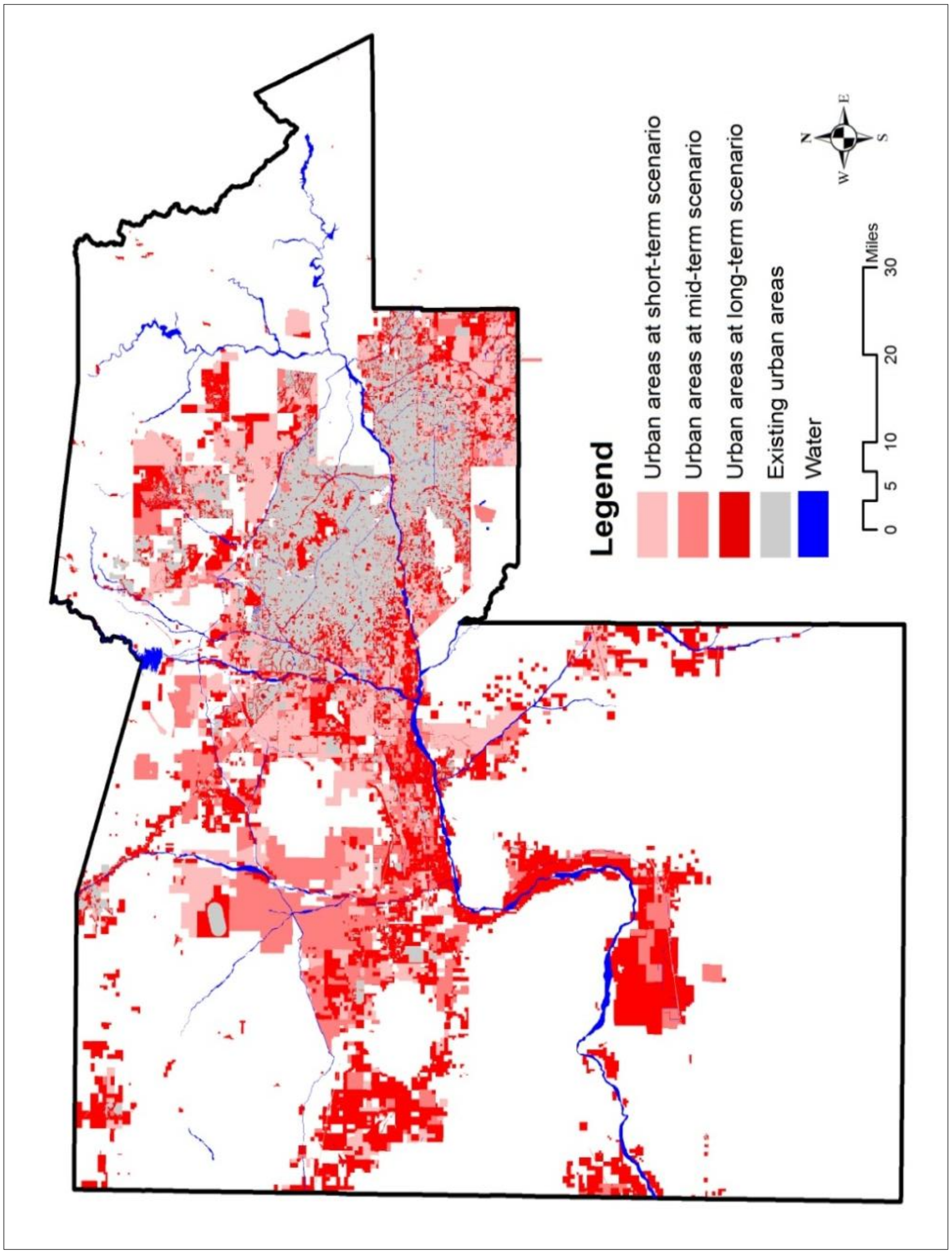
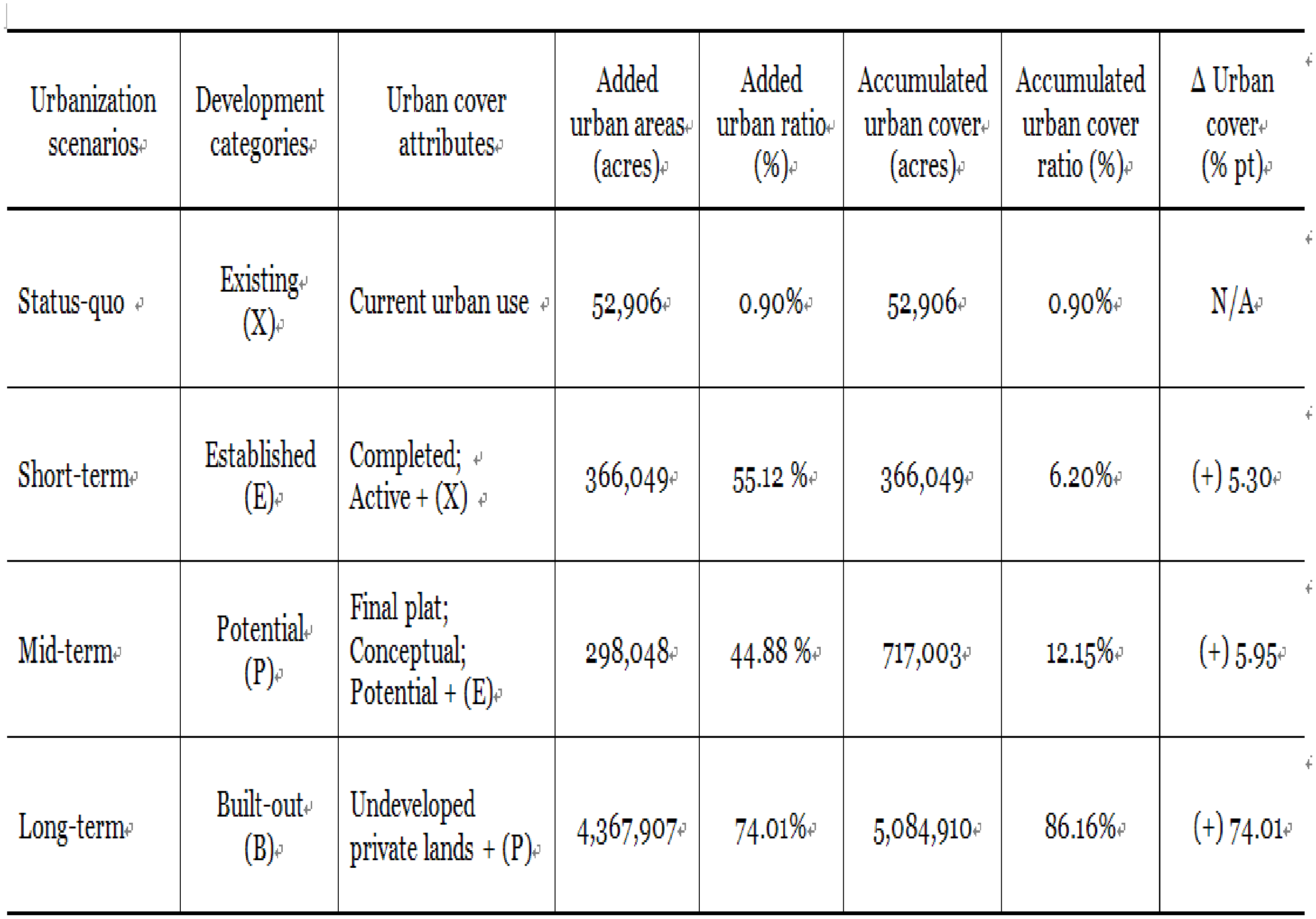


Figure 5.8 Distribution of urban areas by scenarios

Table 5.5 Urban areas at each scenario status



Urbanization scenarios	Development categories	Urban cover attributes	Added urban areas (acres)	Added urban ratio (%)	Accumulated urban cover (acres)	Accumulated urban cover ratio (%)	Δ Urban cover (% pt)
Status-quo	Existing (X)	Current urban use	52,906	0.90%	52,906	0.90%	N/A
Short-term	Established (E)	Completed; Active + (X)	366,049	55.12 %	366,049	6.20%	(+) 5.30
Mid-term	Potential (P)	Final plat; Conceptual; Potential + (E)	298,048	44.88 %	717,003	12.15%	(+) 5.95
Long-term	Built-out (B)	Undeveloped private lands + (P)	4,367,907	74.01%	5,084,910	86.16%	(+) 74.01

Table 5.6 Magnitude of realistic and potential urban development in Maricopa County municipalities

Development Category	Urban projects		Total development area			Mean lot size	Major cities w/ many plans	Major cities w/ large planning size
	Number	Percent	Acres	Percent	Proportion to entire area (%)	Area (acres)		
Completed	465	16%	26,934	4%	0.5%	57.92	PH, CH, ME, AV, TE, GI	PH,CH, SU, ME, AV
Active	1,179	40%	339,115	51%	5.7%	287.63	PH, SC, GI, ME	GO, CO, BU, SC, PH, /WI, SU
Final plat	543	19%	46,092	7%	0.8%	84.88	PH, CH/ SC, SU	CO, BU, CH, PH, SU
Conceptual	533	18%	219,099	33%	3.7%	411.07	PH/, BU/GI, ME, /TE, QC, CO	GB, PE, GC,/EL, CO, FH
Anticipated	194	7%	32,856	5%	0.6%	169.36	CH, SU, PH, ME, TE	SU, BU, GB, PH, CH /GO
Total	2,914	100%	664,097	100%	11%	227.90		

NOTE: Municipal Planning Area abbreviations

AJ = Apache Junction
AV = Avondale
BU = Buckeye
CA = Carefree
CC = Cave Creek
CH = Chandler
CO = County Areas
FM = Fort McDowell

EL = El Mirage
FH = Fountain Hills
GB = Gila Bend
GC = Gila River
GI = Gilbert
GL = Glendale
GO = Goodyear

GU = Guadalupe
LP = Litchfield Park
ME = Mesa
PA = Paradise Valley
PE = Peoria
PH = Phoenix
QC = Queen Creek

SA = Salt River
SC = Scottsdale
SU = Surprise
TE = Tempe
TO = Tolleson
WI = Wickenburg
YO = Youngtown

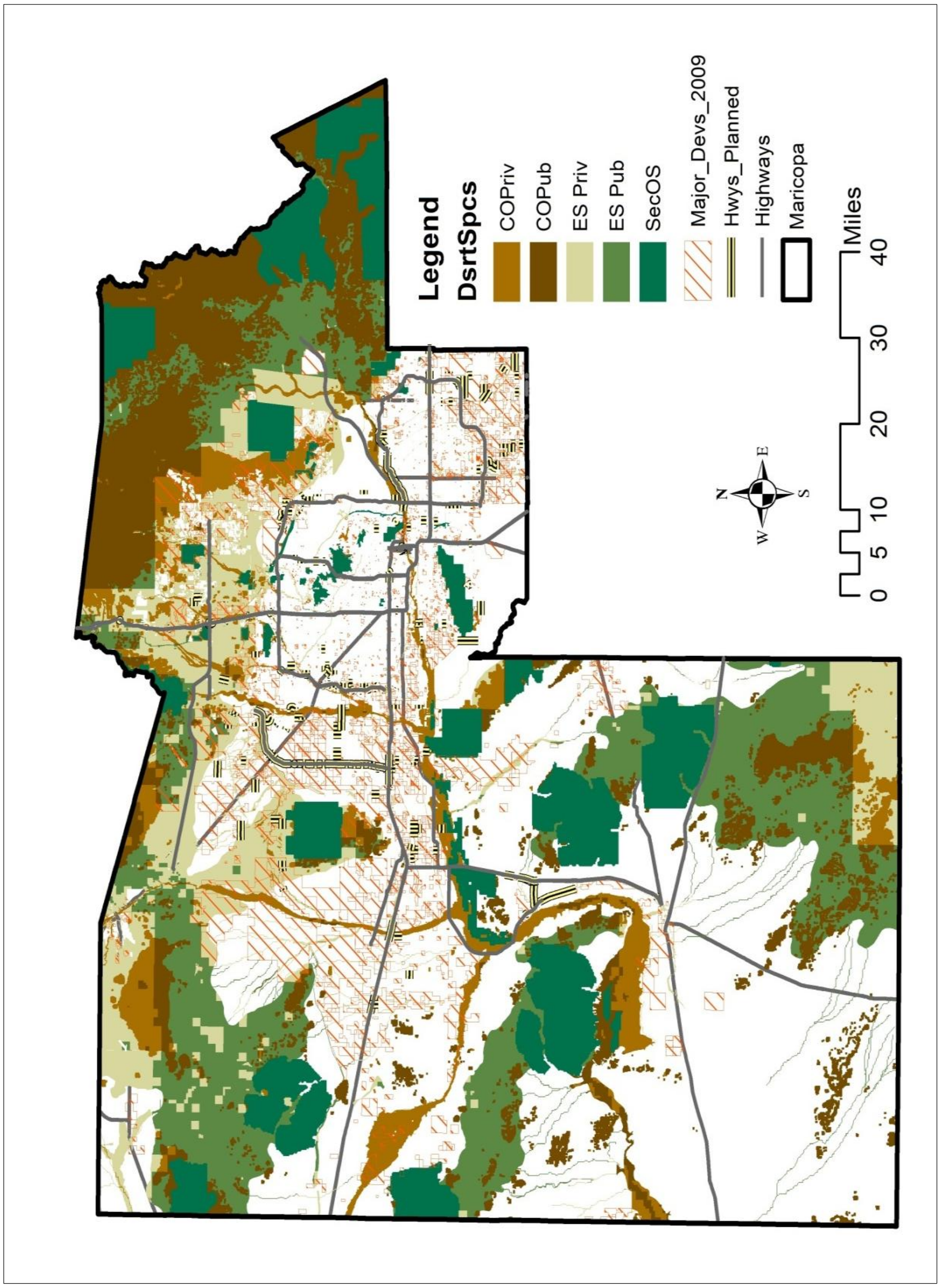


Figure 5.9 Major development plans superimposed onto the Desert Spaces Plan

Table 5.7 Major urban development projects in Maricopa County from 2007 to 2009

Year	2007	2008	2009	07-08	08-09	07-09
Number of projects	1,777	1,865	2,914	(+) 90	(+) 1,047	(+) 1,137
Acres	548,308	612,010	664,097	(+) 62,122	(+) 53,670	(+) 115,791
Percent	9.29%	10.34%	11.25%	(+) 1.1% pt	(+) 0.9% pt	(+) 2.0% pt

In addition, there is a rough correlation between temporal and spatial patterns of urban development. In other words, the majority of completed and active urban projects which will be realized on the ground in the near future are located along the transportation corridors within or close to the urbanized areas, whereas potential plans with less development certainty illustrate intruding pattern into extensive rural areas.

Overall, even though the future urban distribution is marked both within the urban cores and at urban outskirts, the spatial allocation to be occupied by the future developments will be greater going outward. While urban centers accommodate the majority of infill development demands, suburban developments continue to spread out over the urban peripheries.

This region characterizes as urban expansion rather than compact-city type of development. This ever-enlarging doughnut-shape growth seems typical in regions with lower urban density like the Phoenix region. Redman (2003) indicates that this region shows lean-H shape of development pattern that physically characterized by natural barriers such as large desert mountains, canals, and Indian reservations. However, if suburban development continues to take place particularly in southeastern areas of the region, the H-shape pattern will likely transform to lean-E shape, resulting in the conurbation between neighboring counties (particularly Maricopa-Pima) and the creation of a Phoenix-Tucson megapolis.

5.6.2 Quantification of Critical Ecosystem Pattern

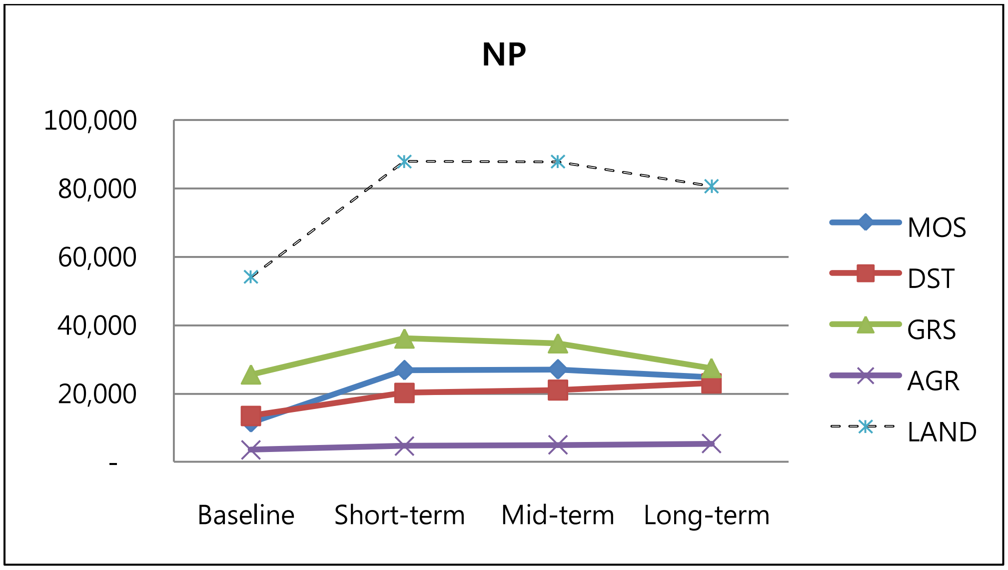
The following line graphs depict the overall pattern of landscape metrics measured for the critical ecosystems and represent how the individual metrics behave across the urbanization scenarios.

5.6.2.1 Selected Landscape Metrics

(1) Number of Patches (NP)

All types of ecosystems abruptly increase in patch number being immediately influenced by the short-term scenario, and then continue to increase until reaching the mid-term scenario. The exception is grassland, where the number of patches slightly decreases with added urban developments. For the long-term scenario, managed open spaces and grasslands show a decreasing pattern, which presumably results from the removal of group of patches by urban development rather than from splitting into several patches

The grassland patches outnumber other ecosystem types throughout the development schemes, whereas croplands ranked the lowest levels at all times, maintaining approximately five thousand patches and seldom changing during the entire course of urbanization. The steady increase in patch number is obvious in desert shrubs, which is the most likely to be influenced by the future urbanization processes. At the landscape scale, the increase of patch number is insignificant because of the offset effect among the different type of ecosystem classes.

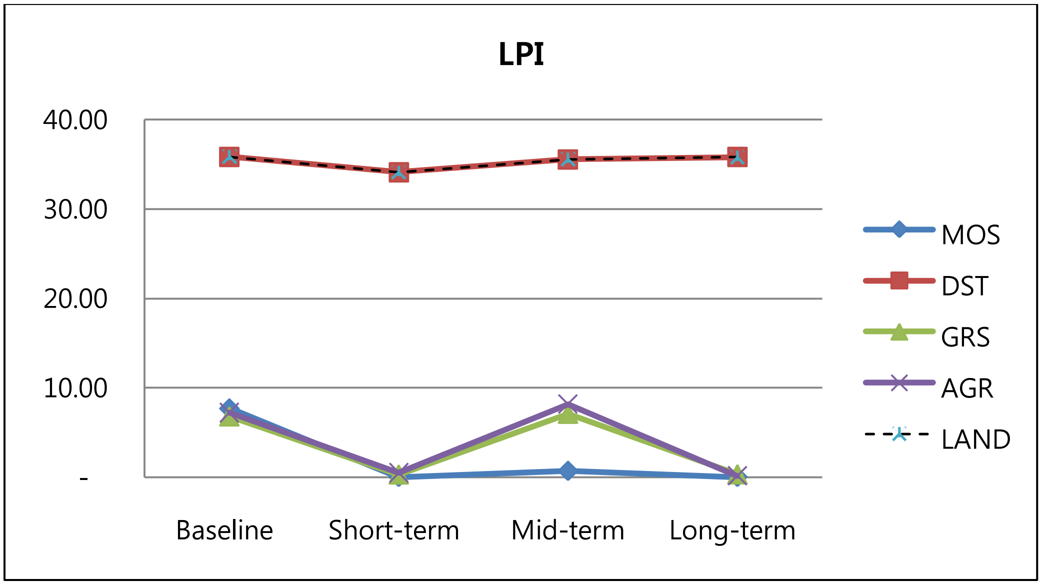


NP	Baseline	Short-term	Mid-term	Long-term
MOS	11,546	26,794	27,031	24,866
DST	13,525	20,258	21,052	23,054
GRS	25,564	36,178	34,771	27,467
AGR	3,536	4,670	5,030	5,349
LAND	54,171	87,900	87,884	80,736

Figure 5.10 Changes in Number of Patches (NP)

(2) Largest Patch Index (LPI)

Largest Patch Index was overwhelmingly high in desert shrubs and was not much influenced by any urbanization stages. The remaining types of ecosystems illustrated very similar patterns with extremely low values for the short-term and long-term scenarios, and with slight peaks for mid-term scenario. It signifies that desert shrub lands, unlike other types of ecosystem, exist in relatively large size in the landscape in the first place, and the largest patch will have the least impact from future urbanization. However, it does not mean that the majority of desert shrub patches with various sizes are never influenced by the future urbanization, because this landscape index simply computes the size of the single largest patch. It is the most likely that the largest patch in desert shrub ecosystem is located in open outlying desert far from the already built-up areas, but other small- or mid-size remnant desert patches are expected to be developed for urban purpose. Unsurprisingly, there is a huge contrast between desert shrub lands and managed open spaces in Largest Patch Index. On average, the largest desert shrub patch is nearly 40 times larger than that of managed open space. It makes sense because the managed open spaces for the most time present in and around the cities. The relatively sharp fluctuation in grassland, agriculture, and managed open space describes the high likelihood that urban development will be positioned in larger natural patches. Such circumstances will be evident when approved, conceptualized, and potential urban plans are all implemented in the real landscapes.

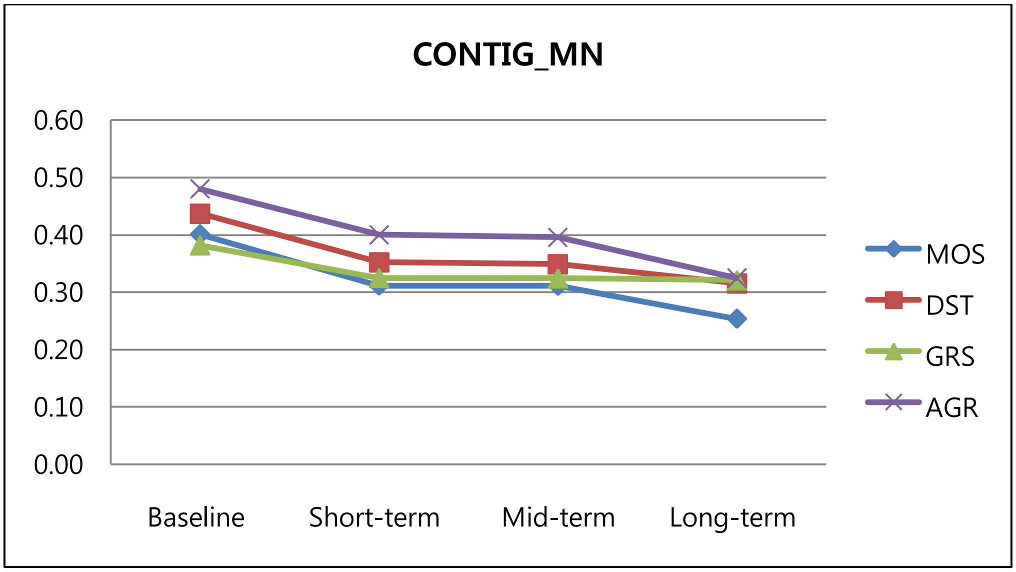


LPI	Baseline	Short-term	Mid-term	Long-term
MOS	7.69	0.02	0.69	0.02
DST	35.84	34.12	35.57	35.81
GRS	6.79	0.30	7.09	0.32
AGR	7.23	0.49	8.16	0.16
LAND	35.84	34.12	35.57	35.81

Figure 5.11 Changes in Largest Patch Index (LPI)

(3) Contiguity Index (CONTIG_MN)

Contiguity Index demonstrates the changing pattern of how much patches are contiguously arranged. It turned out to be common among all types of ecosystems that the accumulation of future urbanization activities will have a negative consequence relative to the degree if contiguity. The contiguity values gradually decline as the urban development are intensified. However, there was almost no change during the short-term and mid-term scenario intervals. The croplands have the largest contiguous patches resulting in higher contiguity index values followed by desert shrubs, grasslands, and managed open space, respectively. This result infers that the existing urban agricultural fields will be less split out even with the added urban development, and thus expected to have a tendency to maintain current landscape form. The proposed potential development doesn't significantly influence the values of contiguity for ecosystem types, but if the undeveloped private areas are transformed to urban land use, the natural patches are expected to be fragmented in less contiguous form.

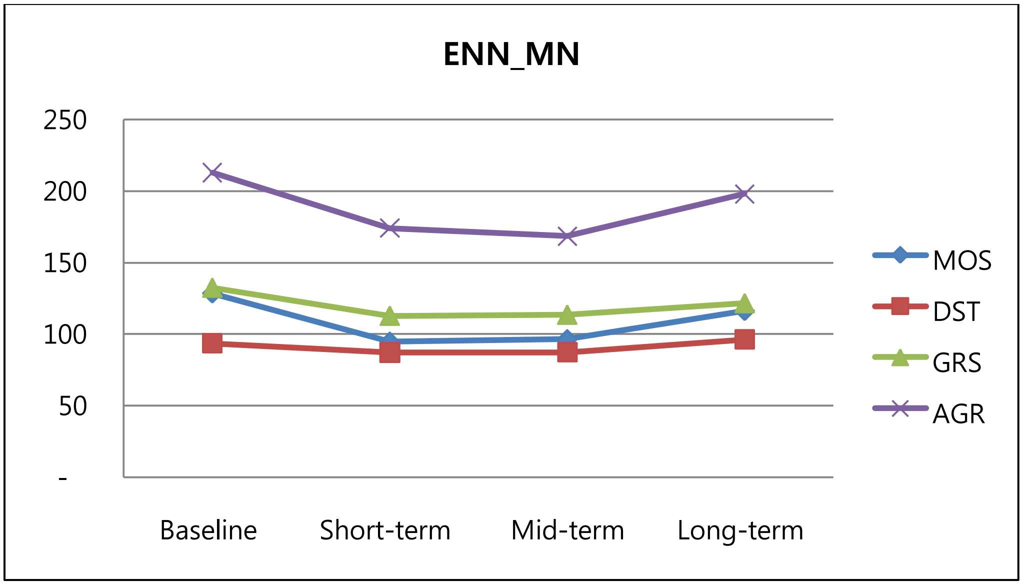


CONTIG_MN	Baseline	Short-term	Mid-term	Long-term
MOS	0.40	0.31	0.31	0.25
DST	0.44	0.35	0.35	0.32
GRS	0.38	0.33	0.32	0.32
AGR	0.48	0.40	0.40	0.32

Figure 5.12 Changes in Mean Contiguity (CONTIG_MN)

(4) Mean Euclidean Nearest Neighbor Distance (ENN_MN)

Mean Euclidean Nearest Neighbor Distance proved the suppositions that the accumulated impacts of urban development will lower the proximity between the same class of patches. As expected, sparsely-placed small open space patches and agricultural land patches are in isolation, particularly for the mid-term and long-term scenarios. It is outstanding that the agricultural patches have the relatively highest mean nearest neighbor distance compared to other three types of ecosystems, which means that the agricultural patches are not proportionately distributed across the landscape. The clumpy and aggregated nature of cropland patches makes the shortest distance to the same class patches much longer than usual. Although it is logical that fragmentation leads to longer distances between patches, the nearest neighbor distances of the critical ecosystems were decreased during the initial stages. However, the proximity seems to be not resulting from the reflection of actual patch nearness, but rather from the omission of the patches calculated for this index. Like the contiguity index, the mean Euclidean nearest neighbor distance values will be much more influenced by private land conversion rather than established or potential urban plans.



ENN_MN	Baseline	Short-term	Mid-term	Long-term
MOS	128	95	96	116
DST	94	87	87	96
GRS	133	113	114	122
AGR	213	174	169	198

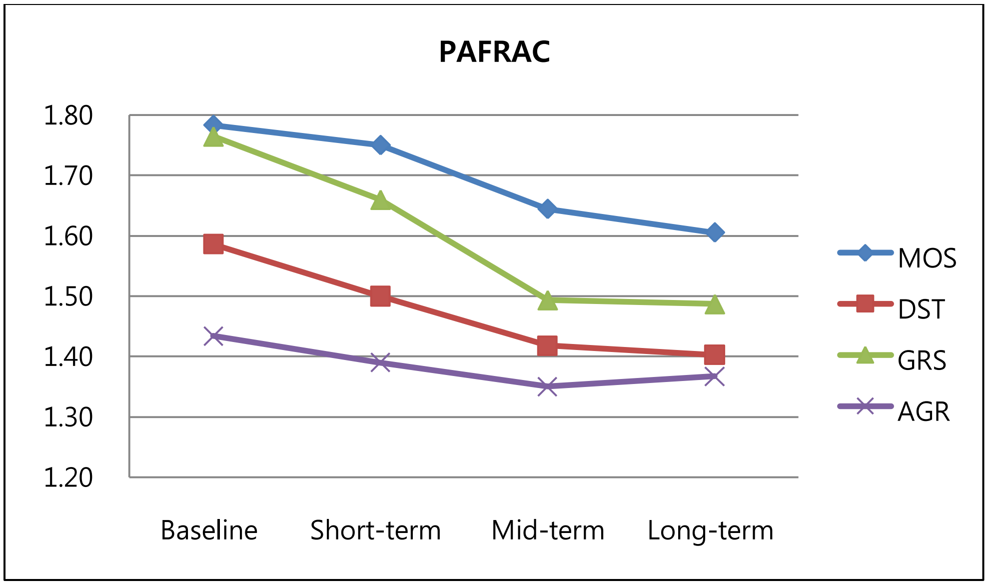
Figure 5.13 Changes in Mean Euclidean Distance (ENN_MN)

(5) Perimeter-Area Fractal Dimension (PAFRAC)

With the incremental addition of urbanization processes, Perimeter-Area Fractal Dimension Index becomes increasingly simplified regardless of ecosystem type. The results reflect that the shape complexity of the patches is eliminated because of the solid and hard boundaries of planning sites. Given the fact that the complex shape of natural patches is considered to be beneficial to ecological processes, future urban attributes are expected to hinder, direct and indirect, various ecological processes.

Technically, the fractal dimension metric always has the value range greater than one and smaller than two for any two-dimensional landscape mosaics. The four ecosystem types shown in the study landscape, therefore, stand around moderate values, most of which are higher than the median value of 1.5, representing relatively convoluted patch shape.

The graph below demonstrates that the managed open space patches rank the highest level at all times, followed by grasslands, desert shrubs, and agricultural patches. The variation in shape complexity is outstanding in grasslands particularly between the short-term and mid-term scenarios. This period also showed the greatest impacts on other types of ecosystems as well. Since the fractal dimension index is based on the regression relationship between patch size and patch perimeter, the ecosystem class with a broad range of patch size variation can be a factor making this index especially effective. It is notable that agricultural patches have the simplest shape among others, denoting that agricultural lands was created and have managed for cultivation purpose and the patch shape will continue to be regulated by human intervention.

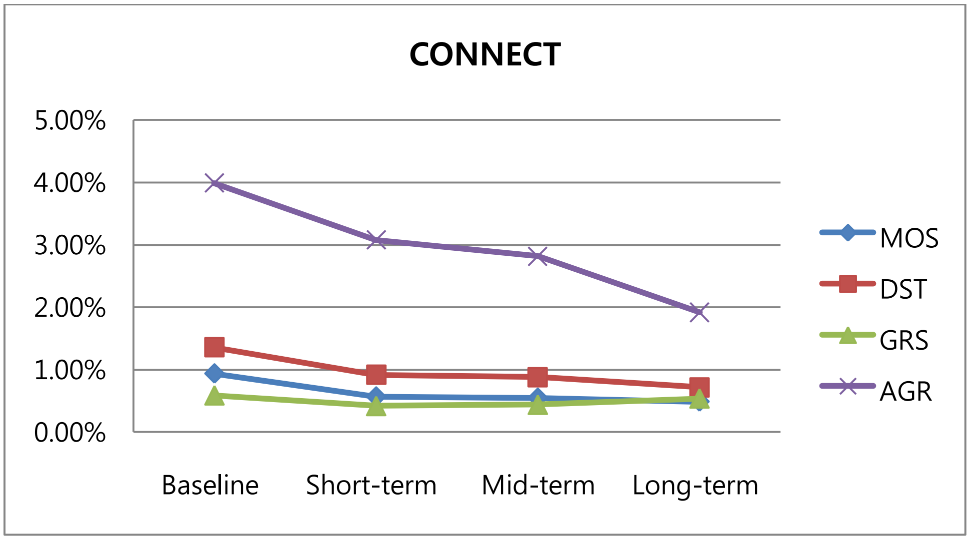


PAFRAC	Baseline	Short-term	Mid-term	Long-term
MOS	1.78	1.75	1.64	1.61
DST	1.59	1.50	1.42	1.40
GRS	1.76	1.66	1.49	1.49
AGR	1.43	1.39	1.35	1.37

Figure 5.14 Changes in Mean Perimeter-Area Fractal Dimension (PAFRAC)

(6) Connectance Index (CONNECT)

Connectance Index illustrates that the patch connectivity will be decreased and isolated due to the future urban expansion. It will be particularly influencing the ecological process native to the critical ecosystems. It is noteworthy that agricultural lands behave distinctively in terms of the degree of connectedness. In the baseline condition, the connectivity value of agricultural patches is exceptionally high compared to other ecosystem types. However, the dramatic change in agricultural patch connectivity is expected with the future urban development. The decreasing pattern is especially remarkable for the first phase and still substantial for the future landscapes afterward. This result accounts for the common assumption that urbanization would reduce the connectivity value in general. All ecosystem types except agricultural lands appeared to have the relatively low connectivity with approximately 0.5 percent value until the all developable lands are built out.



CONNECT	Baseline	Short-term	Mid-term	Long-term
MOS	0.94%	0.57%	0.55%	0.49%
DST	1.36%	0.92%	0.88%	0.72%
GRS	0.59%	0.42%	0.44%	0.54%
AGR	3.99%	3.08%	2.82%	1.92%

Figure 5.15 Changes in Connectance Index (CONNECT)

4.6.2.2 Functional Connectivity at Different Threshold Distances

The connectivity variation contingent upon threshold distances was estimated to reflect a range of species' movement with different dispersal distances. The results show that all classes have lower connectivity with short threshold distances and connectivity values increase as the distances are longer. The mechanism behind the calculation represents patches that are considered more connected unless there are non-habitats between the specified distances. For example, the short-ranging species including small mammals and reptiles that may sense that the same kind ecosystem is not connected beyond a certain distance may have lower connectivity than long-ranging animals that can sustain at least within 5km distances. In this context, structurally disconnected patches can be considered functionally connected to the species with longer dispersal distance. However, the results do not consider any ecological processes occurring at the scale with below 30m. Also, barrier effects are excluded from this scope of analysis. Functional connectivity analysis considering barrier effects that hinder movement will be examined in the next chapter.

Table 5.8 Connectivity index with different threshold distances

Code*	Threshold distances			
	30m	200m	1km	5km
BC1	0.0059	0.0113	0.0875	1.08
BC2	0.0136	0.0225	0.1268	1.28
BC3	0.0399	0.0657	0.2750	2.07
BC4	0.0094	0.0177	0.1170	1.53
BL	0.0084	0.0153	0.1010	1.19
SC1	0.0042	0.0089	0.0839	0.64
SC2	0.0092	0.0164	0.1068	1.01
SC3	0.0308	0.0533	0.2460	1.31
SC4	0.0057	0.0094	0.0599	0.80
SL	0.0036	0.0107	0.0821	0.72
MC1	0.0044	0.0093	0.0862	0.33
MC2	0.0088	0.0158	0.1043	0.94
MC3	0.0282	0.0493	0.2364	1.46
MC4	0.0055	0.0092	0.0599	0.81
ML	0.0033	0.0109	0.0831	0.53
LC1	0.0054	0.0112	0.1023	0.33
LC2	0.0072	0.0141	0.1095	1.85
LC3	0.0192	0.0377	0.2478	0.54
LC4	0.0049	0.0093	0.0730	0.97
LL	0.0055	0.0118	0.0971	0.80

NOTE

*Urbanization scenario codes: B-Baseline, S-Short-term, M-Mid-term, L-Long-term scenario

*Ecosystem class codes: C1-Grassland, C2-Desert shrub, C3-Agricultrual land, C4-Managemed open spaces, L-Entire landscape

5.6.3 Ecosystem Loss due to Future Urbanization

The following maps illustrate the distribution of ecosystem loss by each urbanization scenario (Figure 4.16-19). The majority of Managed Open Space will largely be impacted by the long-term scenario, and more than half of the total areas will disappear by then. Even if the percentage changes on individual scenarios are trivial, desert shrub will have the greatest accumulated loss (30.8 ha) in the absolute patch amount. On the contrary, only small amounts of desert grasslands are lost but the loss ratio is significant, which is in part because of the inherent rarity of grassland patches. It is no doubt that most cultivated areas will disappear rapidly and only very small tracts will likely remain in this region ultimately. Overall, when urbanization persists and reaches the long-term scenario, approximately one fourth of existing natural ecosystems (49ha) will be dedicated to future urban use.

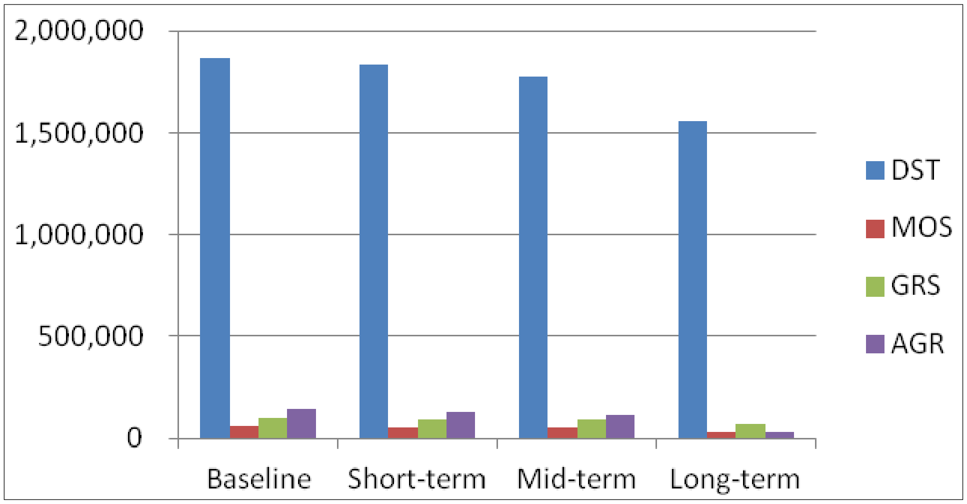


Figure 5.16 Overview of critical ecosystem loss due to future urbanization process

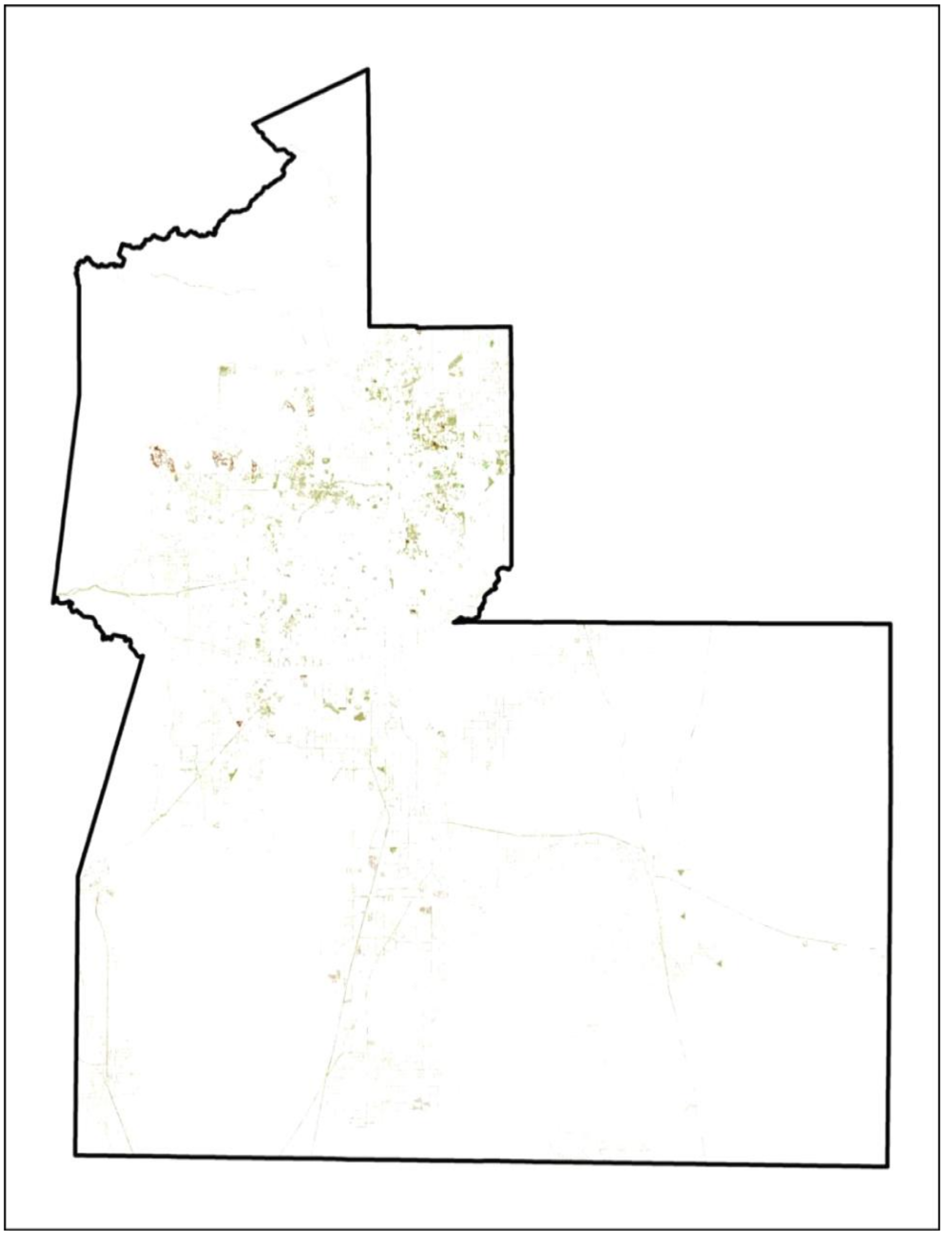


Figure 5.17 Distribution of accumulated managed open space loss by each urbanization scenario

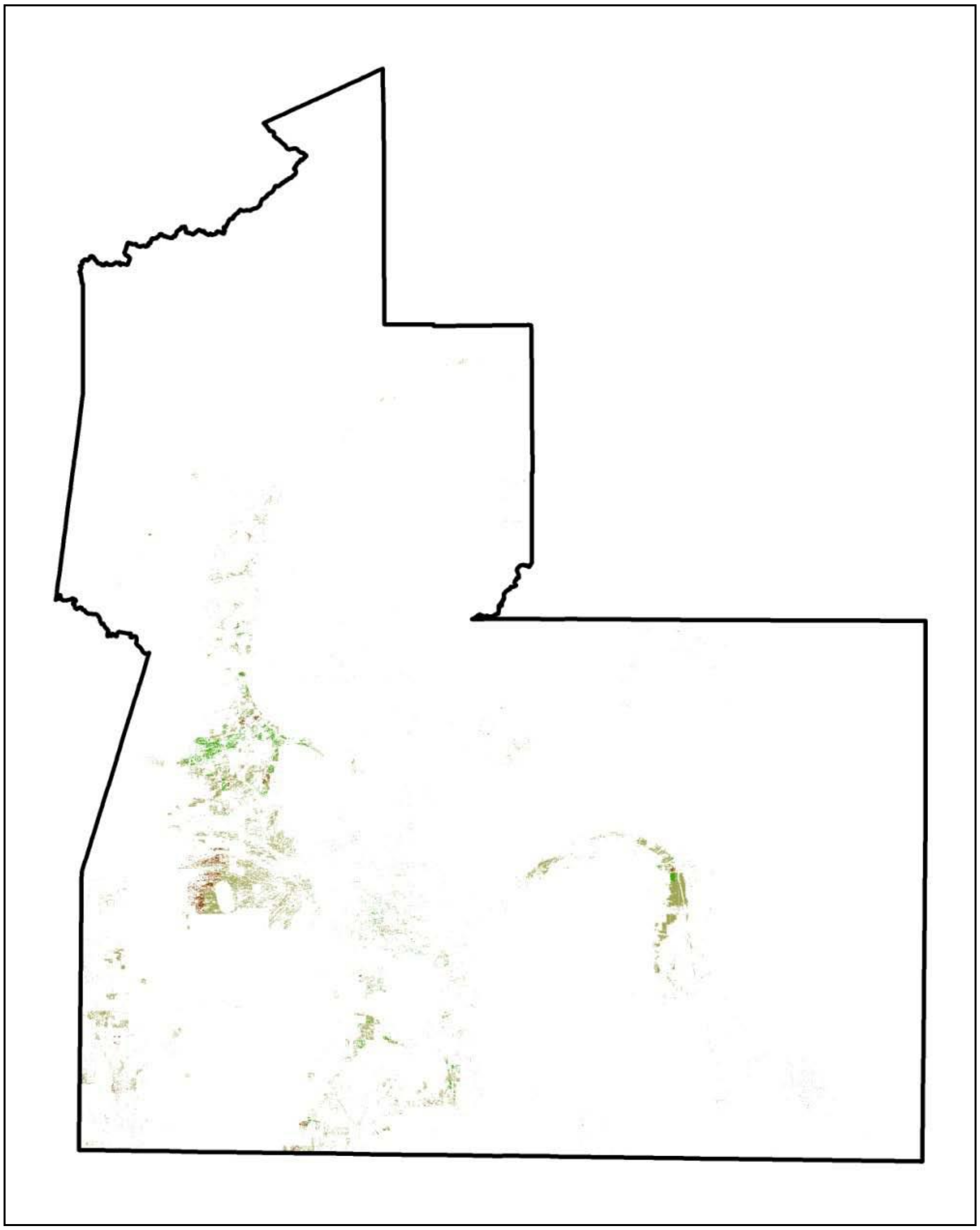


Figure 5.18 Distribution of accumulated grassland loss by each urbanization scenario

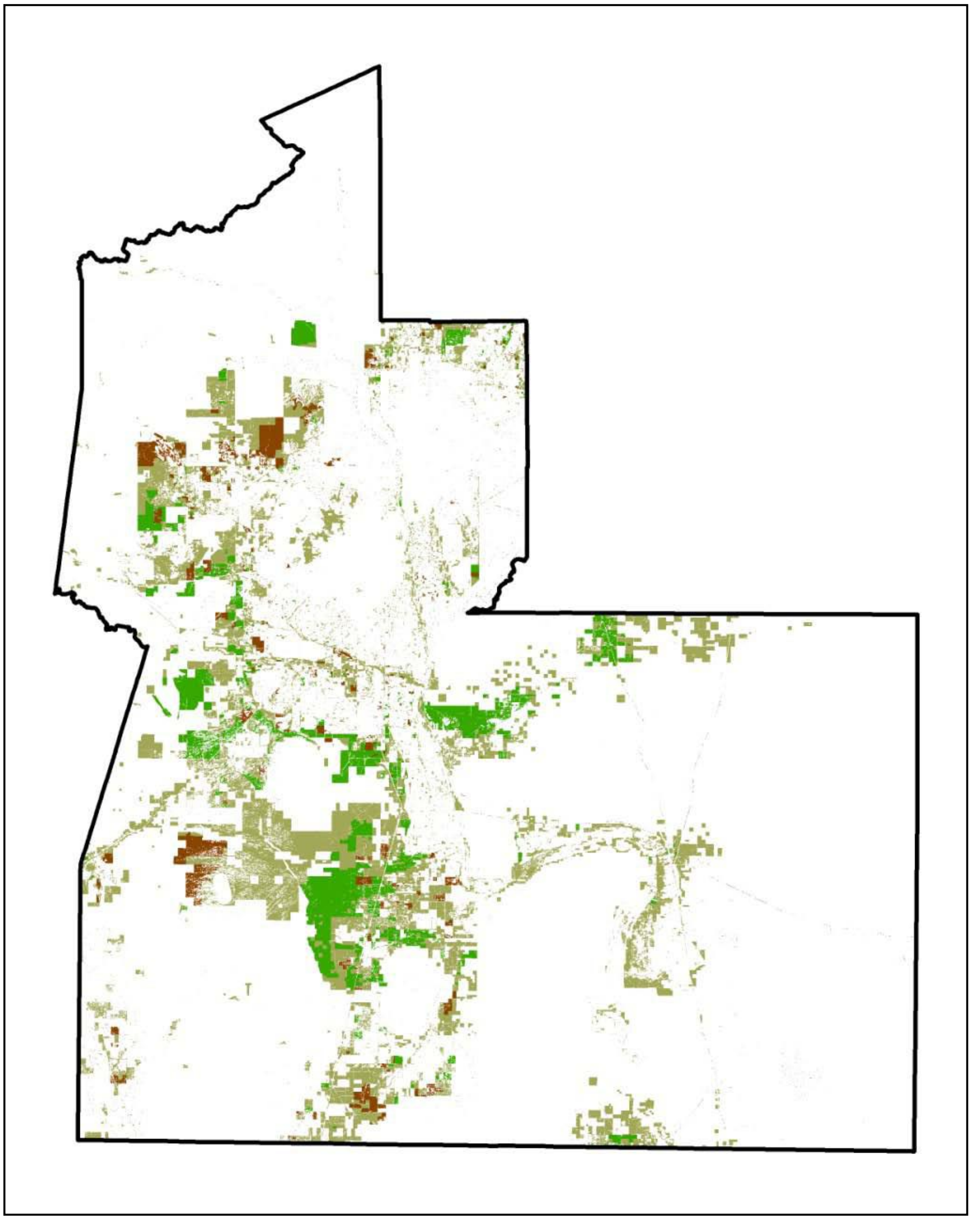


Figure 5.19 Distribution of accumulated desert shrub loss by each urbanization scenario

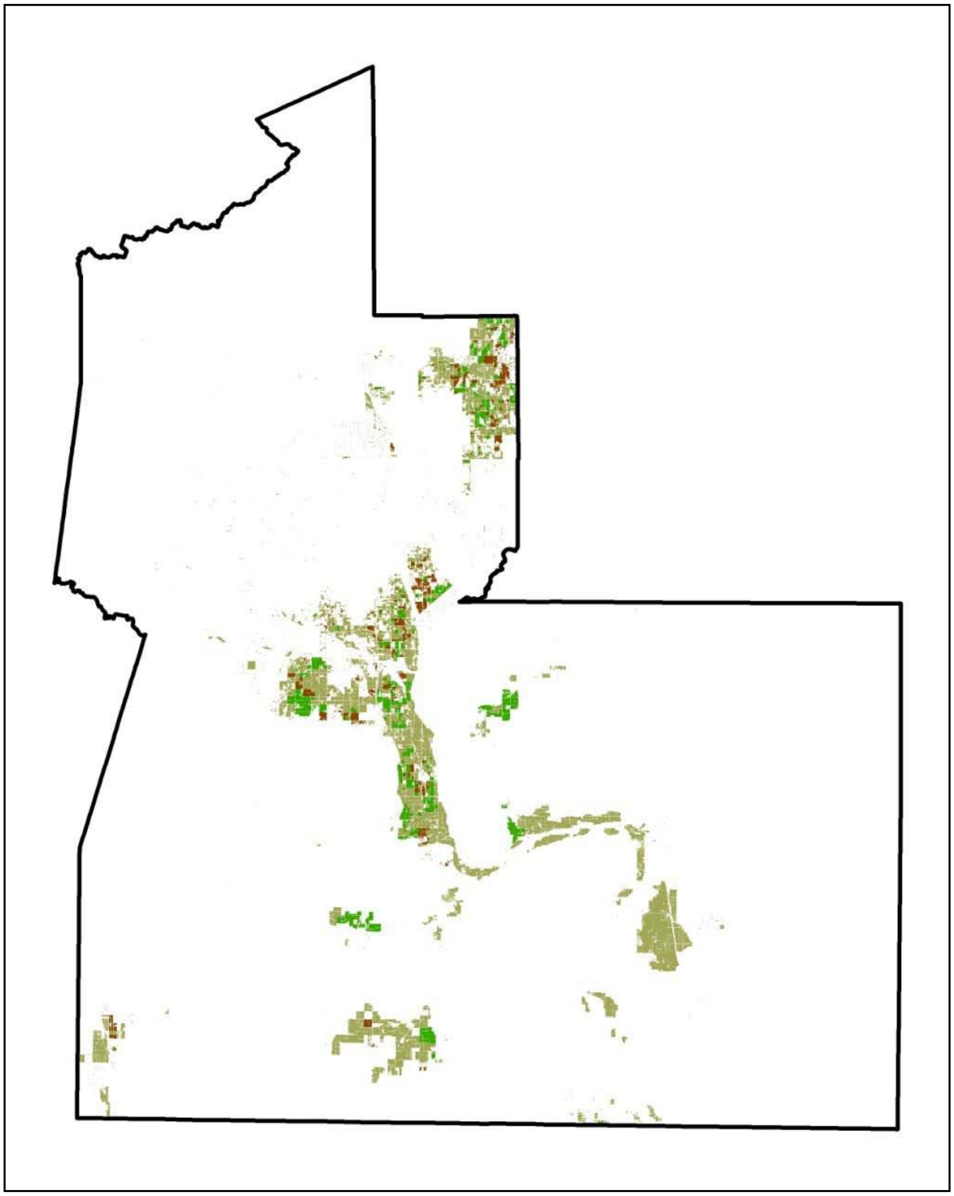


Figure 5.20 Distribution of accumulated agricultural lands loss by each urbanization scenario

Table 4.9 Amount and proportion of critical ecosystem loss

	Loss by STS		Loss by MTS		Loss by LTS		Accumulated Loss	
	km^2	Percent	km^2	Percent	km^2	Percent	ha	Percent
MOS	9,280	14.9%	413	0.8%	24,134	45.8%	3.38	54.2%
DST	33,394	1.8%	58,848	3.2%	215,508	12.1%	30.77	16.5%
GRS	7,250	7.3%	3,157	3.4%	20,133	22.7%	3.05	30.8%
AGR	19,353	13.3%	11,096	8.8%	87,510	75.9%	11.80	80.9%
Total	69,277	3.2%	73,513	3.5%	347,284	17.1%	49.01	22.5%

5.7 Planning Implications

There are a number of ways to better protect and manage urban ecosystems, but this study highlights three key issues that support the use of the landscape connectivity concept in landscape planning and conservation in the study area: (1) landscape-based integrative approach; (2) spatially explicit conservation tools; and (3) open space planning and management.

First, it is necessary to have a comprehensive entity with a role of converging scattered management authorities for individual ecosystem landscapes. Although agricultural land itself may have a less important role for biodiversity, when combined with adjacent vegetation patches, it may convey ecological function that it cannot otherwise. The justification of preserving urban ecosystems and open spaces is not solely for ecological processes, but also provides enormous human benefits. Many people residing in, or coming to, this area highly value the unique open spaces. Based on this study, nearly no agricultural lands will be present in this area. Thus, if some action is not taken immediately many valuable natural lands will be sacrificed. The regional aspect of open spaces needs to be emphasized.

The current approaches in open space conservation and management in Maricopa County relies largely on patch-based efforts where natural landscape elements of particular importance are solely taken care of. This approach may be good to protect individual preserves; however, it may bring further isolation of the wilderness areas without ecological problems caused by interacting processes in the overall landscape mosaic. To secure long-term sustainability and health of the urban ecosystems, therefore, the matrix-based approach should be considered as much as the patch-based approach.

Second, spatially explicit tools such as landscape connectivity as a spatial term need to be incorporated into legal and non-legal conservation plans. The Maricopa Desert Spaces plan is one such plan addressing entire landscape, but no update or revision has been made since 1995. Actual implementation of the Plan needs to be encouraged to respond to and influence other small plans and initiatives.

Lastly, it is noteworthy that shaping ecological patterns in human-dominated areas relates to what type of decision-making approach is taken into account. For instance, top-down approach often requires enforcement in implementation to some extent and thus helps systematic planning and conservation of natural landscape components. Many European countries have used this approach and demonstrated successful cases of applying ecological network concepts into land use planning as a national green infrastructure. By contrast, many cities in North America, like Phoenix, have adopted bottom-up approaches in making decisions regarding both urban projects and open space developments, which ultimately come to appear as a haphazard combination of unrelated individual planning efforts. This study calls for more attention on connecting ecosystems, not just maintaining the size of ecosystems.

5.8 Conclusion

This study examines the impacts of urban growth on the spatial pattern of crucial ecosystems in Maricopa County. Using selected landscape metrics, this study intends to understand how urban ecosystem structure is likely to evolve in response to urbanization scenarios based on proposed urban development plans. The urbanization scenario was developed with a consideration of temporal sequences and the certainty of urban projects. The short, mid, and long-term scenarios are thus relative terms specific to the current points in time in Maricopa County, each of which can be understood as a realistic, potential, and extreme conditions of future urbanization. In total, 384 combinations of landscape metrics were calculated, encompassing four different scenario levels (including baseline), three ecosystem classes, one entire landscape, six different landscape metrics, and four ecological distances.

The study results demonstrated how the landscape metrics behave with different types of urbanization options, and which ecosystem type is most likely to be sensitive to fragmentation and ecosystem loss. According to the study results, number of patches will be mostly influenced during the period of time from the current situation until the construction of the already confirmed urban plans is completed. During the time when all the proposed potential plans are actually implemented, the fractal dimension and the largest patch index will reflect tremendous change. The remaining metrics such as connectance index, Euclidian mean nearest neighbor distance, and mean contiguity will be manifested under the circumstances when all potential plans are developed and the private developable areas are completely built-out.

The future landscape mosaic in Maricopa County will be characterized by the high number of, less-connected and simplified forms of ecosystem patches. This change in ecosystem structure will entail the implications of ecological processes. For example, connectivity decrease, patch number increase, and shape complexity decrease all together will contribute to landscape fragmentation, and may in turn impede species movement and dispersal, because it is hard for animals to find adjacent habitat patches. It will be more difficult for those species whose home range is beyond the minimum patch size. The decrease of ecosystem connectivity, in particular, will eventually lead to reduced dispersal success and patch colonization rates which may result in a decline in the persistence of individual populations and an enhanced probability of regional extinction for entire populations. In addition to the ecological processes, other ecosystem services including climate change mitigation, air quality, food production, aesthetics, and recreation will be less provided, unless special efforts are made for the critical ecosystems in the landscape.

Although all types of critical ecosystems showed the formative fragmentation pattern, this study suggest that we need to pay particular attention to urban agricultural lands and desert shrub land. Agricultural lands only remained just below the critical level and are often used for secondary uses other than cultivation, while desert shrub land is, and will be, experiencing enormous land conversion mainly for large-scale residential development. Therefore, the critical ecosystem structure to be influenced by future urbanization seems to be vulnerable to carrying on the associated ecosystem functions.

The usefulness of this approach lies in its predicting capabilities for future ecosystem pattern and associated function at the landscape scale. The study provides implications for urban landscape planning, helping planners seek more optimal alternatives among various policy decisions and implementation. If the proposed urban development plans and other urbanization activities take place with an understanding of the regional context of overall land fragmentation, it will contribute to achieving landscape sustainability to prevent as much natural and semi-natural ecosystems loss as possible.

CHAPTER 6
METRO-LEVEL ANALYSIS

6.1 Issues and Problems

6.1.1 Metropolitan Landscape

A metropolitan area is usually defined as a core city, its county, and any nearby counties that are socio-economically dependent on the core city (Census Bureau, 2010). The formation of metropolitan areas is closely associated with a mass of human movement and city development, which usually take place under similar temporal and spatial coverages. Accordingly, the metropolitan areas, by nature, tend to place much emphasis on human economic and social processes. For this reason, metropolitan areas as an ecological system have been underestimated and less discussed. However, the landscape, especially the countryside part of the metropolitan areas, indeed, has a considerable amount of open natural lands interlaced with various sizes of urban clusters, and some important natural assets existed even before the cities were built.

Since the metropolitan areas support important urban ecological and cultural functions (Musacchio, 2008), they have unique characteristics that distinguish them from small-scale urban areas or rural landscapes. One of the characteristics is landscape heterogeneity that is usually shaped by patch composite of natural, semi-natural, and urban lands resulting from anthropogenic interventions. Another attribute of the metropolitan landscape is that most of ecological patches are, or will likely be, habitat islands within a vast urban sea. The remnant habitat patches within cities often have no connectivity among themselves or to natural reserves outside the urban area. Despite such challenges, the natural remnants perform multifunctional services in the metropolitan landscape, such as habitat support, micro-climate regulation, human recreation, and mitigation of other detrimental environmental problems.

Like most large cities, the growth pattern of metropolitan Phoenix has developed in the form of very market driven suburban development. Historically, the Valley has grown around the canal systems and then expanded on its periphery where utility extensions are easily installed (Redman, 2003). Leap-frog development was not an important factor in Phoenix's growth but recently has become a major type of development (Berling-Wolff and Wu, 2004) in which developers skip over properties to obtain land at a lower price further out despite the existence of utilities and other infrastructure that could serve the bypassed parcels (Heim, 2001). The green field developments often driven by the “leapfrogging,” combined with the small-scale infill residential developments encouraged by Infill Housing Program, have been major modification agents for the Phoenix metropolitan landscape.

Although it is obvious that urbanization activities influence ecological processes, ecological concerns are hardly considered in planning practices. Urban planners are key group of actors in changing urban landscape pattern but seem not interested in ecological consequences of city planning or community planning.

Ecological concerns could be incorporated in the Phoenix metropolitan landscape, when building sustainable cities or neighborhoods. Recently, several master-planned communities that attempt to deviate from traditional ways of making human communities and envision sustainability as a planning theme have emerged (e.g. Verrado and Superstition Vistas). This phenomenon is inspiring and can be a good indication for quality of life, energy efficiency and alternative transportation, but it is still difficult to find an example that takes local ecological impacts into account. The creation of such a large-scale community that may be socio-economically sustainable but not ecologically sustainable can result in regional land fragmentation and obstruction of various ecological processes.

As an effort to initiate ecological planning, it is essential to understand each planning site's ecological values and the niche of the space in the larger context of the landscape from ecological perspectives. In this regard, metropolitan-scale assessment for landscape ecological connectivity is fundamental not only for providing planners with ecological information on lands at the site scale but for understanding relative ecological importance at the regional scale.

6.1.2 Biodiversity in Phoenix Metropolitan Area

The Phoenix Metropolitan Area has undergone profound landscape transformations and subsequent habitat loss and fragmentation due to the extensive amount of urbanization during the past half century. In many places, private developments have encroached into the tapestry of natural patches and a large swath of natural lands has been under development pressure. Given the fact that habitat loss is a root cause of biodiversity decline (Byers and Mitchell, 2005), the Phoenix Metropolitan Area was deprived of rich biodiversity by swapping with an enormous volume of houses, transportation, and public infrastructure.

On the one hand, the habitat use of important species such as endangered, threatened, or rare species has not been well secured against the ongoing urban development, due in part to the relatively weak regulations on biodiversity in the State of Arizona (Collins, 2005). Particularly, many species dependent on riparian areas were much influenced, as dams built on, and cities developed along, the Salt, Verde, and Gila Rivers destroyed many miles of riparian areas (Witzeman et al. 1997). On the other hand, for some taxa, biodiversity status appears to be enhanced even with the increase of developed areas. For example, avian species that were listed as in total of 346 species in 1972 (by members of Audubon Society) surprisingly increased up to the new total of 427 species in 25 years, along with 171 nesting records (Witzeman et al. 1997). In recent years, an increase in the number of ponds and lakes in new housing developments has led an increase in waterfowl species at the expense of species found in fields, hedgerows, and trees. To a lesser degree, small green spaces, remaining ranches, and designed landscapes constructed as a part of restoration projects (e.g., Gilbert Wildlife Area Ponds) have contributed to urban biodiversity at the local scale.

The biodiversity increase in urban settings is related to species' adaptability to a new urban environment. A body of studies recently carried out corroborates the argument that cities have a complex biological gradient and urban biodiversity can be higher than that in rural areas with relatively homogeneous landscapes. However, the increased urban biodiversity tends to be comprised of habitat generalists rather than habitat specialists, as the former can use a variety of land cover types and can tolerate the presence of humans. The opportunistic species can exploit what humans, directly or indirectly, produced; whereas urban-sensitive species such as desert bighorn sheep cannot adapt to living in fragments (DeStefano and DeGraaf, 2003).

The Phoenix Metropolitan Area has some critical mountain preserves including Papago Park, Fountain Hills, South Mountain, and Piestawa Peak Park., which attract many animals native to the desert environment and enable them navigate the sea of non-habitats (Witzeman et al. 1997). However, if we continue to create the developed lands with the same speed as we do now, even the adapted species may be lost because urban development frequently outpaces their adjustment time. Litteral's study (2009) supports this argument to some extent, as it addresses bird species diversity in the Phoenix urban region. Litteral's findings show that biodiversity will be influenced by the size and distance between native habitat fragments.

Unfortunately, current efforts to conserve biodiversity in the Phoenix Metropolitan Area seem to be limited, with more concentration on specific target species conservation. Coupled with political preferences for such “popular” species, much attention tends to be given to wild lands and far-reaching desert areas the species of concern usually inhabits. Yet, a growing body of literature argues that biodiversity considerations should be addressed in the areas experiencing extreme urban sprawl like the Phoenix Metropolitan area.

In conservation practice, biodiversity is commonly evaluated by either reactive “endangered species” approach that address species already in trouble, or proactive “hot spot” approach that focuses on protecting geographic areas with a high concentration of biodiversity (Ahern et al. 2007). However, it is desirable to have a new approach that better fits metropolitan-scale landscapes, and species-based landscape connectivity approaches can be one of the avenues to conserve urban biodiversity and ecological integrity in heterogeneous metropolitan landscapes. There is a widespread consensus among conservation scientists and planners in Phoenix on the importance of metropolitan-level connectivity conservation, but neither group has initiated any study or program for ecological connectivity assessment and biodiversity planning in this region (personal communication, John Gunn).

6.2 Research Goals, Hypothesis, and Propositions

The overarching goal of this study is to assess landscape ecological connectivity of Phoenix metropolitan landscapes to enhance landscape sustainability. To this end, operational objectives for this study include: (1)

conducting landscape-scale ecological connectivity modeling for a group of species representing the Phoenix urban desert landscape; (2) generating a composite map showing the relative values of ecological connectivity in the Phoenix metropolitan landscape; and (3) coupling landscape ecological connectivity with urban dimensions such as population density and urban land cover proportion.

The main hypothesis is that connectivity of urban habitat patches is largely affected by urban density. The underlying propositions include: (1) lower connectivity is predominant in areas with high urbanization cover; and (2) landscape connectivity values would most likely decrease at the interfaces between urban, suburban, and rural areas, because of the frequent occurrence of local urban development projects.

6.3 Research Questions

To test the hypothesis and propositions discussed above, the following research questions were answered during the study:

(1) To what extent are ecologically important areas for urban desert species connected in the Phoenix Metropolitan Area landscape?

(2) How can landscape connectivity be measured? How are the functional patches determined?

(3) How differently does the connectivity pattern appear in different urban conditions? How does landscape ecological connectivity relate

to urban dimensions such as human population and percent urban cover? Does the urban modification gradient correlate with landscape connectivity?

(4) What are the spatial impacts of the proposed urban development plans on connectivity change? How would the development plans influence future ecological connectivity in the Phoenix metropolitan region? Is there a clear distinction in connectivity measurements particularly in the areas where different urban densities interface with one another?

(5) How does the ecological and cultural context of a place affect approaches for biodiversity conservation?

6.4 Research Setting: the Phoenix Metropolitan Area

The Phoenix Metropolitan Area is one of the fastest growing regions in the United States. Centered on the City of Phoenix, which has a population of approximately 1.5 million, the area has experienced dramatic land use change since the early 1930s (Esbah et al. 2009). The exponential urban growth resulted in nearly half of the entire area being dominated by urban lands through continuous conversion from natural ecosystems and agricultural lands (Park, 2010). In the broad context, the Phoenix Metropolitan Area includes two major Counties, Maricopa and Pinal, which contain more than 20 municipalities and three Native American reservations, and are mixed with extensive, rugged desert lands and rural or completely uninhabited areas. At the smaller scale, the more urbanized, core portion of central Arizona can be defined as the Phoenix Metropolitan Area. This study takes the small-scale, urbanized metropolitan areas to investigate ecological connectivity especially in an urban setting.

The geographical extent is about 773,972 hectare and the regional topography is relatively flat with an elevation range from 100m to 2,300m. Although natural patches are often threatened by anthropogenic activities such as suburban and exurban development (Musacchio et al. 2003), there are still critical ecosystem remnants and other natural components including scattered but quality urban mountains, desert washes, cropland leftovers, and small urban green spaces which together can play a pivotal role in urban biodiversity and climate regulation.

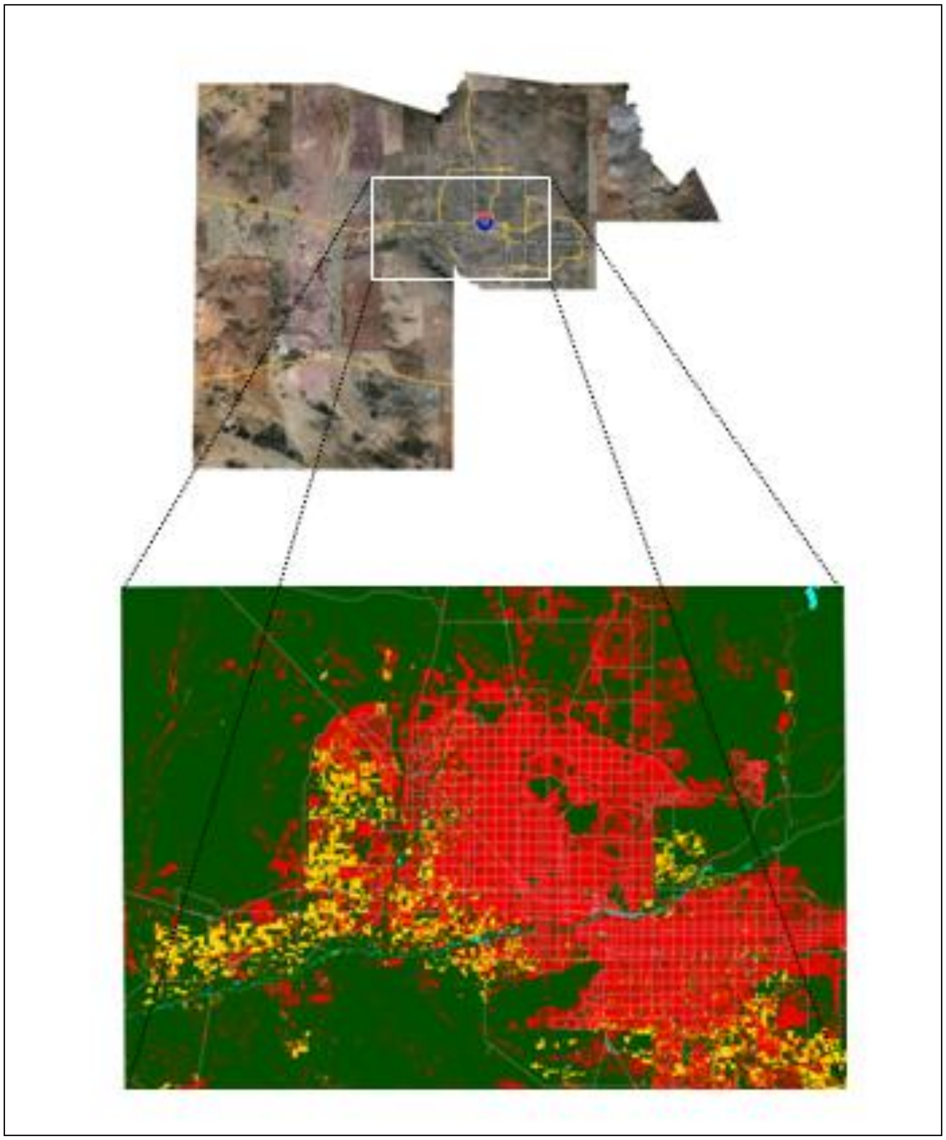


Figure 6.1 Location of Phoenix Metropolitan Area

Although the urban growth in this region has continued to develop rapidly, there are some factors essentially causing urban expansion to stop or slow substantially. For example, some mountain ranges act as barriers making development flows around them. The islands of open space such as South Mountain, Camelback Mountain and North Mountain are now pockets of preserved wilderness within the urban portions of the region, and White Tanks, Estrella, Superstition and McDowell mountains are at the edge of the urban area. Indian communities are another component since they have not sold their lands for non-Indian community use. Hence, development was limited by the Salt River Pima-Maricopa Indian Community to the east and the Gila River Indian Community to the south.

In addition, a substantial portion of federal lands have not been influenced by regional development. All these factors forced the pattern of urban development into a slanted figure eight that is bordered by agricultural areas to the south and desert areas to the north. However, it is anticipated that future urban development will hurdle over the physical barriers, since Native communities and public lands began to be developed for commercial and industrial use (Melnick, 2003).

6.5 Methods

6.5.1 Data

To identify urban habitat patches for landscape connectivity modeling, the Land Cover Dataset (2005) with 30 m resolution was obtained from the Central Arizona Project Long-Term Environment Research (CAP-LTER). Based on the common knowledge that vegetated areas can be an effective proxy for habitats, especially in urban areas, this study took five urban habitat types, including natural vegetation, cultivated vegetation, cultivated grass, undisturbed Sonoran

Desert, and river gravels (Table 6.1 for description) and used them for main habitat data for ecological connectivity analysis. How this classification is distinct from the land cover data classes used for the county-level analysis (See Chapter 5) is that it mostly consists of remnant vegetation patches with more human intervention and disturbance, excluding a huge tapestry of rural, undisturbed areas.

Even if the Land Use Dataset (2009) is more recent than the Land Cover Dataset, the Land Use Dataset was not considered in the urban habitat selection since it cannot account for the actual footprint of vegetated lands. For instance, the exclusion of vegetated lots in residential parcels or inclusion of non-vegetated lands within region park boundaries may misguide about the distribution of urban habitat patches. To validate the accuracy of land cover classifications, the Land Cover Dataset was compared with other supplemental information such as Land Use data, Arizona GAP data, Google maps, and various forms of meta-datasets. Although it is generally known that larger patches are beneficial to ecological processes, all selected natural patches were, regardless of size, taken into account, because even small vegetation patches may be able to play a significant role in local ecology.

Table 6.1 Natural land cover types in Phoenix Metropolitan Area

Categories	Description	Corresponding Land Use Codes
Natural vegetation	Actively photosynthesizing vegetation	Mostly vacant area and passive/restricted open space (mountain preserves)
Cultivated vegetation	Actively photosynthesizing vegetation with agricultural water rights	Mostly agriculture, and parts of vacant and built-up areas
Cultivated grass	Actively photosynthesizing vegetation in urban park areas	Mostly residential, golf courses, active open space, and other built-up areas
Undisturbed Sonoran desert	Undisturbed soil, native vegetation, bedrock outcropts	Mostly active open space (e.g., regional parks)
River gravels	Adjacent to water	Mostly water, passive/restricted open space (washes)

Additionally, population data (Census 2010), Land Use 2009 (MAG), and town point data (ASU ISSI, 2000) were used to delineate spatial boundaries of urban, suburban, and rural areas. The areas being used for urban purposes in the Land Use Data were extracted, except passive and active open space areas, into the urbanization gradient analysis where the three different zones in different urbanization statuses was distinguished (For detailed description, see Section 6.5.4). The Land Use Data (2000) was used for a barrier effect analysis and ecological connectivity modeling.

6.5.2 Indicator Species Approach

A group of urban desert species were selected for assessing landscape ecological connectivity. An indicator species refers to a species whose status provides information on the overall condition of an ecosystem and other species in that ecosystem (Ahern, 2006). The indicator species approach is particularly useful when there is little species-specific knowledge and time and resources are too limited to take the inclusive approach. The concept of focal species is a central theme in large-scale conservation planning and in regional connectivity assessments (Lambeck, 1997; Miller et al. 1998; Solué and Terborgh, 1999). Mammalian carnivores can be effective focal species to evaluate the degree of landscape-level connectivity in urbanizing areas, because they are particularly vulnerable to extinction in fragmented habitats, given their wide ranges and resource requirements, low densities, and direct persecution by humans (Woodrof and Ginberg, 1998; Crooks 2002). Their disappearance may generate ecological cascade that can dramatically alter ecological communities (Solué and Terborgh, 1999).

It is noted that selection process for indicators is critical and should consider sampling techniques and samples sizes, scale, and environmental stressors, but currently there is little consensus in the literature regarding methods of selection for indicator fauna (Hilty and Merenlender, 2000). Indicator species per se tend to be used with expectation for positive correlation with ecological integrity or biodiversity or as negative signals indicating degradation of ecosystem health. Recently, ecosystem patterns, processes, or relationship are receiving more attention as indicators of biodiversity, as species based approaches have been criticized on the ground that they don't provide whole-landscape solutions to conservation problems (Lambeck, 1997). Since this study highlights the collective ecological values of the entire study region with focuses on natural land covers that can function as viable or potential habitats from a connectivity perspective, the mixed approach of multiple indicator species combined with habitat connectivity pattern was assumed to be appropriate to flag biodiversity status in this region.

A detailed selection process was undertaken as following: First, all avian species and large mammals that have been either observed or recorded in the Phoenix metro-area were garnered and placed into a so-called “species profile,” which lists the species-related information. The species profile was developed to build a habitat inventory about habitat type, minimum ecological areas, and home ranges required for the species. Other animal genera representing waterfowl, small mammals, amphibians, reptiles, and insects were excluded from consideration in the species pool, because of different levels of responses to barriers among species, conflicting habitat use, inconsistent scales of analysis, and lack of ecological information, which may result in spurious composite connectivity outcomes.

Second, the collected information was rearranged according to habitat type to categorize habitat-dependent species groups. In doing so, a priority was given to the species with larger minimum habitat areas and broader home ranges, which could serve as umbrella species of which habitats contain a nested subset of species (Wilcove, 1994). Third, the species profile was used as a medium to consult with regional biologists and conservationists for deriving key indicator species out of the entire list. From 2008 to 2010, five experts were consulted, using in-person interviews, phone interviews, and/or electronic communication. The appropriateness of the species as a surrogate for a larger community of species and the degree to which the species can be considered to represent broad landscape attributes to the maximum acceptable levels of threats (Lambeck, 1997) were considered as key factors in the species selection process.

6.5.3 Landscape Ecological Connectivity Modeling

As a main analysis method for assessing landscape ecological connectivity, GIS-based modeling technology was used. The landscape ecological connectivity modeling largely consists of four parts including: (A) Identification of natural land covers; (B) Filtering out functional habitat patches with consideration of indicator species; (C) Evaluating barrier effects; (D) Generation of landscape ecological connectivity index (ECI) and resultant maps. This whole process was based on a modified version of Marull and Marulli (2005)'s approach. The main characteristic of landscape ecological connectivity modeling developed by Marull and Marulli (2005) is that the least-cost distance method and map algebra are used as key means in connectivity quantification.

The reason why this study moderately employs Marull and Marulli's approach is that, first, the spatial scales of the research settings are the same, both of which deal with the metropolitan region as their study area for landscape connectivity modeling; second, the Barcelona region the authors address has similar landscape problems as Phoenix is facing, including rapid urban sprawl and simultaneous need for natural remnants conservation; third, despite complicated intermediate stages in the computational process, the ultimate products of applying their method appears in the form of a series of maps showing the range of numeric values of ecological connectivity across the region, which is easy to understand compared to other methods measuring landscape connectivity and thus more viable for land use planning or regional biodiversity planning; forth, it is arguably the most viable approach for planning application among existing methodologies calculating connectivity.

Two components distinguish the model of this study from the original model. The most important difference is that this study constructs a species-based landscape connectivity model where urban habitat patches are determined by the selected indicator species and their habitat requirements, whereas Marull and Marulli's method relies much on the distribution of minimum ecological areas based on statistical topographical analysis. The GIS model of this study allows not only overall pattern analysis for regional landscape connectivity but also the characterization of habitat connectivity for selected individual species. Moreover, this study links landscape ecological connectivity to urban dimensions investigating spatial variance of connectivity values along the urban modification gradient. In the following sections, each step of the landscape ecological connectivity model is described.

6.5.3.1 Urban Habitat Patches to Be Connected

To identify the kinds of habitat to be connected, corresponding natural covers in tandem with selected indicator species were used as input data for the GIS analysis. If a polygon meets the habitat type criteria, further investigation as to whether or not the polygon meets the required habitat size was made. If a polygon does not meet the size criteria, it is then assumed to be fragmented patch, but still with the potential to act as a corridor or stepping stone for habitat generalists. Both aspatial and spatial datasets and relevant information gained from ecological projects such as Arizona Wildlife Linkages, Arizona GAP analysis, BLM Wildlife Conservation were used.

6.5.3.2 Barrier Effect Index (BEI)

Urban development and artificial structures often hinder the movement of ecological processes, including animal movement. It is especially true of species that do not disperse easily or widely or that have limited abilities to negotiate obstacles. Barriers to animal dispersal at the ground level are abundant in urban and suburban systems, including culverts, concrete ditches, asphalt surfaces, fences, walls, railroads, and even swimming pools.

To reflect the barrier effects in measuring ecological connectivity, a group of artificial attributes were designated with different weights on each attribute depending on the relative influence on the entire landscape (Table 6.2). The maximum level of weight was given to the built-up areas comprised of high-

(more than 10 dwelling units per acre) and medium-density (5-10 dwelling units per acre) residential development, along with commercial and industrial areas, because the built-up areas are for the most time impermeable to movement of many species. The low-density residential areas do not exist within the site boundary according to the Maricopa County land use standard (2004) and thus were not considered for the barrier effect analysis. Instead, the smallest barrier effect weight was given to some public facility building blocks scattered throughout the region because they have a similar influence as a barrier within the low-density residential areas.

Roads are undoubtedly a major obstacle blocking the travel of many species. A considerable body of literatures discloses the evidence of the effects of roadways such as road kills. Unless any green design treatments are made along the road corridors (e.g., greenways), small animals and limited-ranging species cannot across the roads at all (Eigenbrod et al. 2008).

Since the width of roads and traffic volume are important determinants of species distribution and abundance and cause frequent species mortality, the barrier weight on local arteries was doubled for highways and freeways. Water can be used either as a major habitat for such species as waterfowl or at least as resting places for the species passing over the landscape. At the same time, it also can act as a very strong barrier for some species like terrestrial vertebrates. Since this study does not consider water body related species, water bodies such as rivers and streams were counted as medium-level barriers.

Table 6.2 Weighted value system for barrier effect index calculation (Modified from Marull and Marulli (2005))

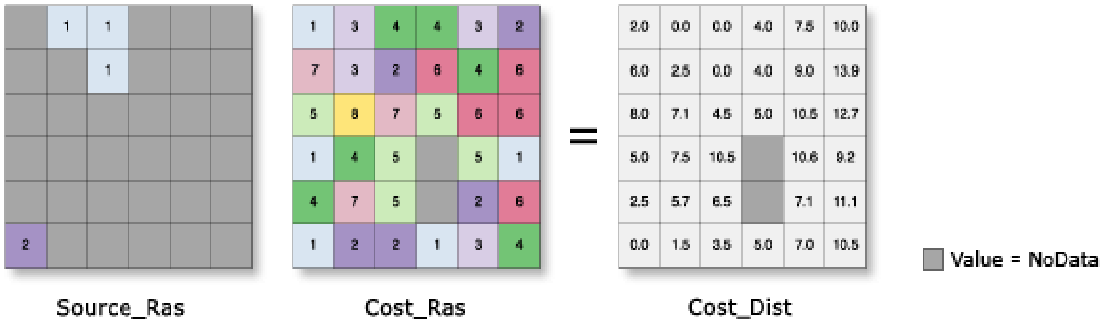
Code	Description	Weighted values	Ks1	Ks2
B1	Public facility, scattered	b1=20	$k11 = 11.100$	$k12 = 0.253$
B2	Local arteries	b 2=40	$k21 = 22.210$	$k22 = 0.123$
B3	Water, canals	b 3=60	-	-
B4	Major Highways, freeways	b 4=80	$k41 = 44.420$	$k42 = 0.063$
B5	Built-up areas	b 5=100	$k51 = 55.520$	$k52 = 0.051$

NOTE: $\alpha = Ys(bs/2)/bs$; $Y3 = b3$

6.5.3.3 Cost-Distance Analysis

The ecological connectivity model is primarily based on the cost-distance analysis that considers the different “urban habitat patches” and an “impedence surface” which incorporates the “barrier effect” and a “potential affinity matrix” (Marulli and Mallarach, 2005). The principal algorithm underlying the cost-distance analysis is the least-cost method. The least-cost algorithm calculates the cumulative costs to move from one cell to another (Adriaensen et al. 2003) in the entire landscape. The average cost value to move through the particular cell is given back to the cell with the rules of edge to edge distance and eight neighbor-cell calculations where vertical, horizontal, and diagonal movement is allowed. In case of diagonal directions, the cost is multiplied by the square root of two to compensate for the longer distance (ESRI, 2010). In this way, the cost value in each cell represents the distance to the source, measured as the least effort (lowest cost) in moving over the resistance layer.

The cost-distance analysis requires two GIS layers; a source layer and a friction resistance layer as the input of the model. The source layer indicates the habitat patches from which the connectivity is calculated. This may be a single patch, or a complex of patches (Adriaensen et al. 2003). This study prepared a suite of source raster layers of urban habitat patches specific to each focal species. The resistance layer generally indicates the resistance values. Some ecology behavior studies take the orientation or altitude of the relevant landscape elements as barrier attributes (Belisle, 2005). In this study, the resistance layer uses two surfaces such as “barrier surface” and “impedance surface”. While the barrier surface assigns the pre-specified weight values on each raster cell based on the land use class and the barrier weight system (See Section 6.5.3.2), the impedance surface was made by the potential affinity matrix that considers to what extent each cell in the grid is similar to the neighboring cells. From this process, an adapted cost distance was obtained:



Source_Ras

	1	1			
		1			
2					

Cost_Ras

1	3	4	4	3	2
7	3	2	6	4	6
5	8	7	5	6	6
1	4	5		5	1
4	7	5		2	6
1	2	2	1	3	4

=

Cost_Dist

2.0	0.0	0.0	4.0	7.5	10.0
6.0	2.5	0.0	4.0	9.0	13.9
8.0	7.1	4.5	5.0	10.5	12.7
5.0	7.5	10.5		10.6	9.2
2.5	5.7	6.5		7.1	11.1
0.0	1.5	3.5	5.0	7.0	10.5

▨ Value = NoData

Figure 6.2 Cost-distance calculation (Source: 1995-2010 ESRI inc.)

This model individually calculates the barrier effect and the impedence surface for both each barrier subclass type and each indicator species. The simple and adapted cost-distance analysis was conducted using the CostDistance function available in the Spatial Analysis extension in ArcMap software version 10 (ESRI, 2010). The various types of databases were converted into raster data with a cell size of 10 m to operate the connectivity modeling. The entire procedure was conducted using ModelBuildier in ArcGIS 10 to systematically display and run a sequence of cost-distance functions and other map algebra (See Appendix I for the full model diagrams).

6.5.4 Urban Modification Gradient Analysis

The landscape gradient analysis is often utilized to understand a certain pattern of interest through one or more specified sections of spatial continuum which can best represent the characteristics of an entire region. There are significant amount of gradient analysis research in the Phoenix region especially focused on the effects of urbanization (Zhang et al. 2010). Most of the previous studies tacitly suppose that the Phoenix Metropolitan Area follows the mono-centric urban model where urbanization takes place and spreads from only one city core. In reality, however, the urbanization pattern of the Phoenix Metropolitan Area does not coincide with the single concentric form in theory and rather allows multiple urban clusters in the agglomerated fashion. This study recognizes that the Phoenix Metropolitan Area is far closer to multiple-concentric urban model with the assumption that urban growth evolves along and around pre-established urban development paths.

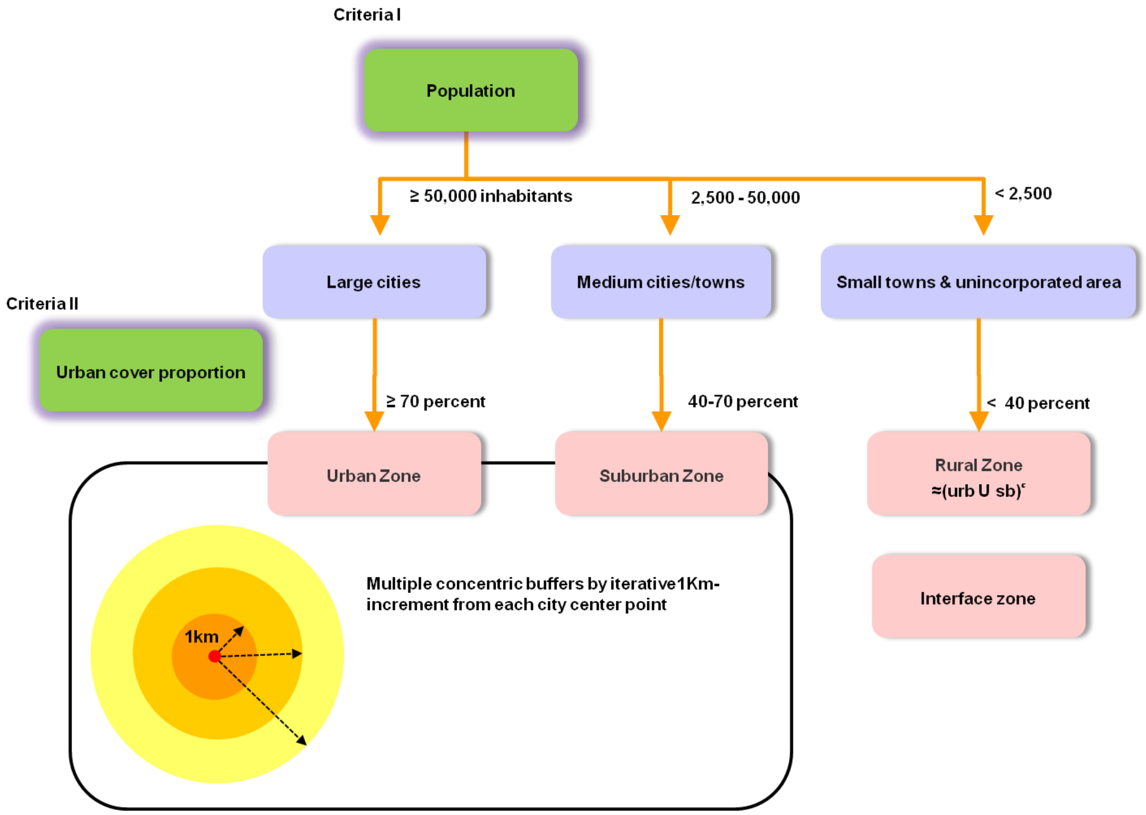


Figure 6.3 Diagram of urban gradient modification analysis

Along this line, this study attempts to transform the somewhat context-driven terms of urban, suburban, and rural areas into the simplified spatial framework with physical boundaries so that they can be compatible with spatially explicit ecological connectivity modeling. Consequently, the urban modification gradient analysis in this study classifies the three different spatial zones according to urbanization status, such as urban, suburban, and rural zones. The mechanics of the whole analysis starts with two underlying criteria, including human population and urban land use proportion (Figure 6.3). The population thresholds are determined based on the operational definitions from the United States Census Bureau and United States Department of Agriculture's Economic Research Service. If a city has a population of greater than 50,000, the city's center point (i.e., location of a city hall) is buffered with one kilometer increments until the buffered areas fulfill the criteria of the urban land use proportion. Operated by a GIS-based buffering method, the multiple concentric buffers were iteratively created with one kilometer increments for all the corresponding cities and towns. Since the built-up areas tend to become diluted with increasing distance from an urban core, if the urban land use proportion begins to fall below 70 percent, the operation stops and then the buffer area is defined as an urban zone.

On the other hand, suburban zones are determined when cities or towns have a population from 2,500 to 50,000 and at the same time the buffered areas have 40-70 percent of the total urban land use. It is possible though that some town points exist within, or adjacent to, the predefined urban zones. In such case, the portion already taken up by urban zones is ruled out in measuring urban land use proportion. In other words, only the part of the buffer area protruding over the urban zone boundary is counted (Figure 6.4). Several towns were selected as candidate cities fulfilling the population criteria for suburban zones but eventually not included in suburban zones because the buffered areas didn't meet the 40-70 percent urbanized land cover.

The rest of the areas being neither urban zones nor suburban are defined as rural zones, and no buffering work is applied to this area since there are essentially no significant urban nuclei which by themselves cannot develop an urbanized buffer form. The rural zones are characterized by some small towns under 2,500 population (source: Office of Management and Budget, USDA Economic Research Service, U.S. Census Bureau) and natural landscapes.

Those areas where the edges of different zones converge or intersect each other are called "interface zones." The interface zones are a conceptual representation contingent upon the location of urban, suburban, and rural zones and thus subject to landscape-specific change. This concept is used to examine the likelihood of extraordinary influences of ecological connectivity at the particular in-between spaces. Based on the various cases of the interface zones that can be found in the context of the Phoenix Metropolitan Area, a spatial typology for interface zones was developed.

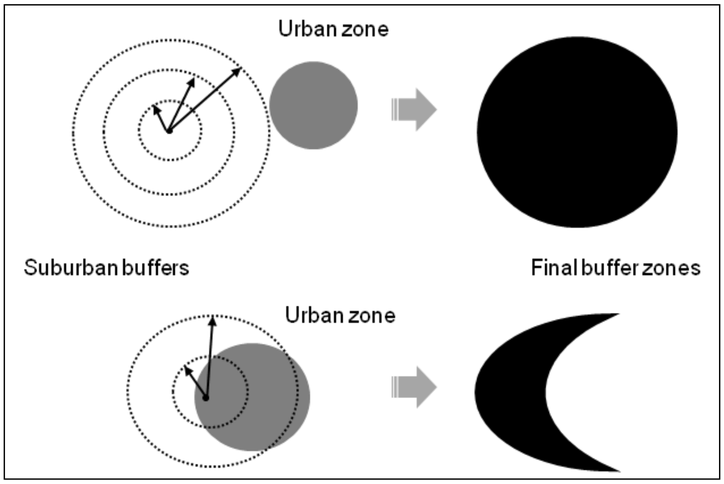


Figure 6.4 Diagram for suburban zone delineation

6.6 Results

6.6.1 Indicator Species for Urban Desert Landscape

Through the selection process, seven focal species were chosen to represent the Phoenix Metropolitan Area's critical urban habitats, including three avian species, three terrestrial vertebrate mammals, and one reptile species. The avian species include Cactus Wren [A1], Abert Towhee [A2], and Annas Hummingbird [A3], and the terrestrial mammals include Coyote [M1], Grey Fox [M2], and Mountain Lion [M3]. Desert tortoise [R1] was considered as an important reptile species native to the desert environment. The summary of the habitat requirements and minimum habitat sizes of the selected group of species is described in Table 6.3.

The habitats for each indicator species are considered to be suitable enough to encompass other species that use the habitat type with a smaller range. For example, the habitats of coyote are oftentimes overlapped with that of bob cats (Tigas et al. 2002) and the distribution of mountain lions corresponds with the distribution of its major prey species, deer (Arizona Game and Fish Department, 2009). These umbrella species capture the variation in the degree of fragmentation sensitivity and habitat requirement, yet have a certain level of limited mobility because the landscape ecological connectivity modeling is supposed to measure a distance relationship. For this reason, some important but omnipresent species like the ornate tree lizard (*Urosaurus ornatus)* were counted out, despite their biological importance in the Phoenix desert landscape (personal communication, John Gunn). Below is a brief description about ecological characteristics of individual indicator species and their potential habitat patches.

[A1] Cactus Wren (*Campylorhynchus brunneicapillus*)

The cactus wren is a passerine that can be easily found in arid regions (IUCN, 2006). In the Phoenix area, this species is present all year round in moderate numbers (Witzeman et al. 1997) and known to nest in cactus plants or saguaro holes. It is a common resident in the Lower Sonoran Zone, especially in cholla cactus habitat and also an uncommon resident in Upper Sonorant mesquite habitat. Accordingly, most undisturbed desert lands excluding Sonoran upland were identified as potential habitats of cactus wren. Since literature indicates that the elevation higher than 4, 000m is unsuitable for this species (U.S. Fish and Wildlife Service, 1985), Digital Elevation Model (DEM)-based altitude analysis was carried out. The highest point in this region appeared around the top of the Browns Peak (one of the Four Peaks) with an elevation of about 2,300 m, so all the potential habitats identified were fed into the habitat size analysis to select out the habitat patches with more than 0.4 hectare. Of the potential habitats (975,880ha), approximately 51 percent of the land was identified as urban habitats for cactus wren (502,390 ha).

[A2] Abert Towhee (*Pipilo aberti)*

The Abert's towhee is native to a small range in southwestern North America, generally the lower Colorado River and Gila River watersheds, nearly endemic to Arizona. This bird is very famous species that can be seen all year around in Maricopa County more than any other places in the United States (Witzeman et al., 1997). It is particularly abundant in the Lower Sonoran desert and requires brushy riparian areas to forage for seeds. It is classified as a species of least concern in the IUCN Red list (IUCN, 2006). Riparian areas in Sonora desert and cottonwood-willow mesquite vegetation are major habitat for this species, and they have successfully colonized suburban environments in the Phoenix Metropolitan Area (Alcock, 1993). However, this species tends to be threatened by the increasing loss of riparian habitats, as Alcock (1993) indicates that only 5-10% of Arizona's riparian vegetation remains. Therefore, exotic vegetation becomes alternative habitats, and recently their presence is reported even in Phoenix suburban backyards (Alcock, 1993). All natural vegetation patches with an elevation of lower than 1,300m and larger than 1.5 ha were identified for this species. Due to the rarity of riparian areas in the Phoenix area, all riparian areas were considered regardless of habitat size. The relatively small areas of lands (194,426 ha) were selected as potential habitats for Abert Towhee and then nearly half of the lands (98,377ha) were finally considered for ecological habitat areas for this species.

[A3] Annas Hummingbird (*Calypte anna)*

The Annas hummingbird is non-passerine and present in moderate numbers all year round in the Phoenix area. Its nesting was first founded in 1964, and Sunny slope and Scottsdale were the places where initial observation of this species was made in mid-sixties. Since 1969, the nesting activity has increased and this species has spread rapidly throughout the Phoenix area. This species is a common resident, especially in fall and winter. There are few summer records, as the species usually departs the Phoenix area by early April and does not return until October, although there is a record of a small number of the birds in the summers in 1970s (Witzeman et al., 1997). The habitat coverage for this species was created by combining vegetation, cultivated grass, fields, riparian areas, and Sonoran scrub lands. In addition, vegetated areas comprising of chaparral, palo verde mixed with cacti, and chaparral mixed with evergreen sclerophyll were added to the habitat coverage. The combined habitat polygons were reevaluated with a minimum habitat size of 0.9 ha and then selected polygons were prepared as potential habitats for Annas Hummingbirds. The majority of the potential patches (402,250ha) were designated as ecological patches.

[M1] Coyote (*Canis latrans)*

Coyotes have become dominant predators in many parts of North America (Jantz et al., 2010). Home ranges vary depending on regions and gender. For example, a study in Texas found that the average home range is 2 square miles and another study in Washington indicated 21 to 55 square miles for their range. Males tend to have larger home ranges than females. In Minnesota, male home ranges averaged 16 square miles (42 sq km), whereas those of females averaged four square miles (10 sq km). The home ranges of males overlapped considerably, but those of females did not. In Arkansas, Gipson and Sealander reported that male coyote home ranges were eight to 16 square miles (21-42 sq km) and female home ranges were three to four square miles (8-10 sq km). In Arizona, average home range for adult females is 55 km2 (5500ha) and adult males are 53 km2 (Litvaitis and Shaw, 1980).

Coyotes can be found anywhere in the Phoenix area. Coyotes tend to range throughout urban areas. Recently unofficial records demonstrate that coyote's emergence has been sighted in even heavily urbanized and populated areas such as New York and downtown Chicago and Los Angeles. The decrease in quality habitat and food shortages often makes this species move close to human residential areas.

All kinds of natural land covers were merged with desert grasslands and the saltbrush and sagebrush vegetation areas and then only more than five square kilometers patches were considered to be connected. Bob cats will most likely benefit from the potential habitats because coyote and bob cats share their habitats, and bob cats have the smaller home range of 634ha than coyotes. In this study, 441,192 ha of potential patches were identified and 97 percent of the lands (427,234 ha) were selected for ecological patches.

[M2] Kit Fox *(Vulpes macrotis arsipus)*

Kit foxes favor arid climates, like desert scrub, chaparral, and grasslands. The recent record also indicates that this fox species occurs in agricultural and urban areas (Frost, 2005). The urban kit fox population in Phoenix is most often seen at night and was also found on sandy plains in the southwestern deserts (Arizona Game and Fish Department, 2009). According to Zoellick et al (1989), the desert kit foxes in the Sonoran Desert dens and rests in creosotebush flats and riparian habitats. A more recent study (Frost, 2005) in San Joaquin Valley, California revealed that kit foxes use urban lands features and spend the most time in sump (water catchment basins) and open habitats. The empirical survey also indicated that kit foxes primarily used subterranean dens but also used pipes and other man-made structures such as culverts and bridges.

Given the fact that the urban kit fox population can use the transition and manicured urban habitats for resting, foraging, and traveling, the wide-reaching canal system in the Phoenix Metropolitan Area may have a potential for the species recovery by serving as a corridor, if it is well restored for this purpose. The conservation of open habitats around Phoenix exurban areas can contribute to the distribution and abundance of the urban kit fox population. With the mean home range size of 172 ha for this species (Patton and Francl, 2008), potential patches of 400,871 ha were identified and 83% of the lands (331,876 ha) were designated as ecological patches.

[M3] Mountain Lion (*Puma concolor*)

The mountain lion is Arizona's second largest carnivore and conventionally managed as a big game animal (Thompson et al.) Mountain lion distribution was documented in 1987 (Shaw et al. 1988) and 1996 (Germaine et al. 2000), and recent records indicate that the species population is increasing statewide. Since late 2005, total of 405 observations of mountain lions in human settlements were made. Mountain lions prefer spacious habitats, with larger than 5,180 ha of desert shrubs and grasslands. Even though mountain lion habitats are distributed mostly in the distant mountain ranges (e.g., Kofa, Castle Dome, New Water, Palomas, and Eagle Trail Mountain) outside the study area, their emergence is occasionally observed in urban open spaces such as golf courses located in the Phoenix exurban areas.

Mountain lions in Arizona are currently managed on the adaptive site-specific predator management plan, because this species influences the population of desert bighorn sheep. Based on some ongoing research, this species' population density is estimated to be significantly affected by human development (Sweanor et al. 2000). Due to the mountain lion's large home range, a relatively large amount of land (1,374,934 ha) was considered for potential patches, and 66 percent of the land (908,063ha) was selected for ecological patches.

[R1] Desert Tortoise (*Gopherus agassizii*)

The desert tortoise is an herbivore that may attain an upper shell length of 9 to 15 inches. At least 95% of its life is spent in burrows, where it is also protected from freezing while dormant from November through February or March. Herbs, grasses, shrubs, cacti, and flowers comprise a major portion of their diet. Ravens, Gila monsters, foxes, roadrunners and coyotes are all natural predators of the desert tortoise. They tend to live on steep, rocky hillside slopes in Palo Verde and saguaro cactus communities. In Utah, the desert tortoise has been listed as a threatened species, and their habitat was designated as critical habitat (Fish and Wildlife Service, 1980). They have a small home range of 0.75 square miles.

In Arizona, the Bureau of Land Management conducted a study of this species' distribution. The desert tortoise distribution map categorizes their habitats into Cat1, Cat2 and Cat 3, depending on conservation value. Even though there is no Cat 1 zone (high conservation area) in the study area, some areas with Cat2 and Cat 3 zones occur in urban mountains in the northwestern and southwestern part of the region. The vegetation types considered for this species include palo verde, saguaro cactus, creosote bush, and semi desert grass. Some river gravel areas were merged into possible habitats, and the patches with larger than 194 ha were reselected for final delineation of the habitat patches. Due to the species small-ranging characteristics, all the potential patches (254,026 ha) were designated as ecological patches.

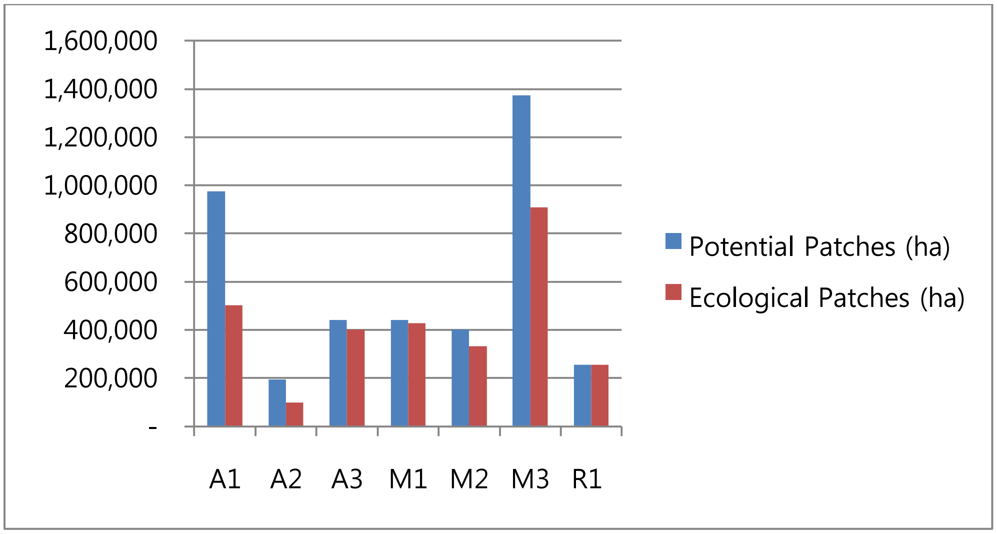


Figure 6.5 Total amount of potential and ecological patches for indicator species

Table 6.3 Total amount of potential and ecological patches for indicator species

Species Codes	Potential Patches (ha)	Ecological Patches (ha)
A1	975,880	502,390
A2	194,426	98,377
A3	442,419	402,250
M1	441,192	427,234
M2	400,871	331,876
M3	1,374,934	908,063
R1	254,026	254,026

Table 6.4 Selected Indicator species, habitat types, and home ranges

Species Group	Code	Species Names (Scientific Names)	Habitat Type	Data Sources	Home Range	Literature Sources	Fragmentation Sensitivity
Avian	A1	Cactus Wren *(Campylorhynchus brunneicapillus)*	Desert Scrublands	Undisturbed. Sonoran desert below 4,000 ft	0.4ha	Anderson & Anderson (1973)	Medium Tolerant
	A2	Abert Towhee *(Pipilo aberti)*	Riparian in Sonoran; Cottonwood-Willow Mesquite Natural+exotic vege; Remnants of riparian woods and shrubs, marshes, and exotic vegetation	Riparian (ISSI); Vegetation, Cul_vege below 1,300m (CAP-LTER); Agriculture attached to the habitats above	1.5-2ha	Rosenberg et al. (1991)	Medium Tolerant
	A3	Annas Hummingbird *(Calypte anna)*	Arid scrub Semi-desert, open situations in arid habitats. Urban and suburban Chaparral (vege is low and uniform)	Cultivated grass Natural vege Undist-Sonoran (CAP-LTER) Chaparral (GAP)	0.9–1.3 ha	Powers (1987)	Medium Tolerant (exotic)
Mammals	M1	Coyote *(Canis latrans)*	Adaptable to almost all habitat, Desert Mountain Desert scrub, Chaparral, Grasslands; Urban and suburban with green, mowed grass	Natural vege, Undist Sonoran, Cul_Grass, Cul_Vege (CAP-LTER) Grassland (NLCD) Saltbrush & sagebrush (GAP)	1,295-	Litvaitis & Shaw (1980); Jantz (2010)	Low (Enhanced)
	M2	Kit Fox *(Vulpes macrotis arsipus)*	Sump and open habitats; Agriculture and urban habitats in elevation range of 400-1900m	Undist Sonoran, Cul_Vege (CAP-LTER)	172 ha	Frost (2005); Patton & Francl (2008)	High Sensitive
	M3	Mountain Lion *(Puma concolor)*	Desert Mountains	Undis-Sonoran Natural vege Grass (NLCD)	5,180ha	Arizona Game and Fish Dept.(2011)	High Sensitive
Reptiles	R1	Desert Tortoise *(Gopherus agassizii)*	Semi-arid grasslands; Gravelly desert washes; Canyon bottoms and rocky hillsides below 3,530 ft	CAT2/ CAT3 (BLM) River Gravels; Grassland (NLCD) Palo Verde and Saguaro Cactus (GAP)	194ha	IUCN (2006)	High Sensitive

5.6.2 Matrix-Influenced Barrier Effects

Figure 6.5 illustrates the overall barrier effects with weighted values on each barrier type in the Phoenix Metropolitan Area. The barrier effect index values given on each grid cell were re-calculated with the matrix affinity attributes. Table 6.4 demonstrates affinity values between different neighboring cells in each type of habitat-barrier combination. The affinity matrix numbers reflect the relative coherency in, and species' response to, the landscape mosaic and are incorporated into the adjusted barrier effects. Figure 6.6 shows the matrix-influenced barrier effects.

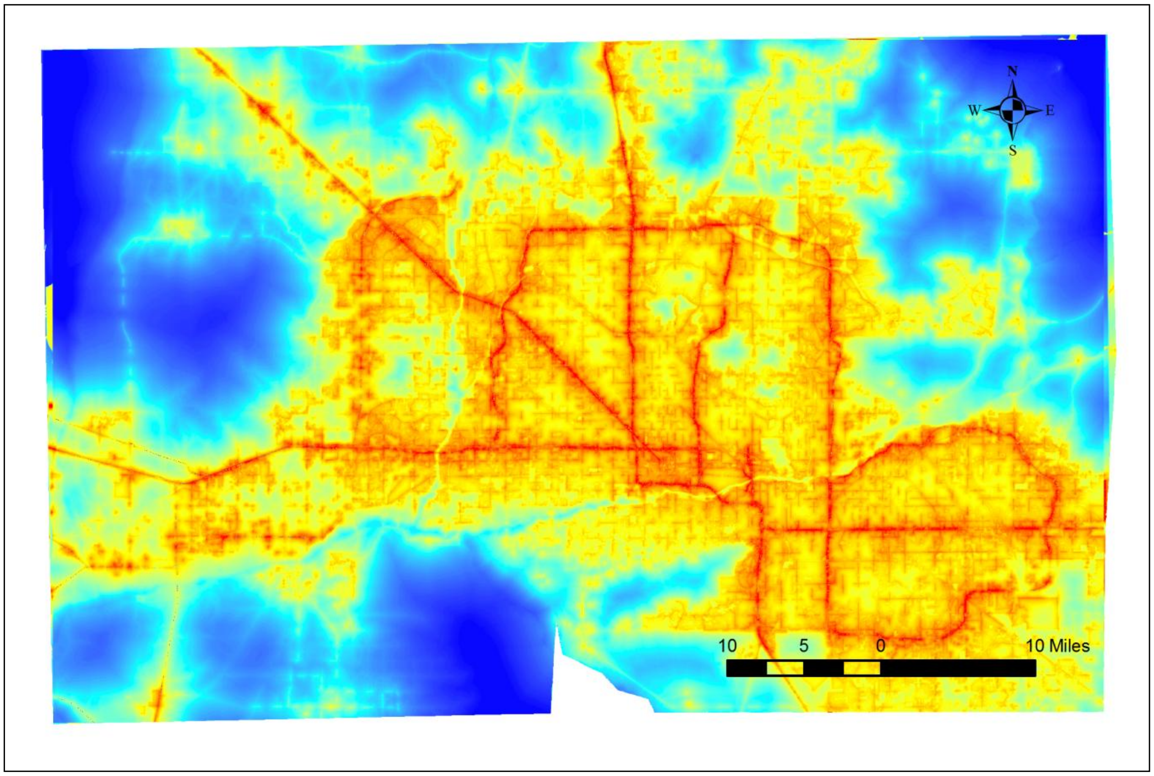


Figure 6.6 Original barrier effect index map

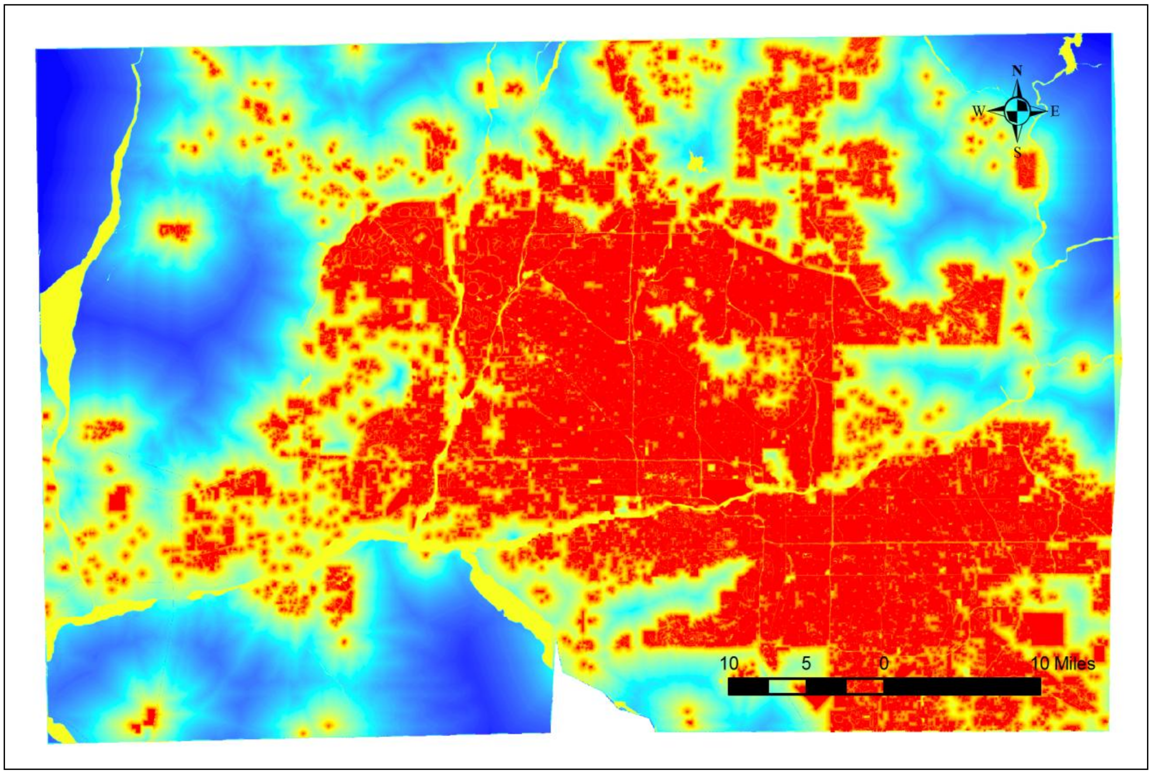


Figure 6.7 Matrix-influenced barrier effect index map

Table 6.5 Matrix affinity attributes

Codes	A1	A2	A3	M1	M2	M3	R1
A1	0.0	0.2	0.2	0.2	0.2	0.2	0.2
A2	0.2	0.0	0.2	0.2	0.2	0.2	0.2
A3	0.2	0.2	0.0	0.2	0.2	0.2	0.2
M1	0.2	0.2	0.2	0.0	0.2	0.2	0.2
M2	0.2	0.2	0.2	0.2	0.0	0.2	0.2
M3	0.2	0.2	0.2	0.2	0.2	0.0	0.2
R1	0.2	0.2	0.2	0.2	0.2	0.2	0.0
B1	0.8	0.8	0.8	0.8	0.8	0.8	0.8
B2	0.9	0.9	0.9	1.0	1.0	1.0	1.0
B3	0.6	0.6	0.6	0.9	0.9	0.9	0.9
B4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
B5	1.0	1.0	0.9	1.0	1.0	0.9	1.0
Others	1.0	1.0	1.0	1.0	1.0	1.0	1.0

5.6.3 Creation of Landscape Ecological Connectivity Maps

Figures 6.8 to Figure 6.14 depict a series of ecological connectivity maps for individual species. The value distribution ranging from zero to 10 shows the relative importance of natural habitat patches with regard to ecological connectivity. The algorithm of the map representation is based on the GIS modeling for calculating Basic Ecological Connectivity Index. As shown in Figure 6.8, the highly connected areas for cactus wren [B1] are aggregated compared to those for other two bird species. The landscape structure looks like it would be more beneficial for sustaining the Annas Humingbird [B3] communities than

Abert Towhee [B2], since the latter has a lower connectivity values across the landscape and does not actively use urban lands. The ecological connectivity values for mammals [M1]-[M3] demonstrate a similar pattern but most of the higher connectivity areas are distributed in urban peripheries. Desert Tortoise [R1] reveals a contrasting division between higher and lower connectivity implying specificity to their habitats. Based on data distribution, the ecological values both higher than, and lower than, the median value, were plotted on the positive/negative scale (Figure 6.7). The fact that larger amount of areas have above-median connectivity values signifies that the urban habitat remnants dominated in the landscape have a relatively high capacity for this urban desert species.

The individual species connectivity maps were superimposed and combined to create a composite ecological connectivity map. Each score on the connectivity maps was added up and averaged to arrive at the final connectivity values. Accordingly, the continuum range of connectivity values were classified into decimal numeric measures for easy interpretation of the overall connectivity status of the entire landscape. As shown in Figure 6.16, there is a sharp point where connectivity variance is maximized, which reflects an extreme deviation of habitat size. In other words, the areas with higher connectivity values are either too small or too large in patch area.

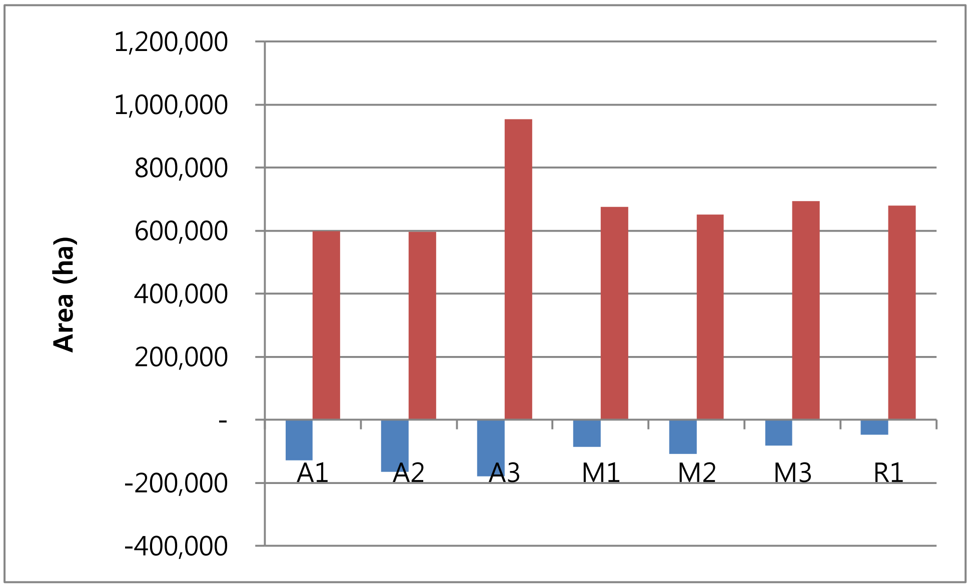


Figure 6.8Connectivity values higher and lower than median

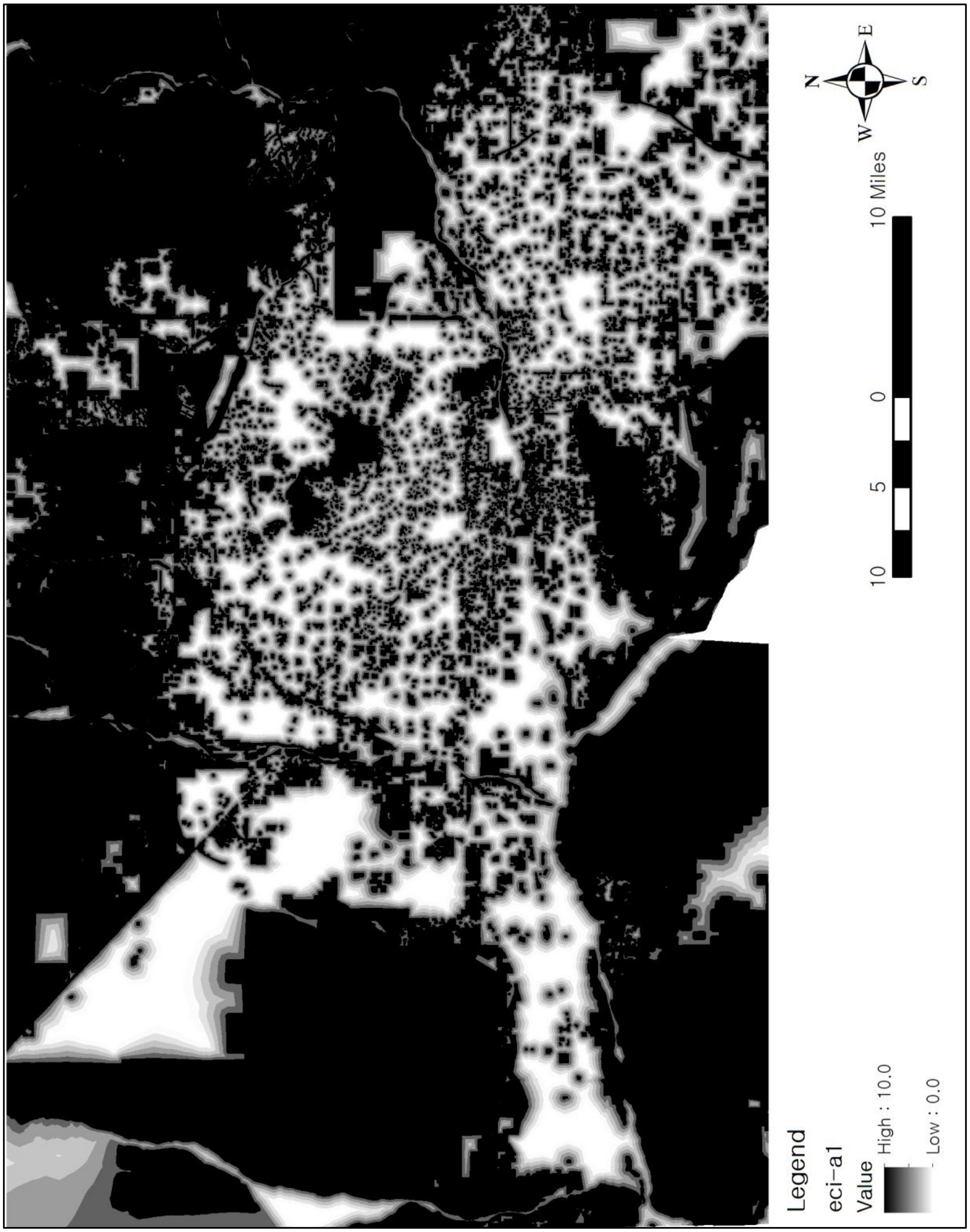


Figure 6.9 Ecological connectivity index map [A1]

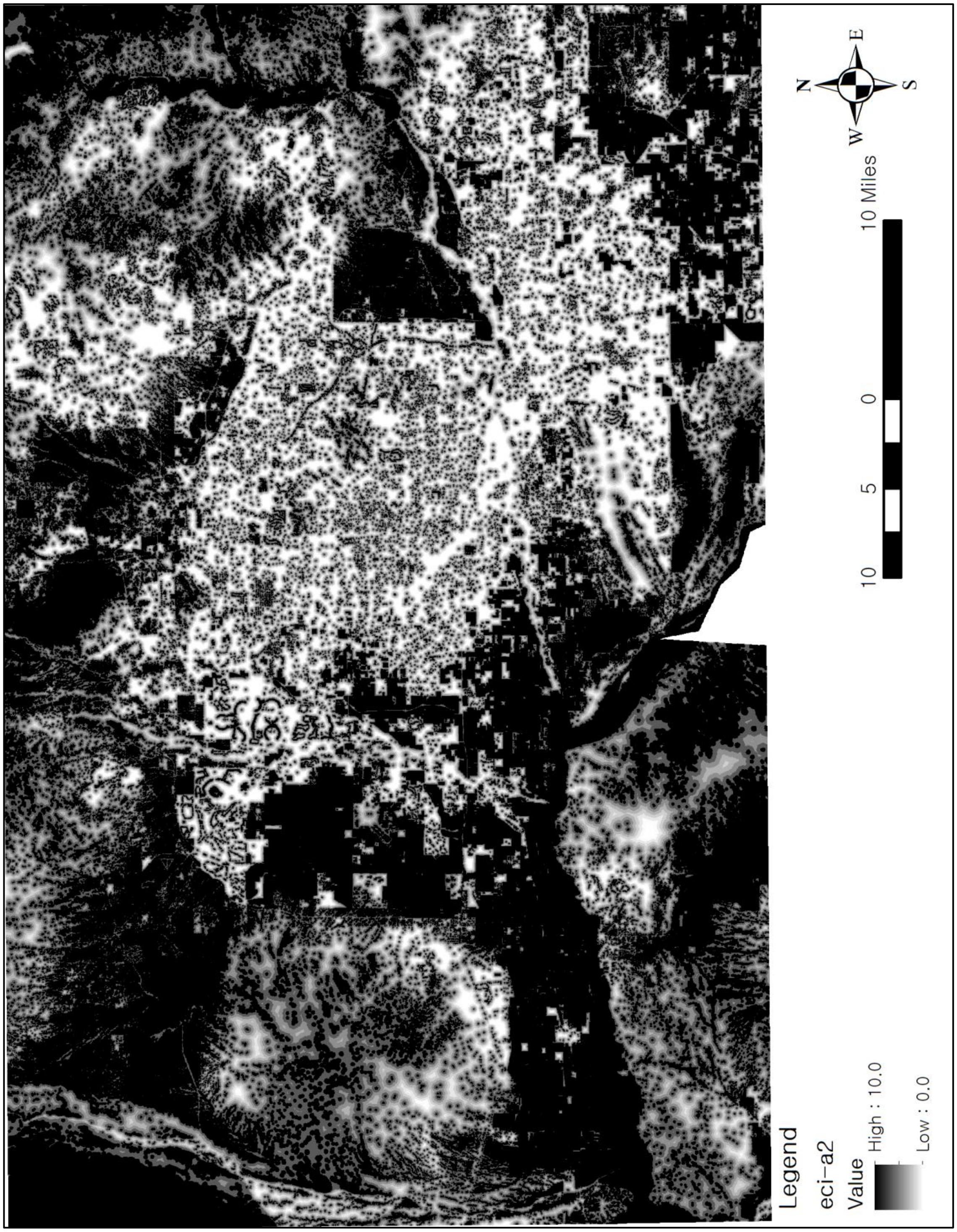


Figure 6.10 Ecological connectivity index map [A2]

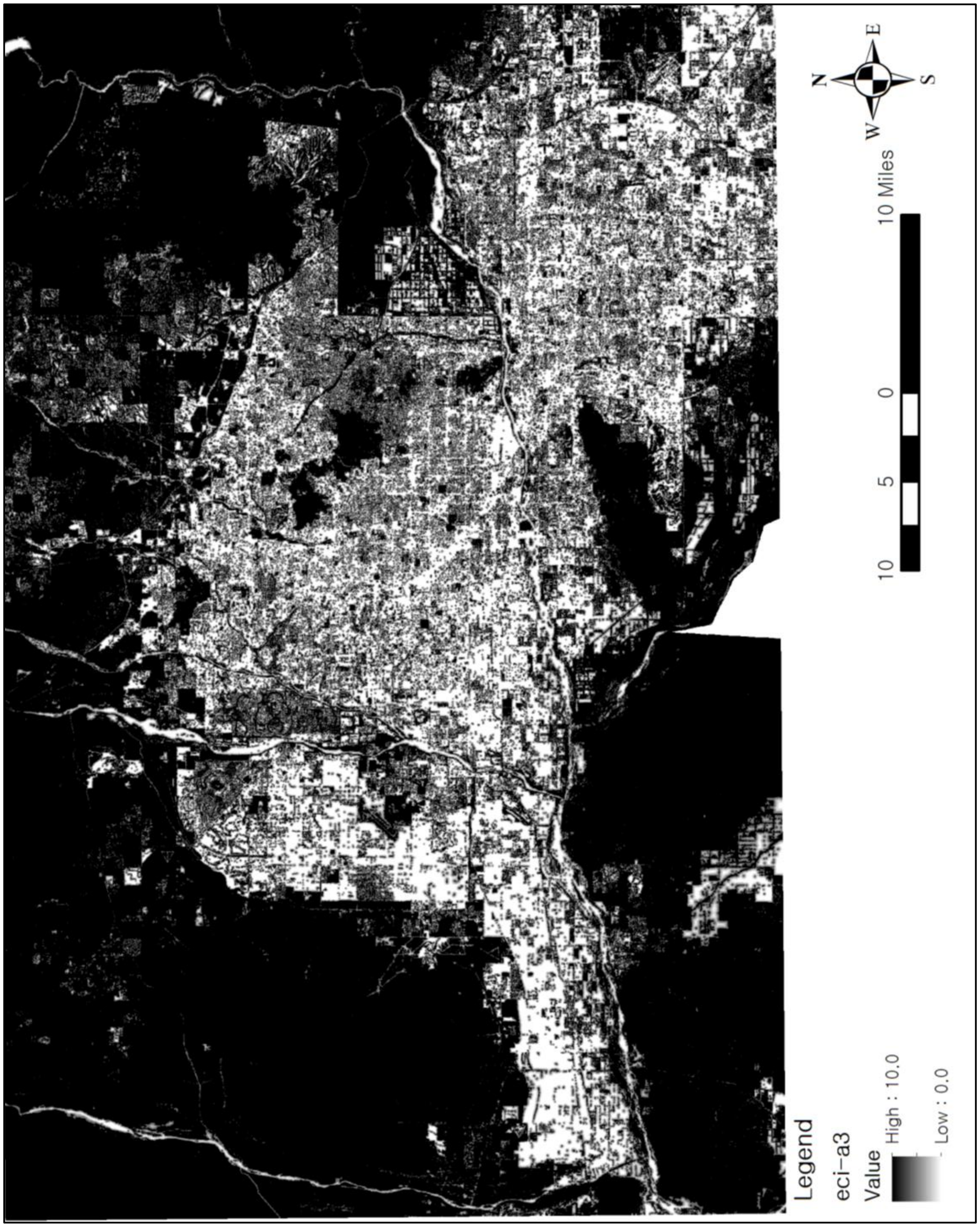


Figure 6.11 Ecological connectivity index map [A3]

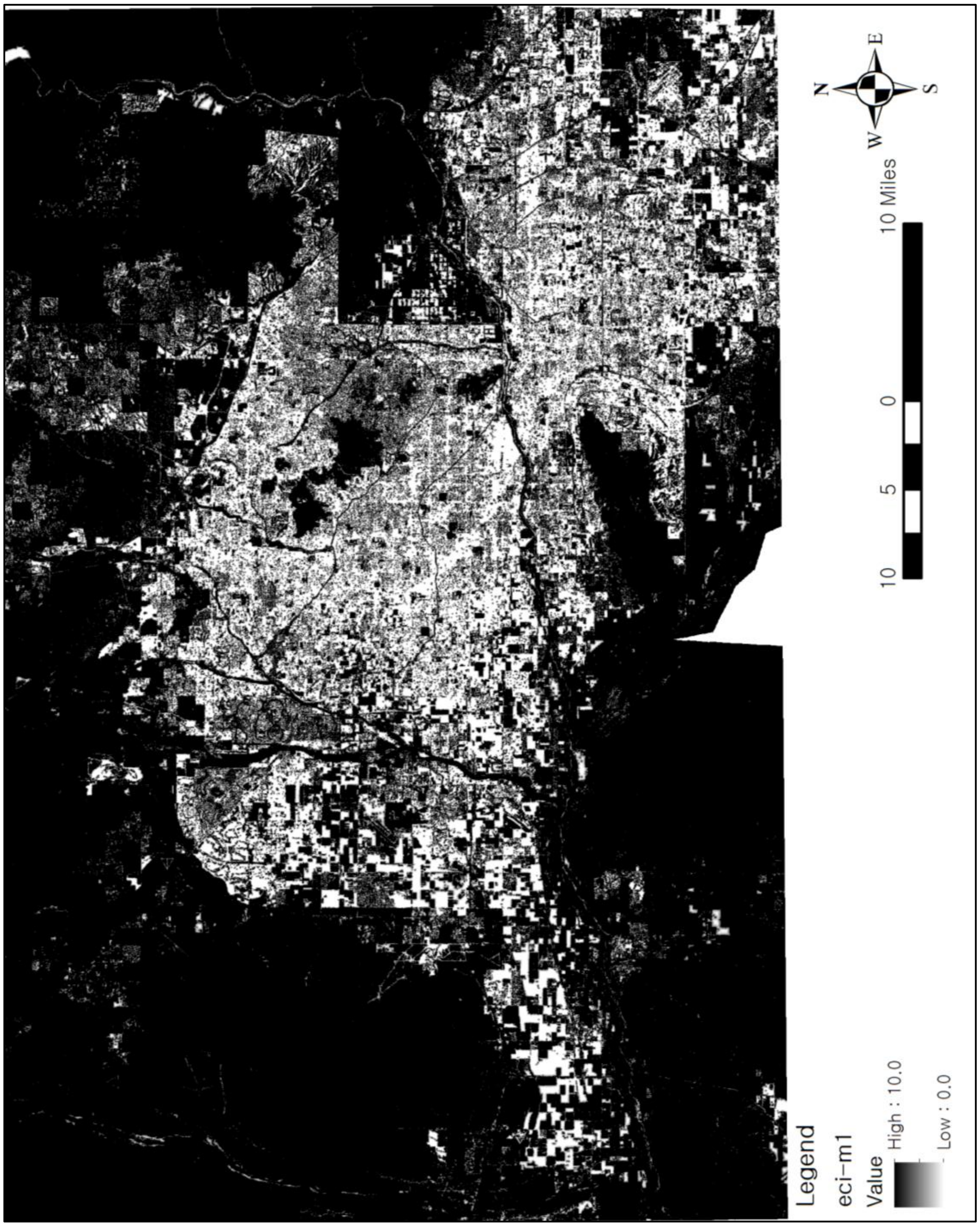


Figure 6.12 Ecological connectivity index map [M1]

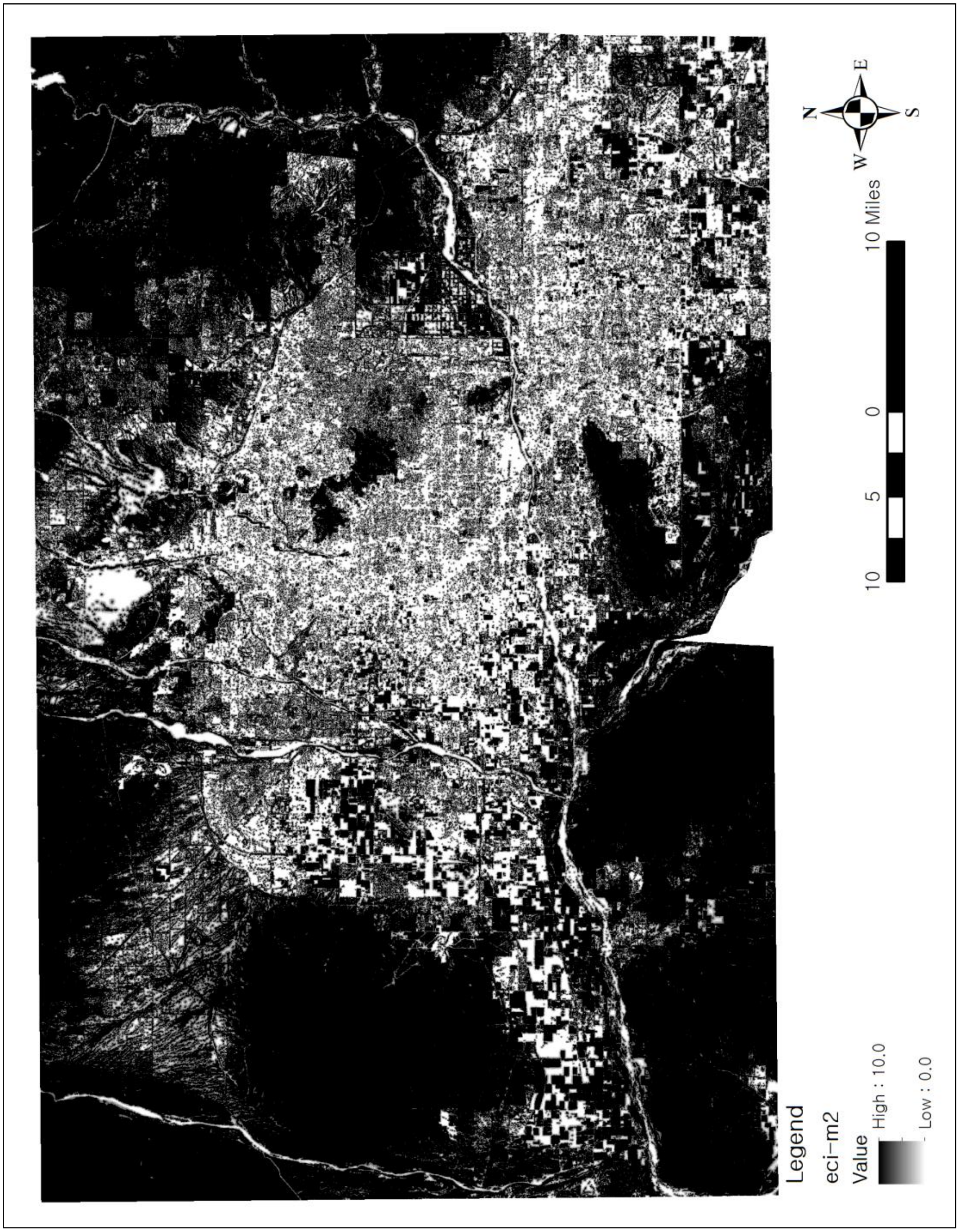


Figure 6.13 Ecological connectivity index map [M2]

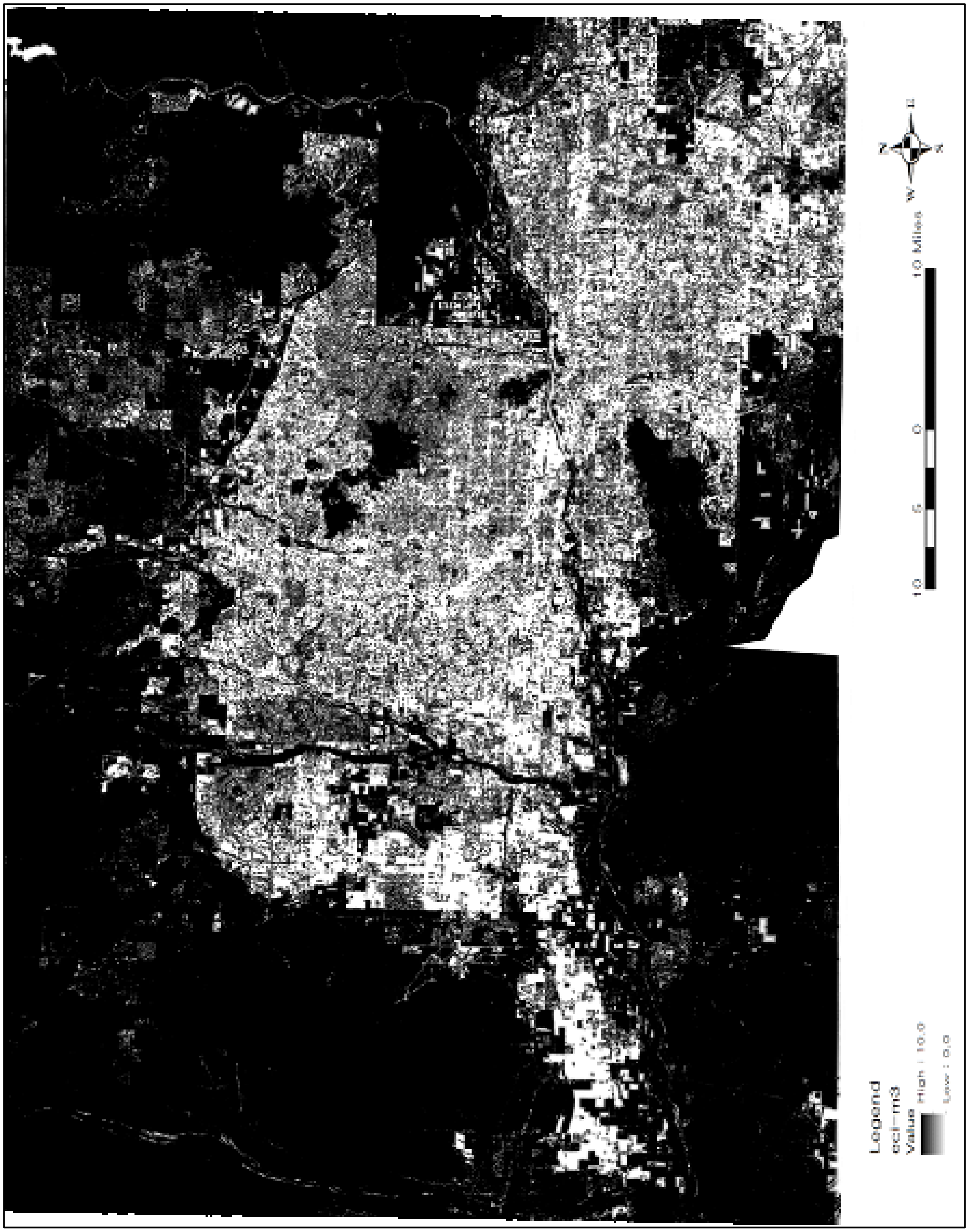


Figure 6.14 Ecological connectivity index map [M3]

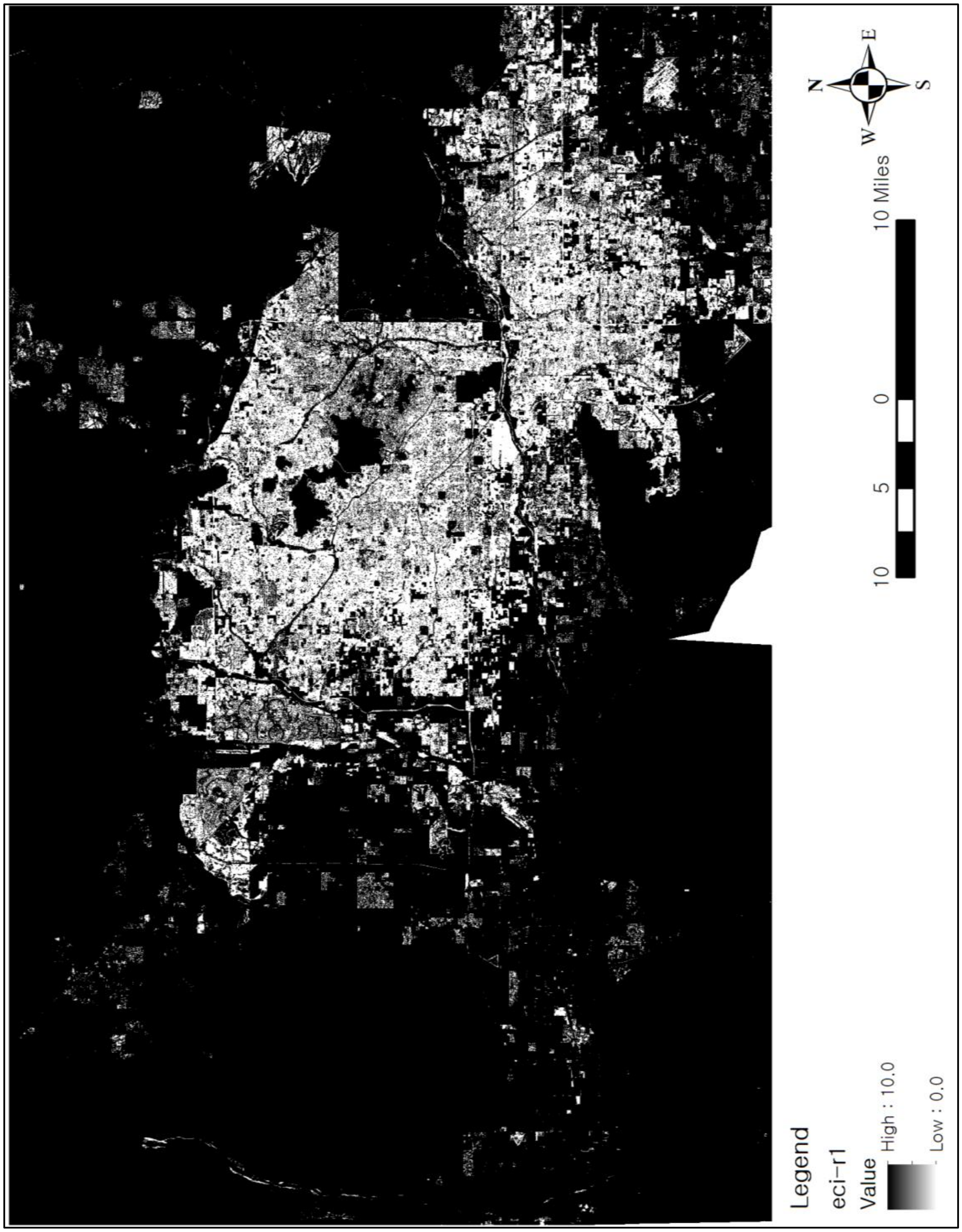


Figure 6.15 Ecological connectivity index map [R1]

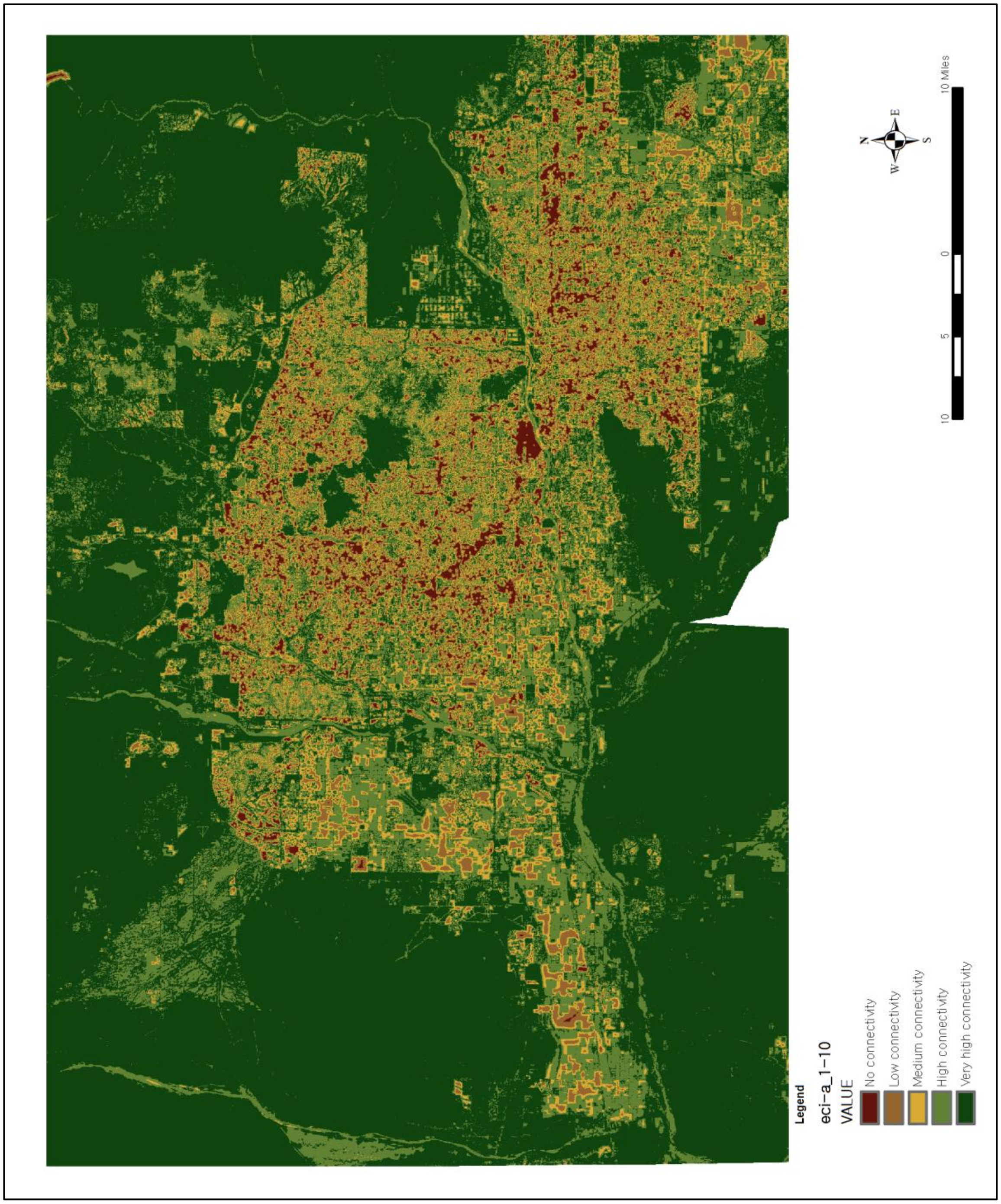


Figure 6.16 Composite relative ecological connectivity index map

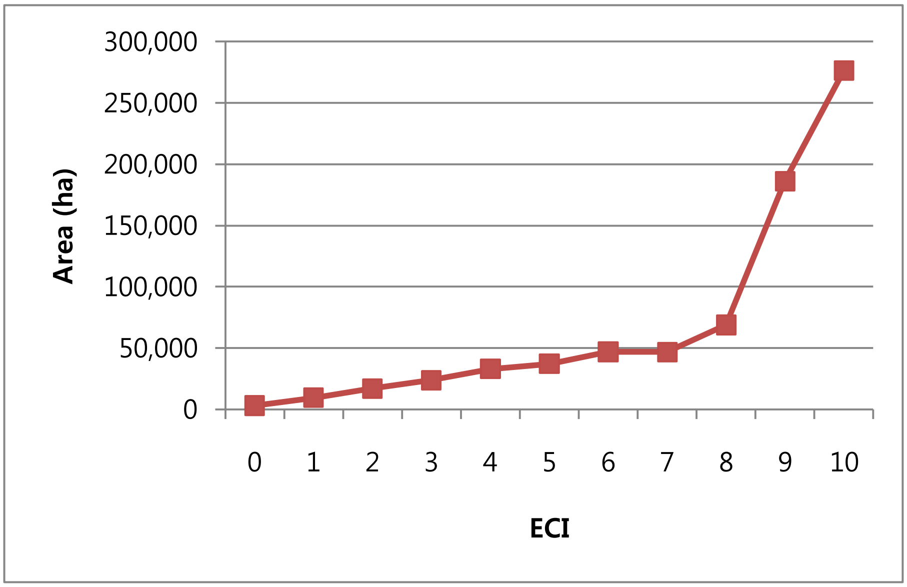


Figure 6.17 Land area for ecological connectivity index

5.6.4 Spatial Typology of the Urban Modification Gradient

5.6.4.1 Urban Zones

Of a couple of dozen cities and towns in the Phoenix Metropolitan Area, eight large cities with more than 50,000 residents (as of the year 2000) were selected, including Phoenix, Mesa, Glendale, Scottsdale, Tempe, Chandler, Peoria, and Gilbert. From the center points of the eight cities (i.e., the location of city hall) which may be urban zone candidates. Not surprisingly, the larger the buffers size the smaller the urban cover fraction within the buffer areas.

With some exceptions, most of the cities begin to drop down at a cutoff point of 10 km distance. The City of Mesa has a broad span of urban land uses, whereas the City of Chandler is not as spread out as other cities in this group. It is notable that the order in population size does not match with the percent urban cover rank. The City of Scottsdale has a drastic decline of urbanized lands as it passes five kilometers in diameter and then gradually increases, which infers that the city is near the urban zones limit with less shared neighboring urban lands. Avondale might have been added when using more recent population data (e.g. the population of the City of Avondale had been increased from 24,370 in 1996 to 75,403 in 2006), and yet the city still does not have enough urban lands to meet the urban cover proportion criteria. Therefore, the multiple urban cores comprising the chosen eight cities are delineated as urban zones.

Table 6.6 Selected cities for urban zone

City	Population (Year 2000)	Distance from Urban Cores	Urban Cover Proportion (%)
Phoenix	1,321,045	12K	0.72
Mesa	396,375	12 K	0.71
Glendale	218,812	14 K	0.72
Scottsdale	202,705	5 K	0.72
Tempe	158,625	15 K	0.71
Chandler	176.581	5 K	0.71
Peoria	108,364	3 K	0.70
Gilbert	109,697	10 K	0.70

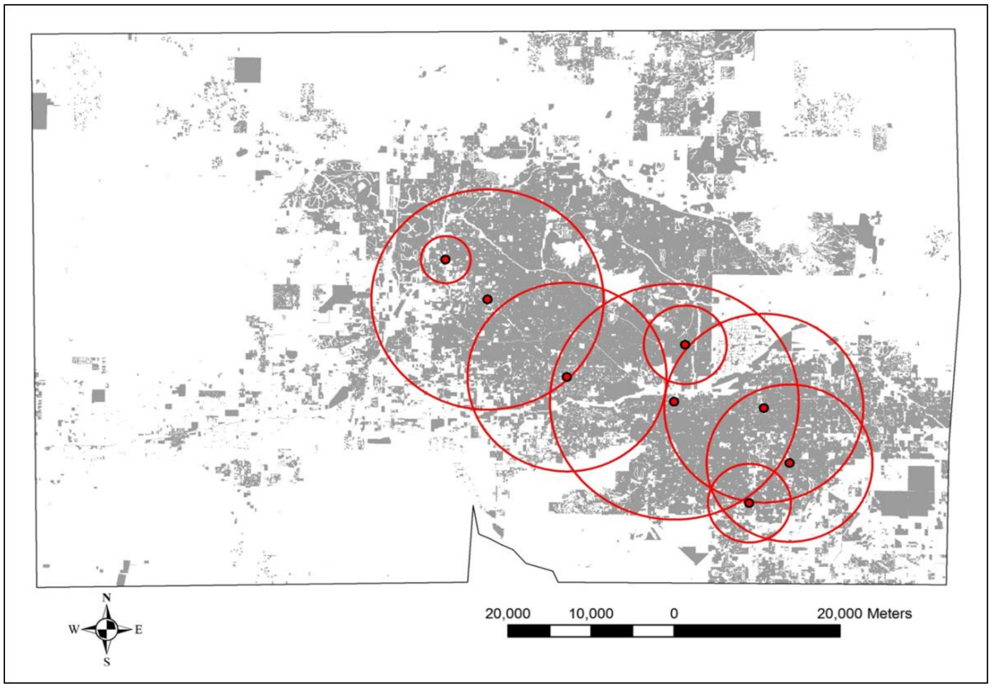


Figure 6.18 Distribution of urban zones

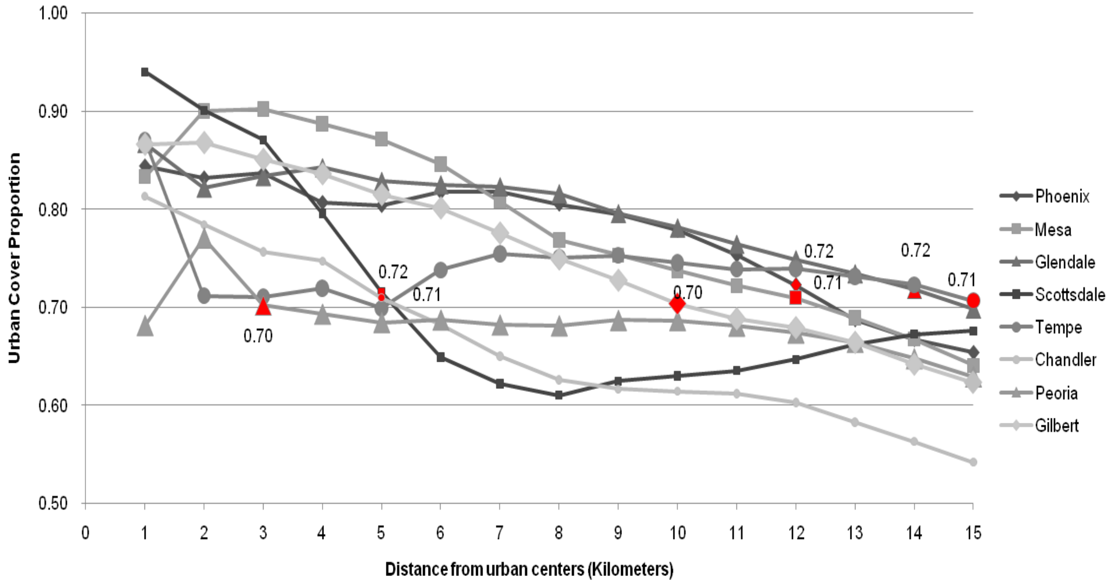


Figure 6.19 Change in urban cover proportion in response to the distance from urban centers

6.6.4.1 Suburban Zones

Fourteen cities satisfied the criterion of between 2,500 to 50,000 populations, as shown in the Table 6.6. The majority of the cities are located either within the predefined urban zones (e.g., Youngtown, Tolleson, Paradise Valley, and Guadalupe), or are very close to the urban zones (e.g., Avondale, Fountain Hills, Surprise, Goodyear, El Mirage, Litchfield Park, and Queen Creek). The cities embedded in the predefined urban zones have relatively small populations but often make use of land resources from adjacent cities in urban zones. Other designated suburban zones include Buckeye, Wickenburg, and Cave Creek. These are geographically detached from the clusters of the urban zone. Of those fourteen cities, four cities were removed because they are all within predefined urban zones and never drop off enough to be considered suburban. The buffers around those cities actually showed an extraordinary increased percent urban cover when the distance is added up. Even if not in this case, there were some cities on the extended development path coming from urban zones, such as Youngtown, Surprise, and El Mirage. These cities are situated along the same development axis with Peoria and Glendale that belong to urban zones.

The GIS-based buffering method used for urban zone identification was technically a little bit differently applied in making out suburban zones. Since suburban zones, by nature, are placed very close to urban zones, the normal buffering process should have an extraordinarily high percent urban cover, which can result in no suburban zones in this region. To cope with this issue, the following mechanics were considered. First, if the town is outside the preset urban zones, the normal buffering method was used as long as the percent urban cover was in the range of 40-69 percent of the total buffered areas. If the urban lands in buffers continued to maintain a certain level and did not drop below 40 percent, the buffer operation stopped and was assigned suburban zones when the buffers reached one of the boundaries of the urban zones. If a town center is within any urban zones, only the residual buffers being not overlapped with the urban zones are fed into the calculation of urban cover proportion. This approach seems reasonable in a sense that suburban areas are typically emerged around the urban periphery and the process of suburbanization growth per se expands outward. Hence, to get a sense of suburban distribution, solely exclusive buffers needed to be considered.

As Figure 6.19 shows, suburban zones are attached to the adjacent urban areas, making the urban pattern a seamless urban agglomerate. These cities are examples of satellite cities that are economically tied to cities urban zones and thus have a significant possibility to convert to urban zones in the near future. The leap-frog type of urban development arising from non-core cities forms suburban zones that are set apart from the established urban clusters.

Table 6.7 Selected cities for suburban zone

City	Population	Distance from Urban Cores	Urban Cover Proportion (%)
Avondale	24,370	2K	0.47
Fountain Hills	15,220	3K	0.40
Paradise Valley	12,785	23K(e)	0.44
Surprise	11,335	9K(e)	0.40
Goodyear	10,215	2K	0.55
El Mirage	5,765	12K(e)	0.40
Buckeye	4,905	2K	0.35
Litchfield Park	3,760	4K(e)	0.43
Cave Creek	3,255	5K	0.40
Youngtown	2,715	13K(e)	0.41

NOTE: (e) indicates that corresponding suburban zones were determined by the exclusive buffering method

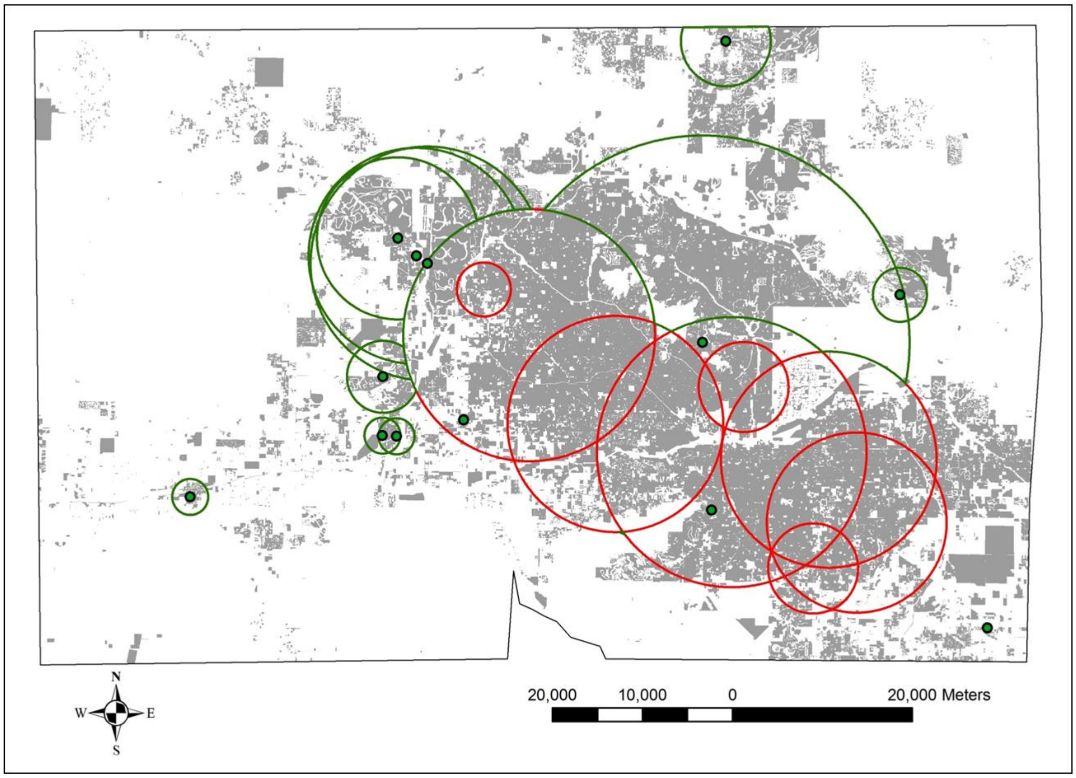


Figure 6.20 Distribution of suburban zones

6.6.4.3 Rural zones

The remaining areas that were neither urban zones nor suburban zones were designated as rural zones. The small towns in the zones have less than 2,500 total inhabitants. Most areas are dominated by natural landscapes. Approximately 10.22 % (516.21 Km^2) of the entire rural zone is comprised of the lands for urban use for several municipalities and unincorporated communities, and the figure was lower than the urban criteria of 40 percent as expected.

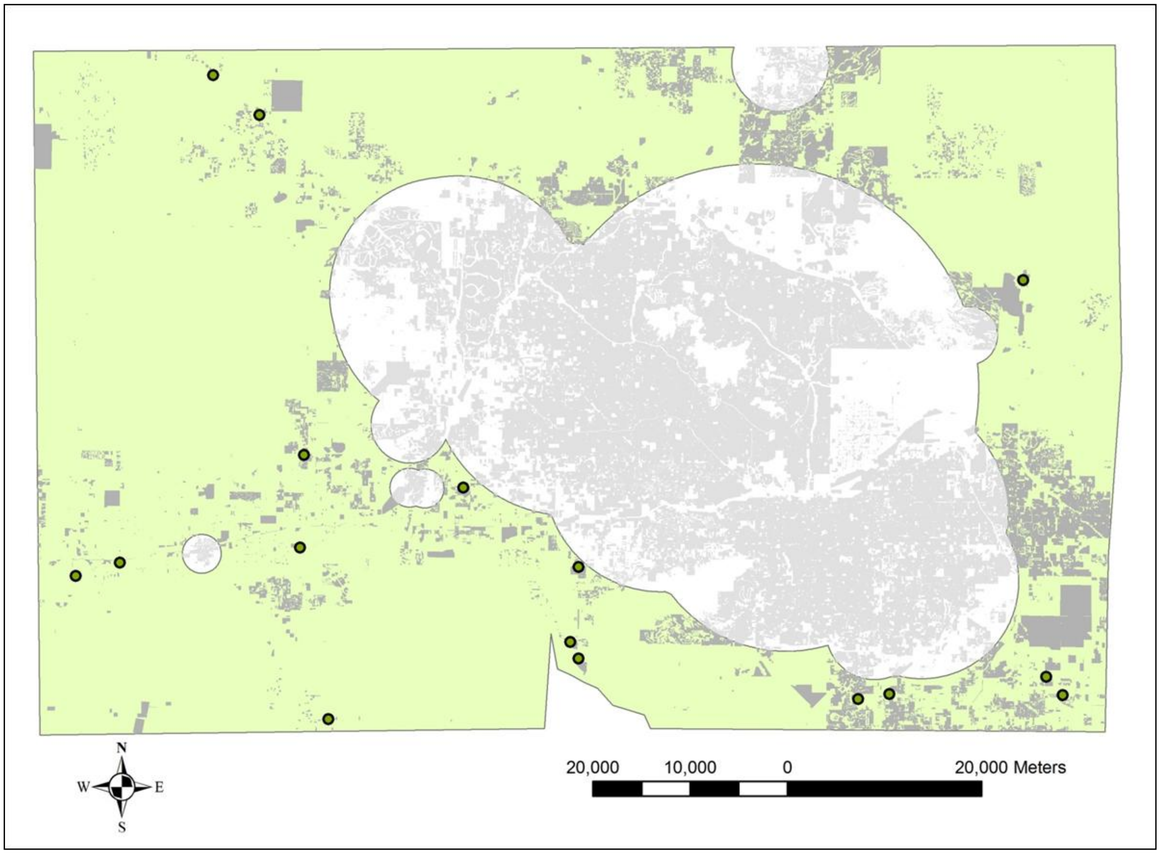


Figure 6.21 Rural zone

6.6.4.4 Interface zones

In addition to urban, suburban, and rural zones, the author developed a "in-between" concept to represent the edge effects from an urban perspective (not ecological edge effect), and named it the "interface zone". The interface zone indicates the areas where more than two different types of zones meet each other. Based on the spatial delineation of urban modification gradient, this study attempted to draw some possible cases shown in the Phoenix Metropolitan Area, and listed and coded seven prototypes for interface zones in order of density variation (See Figure 6.21).

The first type is narrow rural areas sited between heavily developed large urban areas [URU]. Such areas are assumed to have the highest pressure of imminent urbanization, presumably in the form of urban infill development because of nearby urban epicenters. In the case that rural areas are squeezed in between one large urban zone and an independently-developed single suburban zone [URS-s], the areas are often positioned in an urban outskirt with a significant likelihood of incorporation either into urban or suburban zones. It is particularly true because of the small distance to reach any urban areas although the suburban zone is not subjugated to the neighboring urban zone per se.

As a variant of [URS-s], narrow rural areas sometimes can be placed next to a suburban zone that surrounds a single or multiple urban zone (big urban clusters), that is not a solid suburban as in URS-s. In this case, urban influence will be likely to be far more severe because suburbanization has developed with an urban kernel in its core [URS-b]. Next, suburban margins got jammed in various sizes of urban circles and can be a type of interface zone [USU]. The narrow suburban zone is often a residue from urban activities at city scale. Due to the proximity to neighboring urban zones and the suburban ground matrix, a local-level conurbation possibly can take place. If we zoom in on the urban yolk implanted in the suburban zone shown in the [URS-b] type, another case can be found where urban and suburban zone boundaries touched one another [US-n]. If the spatial arrangement of urban-suburban is overlap rather than nesting, it will then make another derivative case [US-o].

Lastly, the areas near the suburban peripheries facing undeveloped rural areas fall into the final type of interface zone with the farthest distance from the main urban nuclei in the entire urban landscape [RS]. The developed spatial typology of interface zone was used as a spatial frame to understand urban impact on landscape ecological connectivity in the following section.

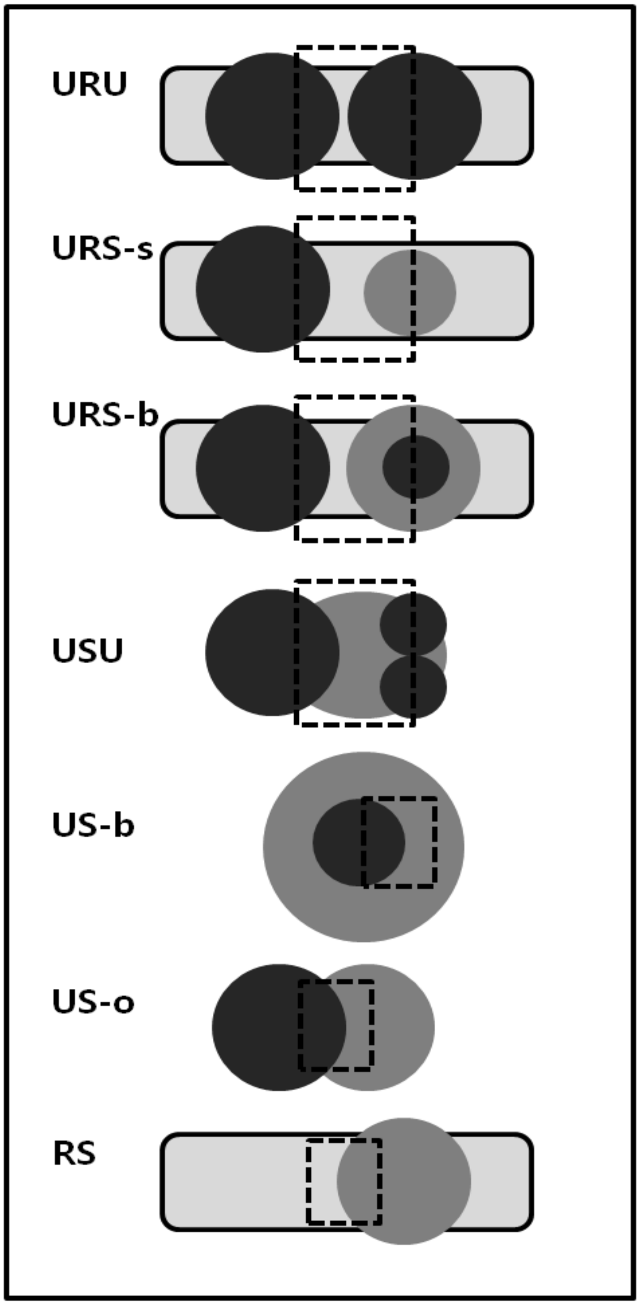


Figure 6.22 Spatial Typology of Interface Zone

6.6.5 Landscape Connectivity Pattern across the Urban Modification Gradient

In this section, distribution of calculated connectivity values was evaluated with the predefined spatial frames of urban, suburban, rural, and interface zones. Overall, the degree of landscape connectivity significantly decreased as urbanized acreage increases. As expected, the total areas with the connectivity values below the average appeared to be highest in the urban zone and dropped off in order of suburban and rural zones. The low landscape connectivity was a characteristic of urban zones, even with the proactive inclusion of urban habitats and urban wildlife species for the landscape ecological connectivity analysis. As Table 6.7 indicates, the areas with no connectivity within urban zones are 10 times bigger than those in rural areas, reflecting that the urbanized zones are dominated by either non-connected habitats or non-habitats.

It is obvious that there is extreme disparity between urban zones that have a lot of no-connectivity lands and rural zones with large amount of very high connectivity lands. The difference gap was very distinctive relative to other density zones. However, the total quantity of lands with a modest level of connectivity values was somewhat similar among the different urbanization zones. The existence of medium connectivity areas in urban or suburban zones can provide an opportunity for increasing micro-habitats and urban species abundance. Besides, those lands, if not complete, can partly support species persistence serving as stepping-stone habitats in the landscape mosaic.

Given the fact that the landscape ecological connectivity maps demonstrate the relative priority for land conservation management, it would be important to identify what locations would likely be influenced by future development. As illustrated in Figure 6.23, the anticipated future urban development is tremendously focused on rural areas. More important, a doubled volume of urban development will be seated within the interface zones. Considering that the interface zones have a great deal of highly connected lands, there seems to be a conflict between development capacity and ecological capacity in these areas within couple of years.

Figure 6.24 to 6.27 demonstrate the distribution of proposed urban development for each urbanization zone with the relative ecological connectivity maps, which provides a geographical sense for landscape connectivity vulnerability.

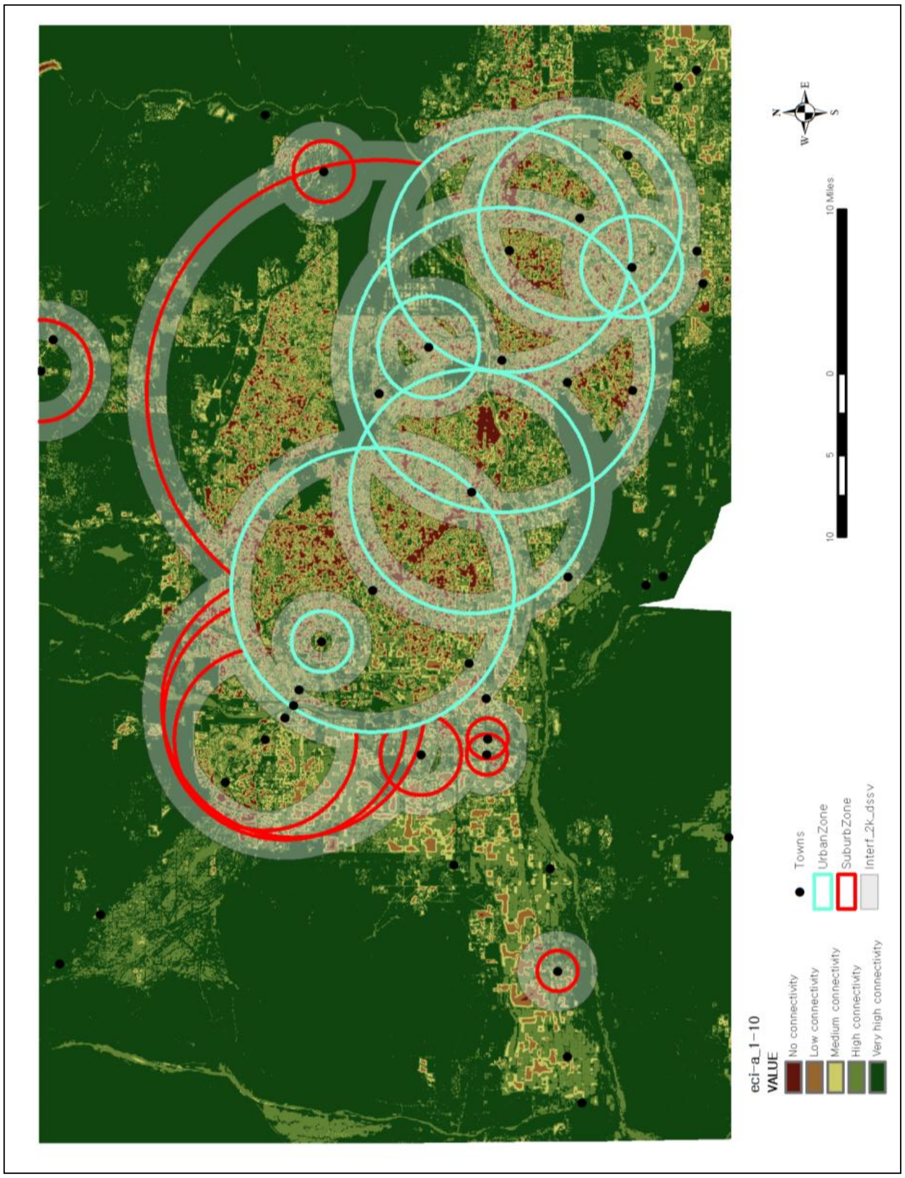


Figure 6.23 Distribution of urban, suburban, rural and interface zones superimposed on relative connectivity values

Table 6.8 Relative connectivity values in urban, suburban, rural and interface zones

Category	Urban zone	Suburban zone	Rural zone	Interface zone
No connectivity	2,398	375	220	1,343
Low connectivity	17,972	4,817	3,475	14,165
Medium connectivity	31,623	11,477	13,401	30,221
High connectivity	56,418	27,773	45,551	65,572
Very high connectivity	50,421	57,978	402,315	102,306

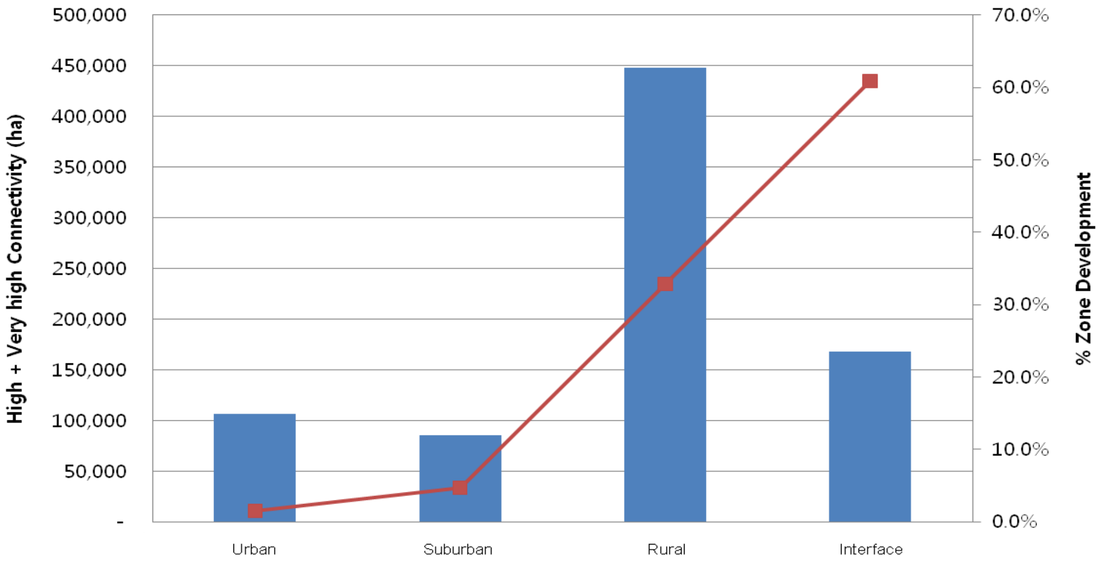


Figure 6.24 Land amount with high and very high connectivity and ratio of to-be-influenced-land by proposed urban plans

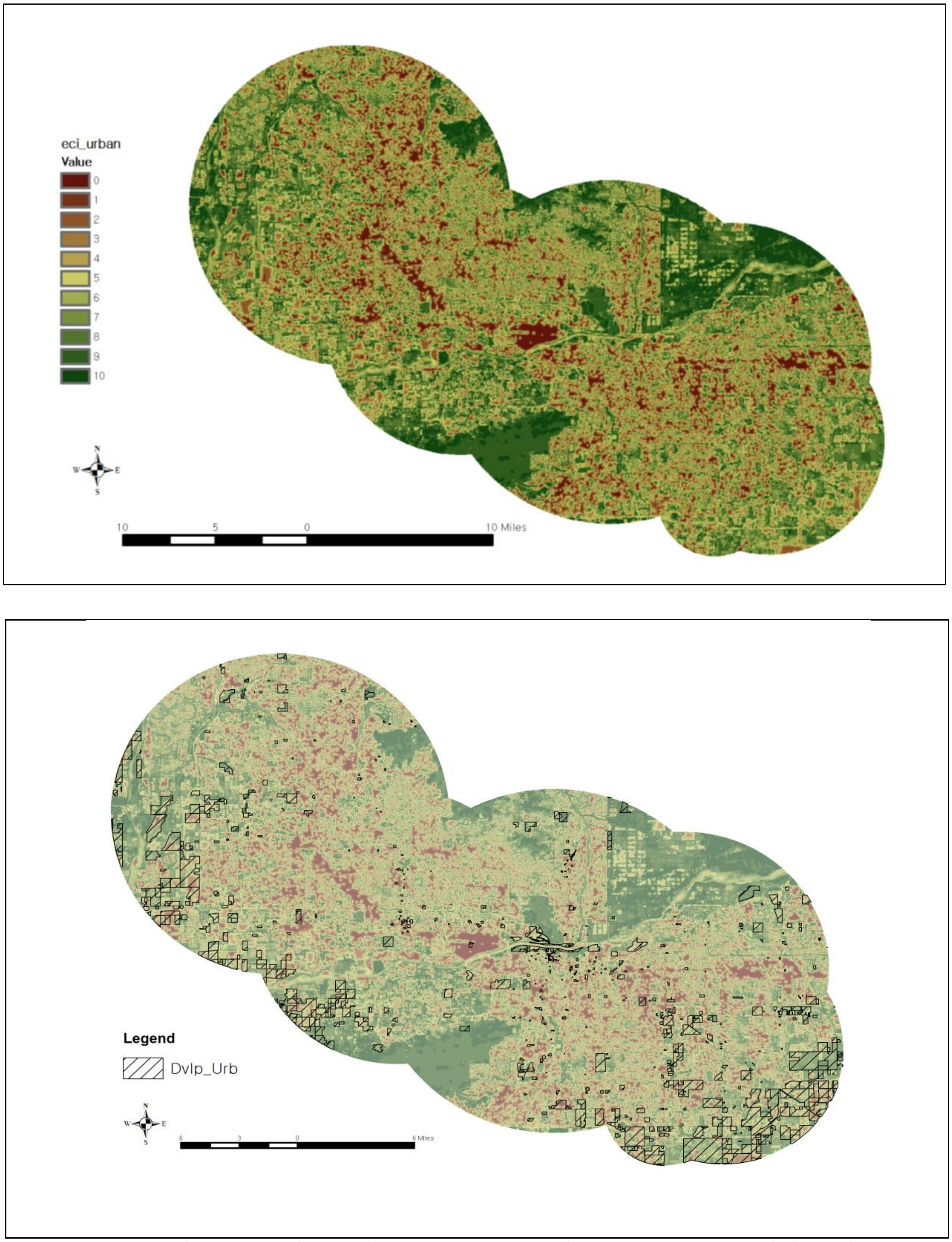


Figure 6.25 Relative ecological connectivity index map (top) and distribution of proposed urban development in urban zones (bottom)

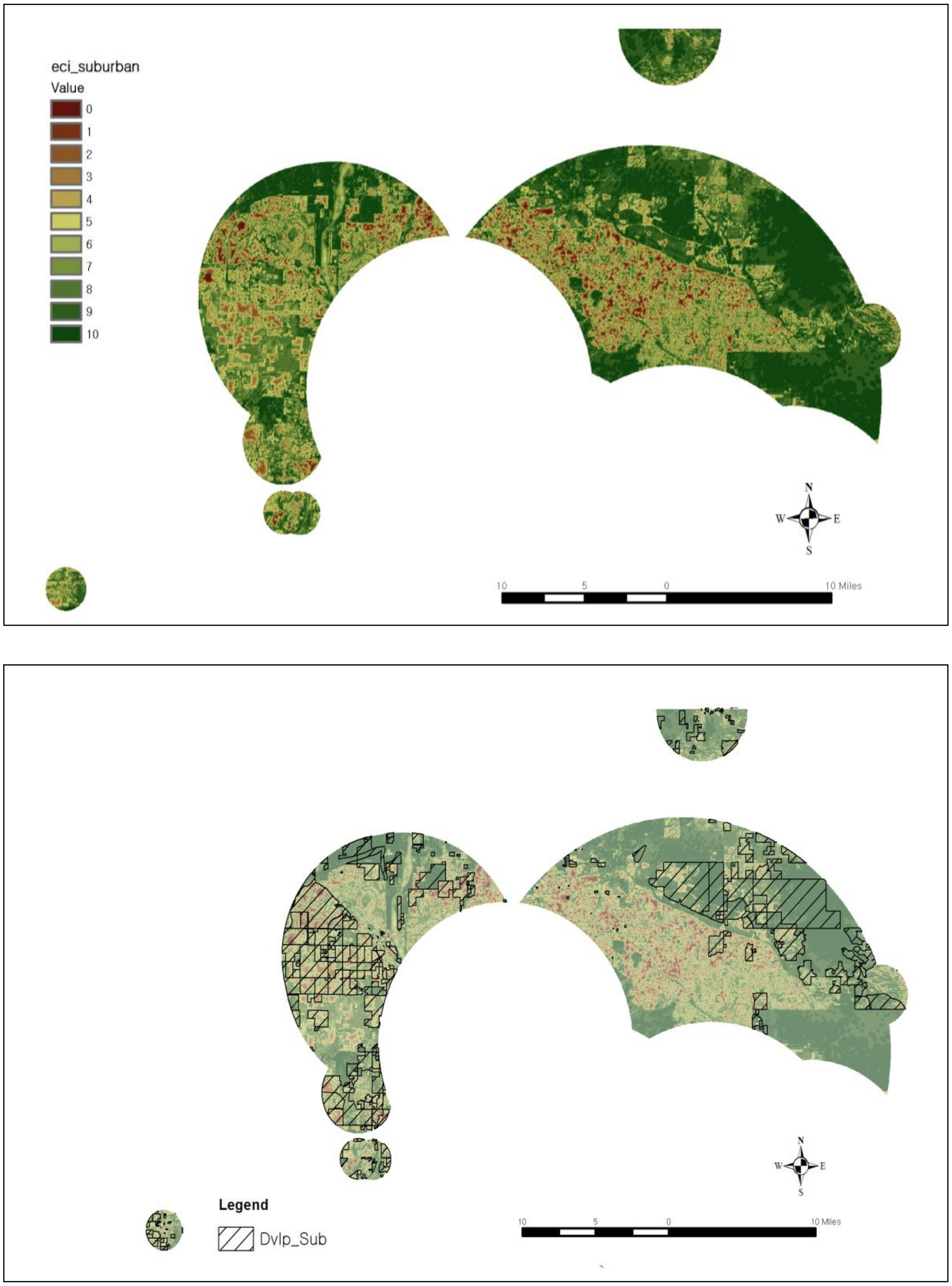


Figure 6.26 Relative ecological connectivity index map (top) and distribution of proposed urban development in suburban zones (bottom)

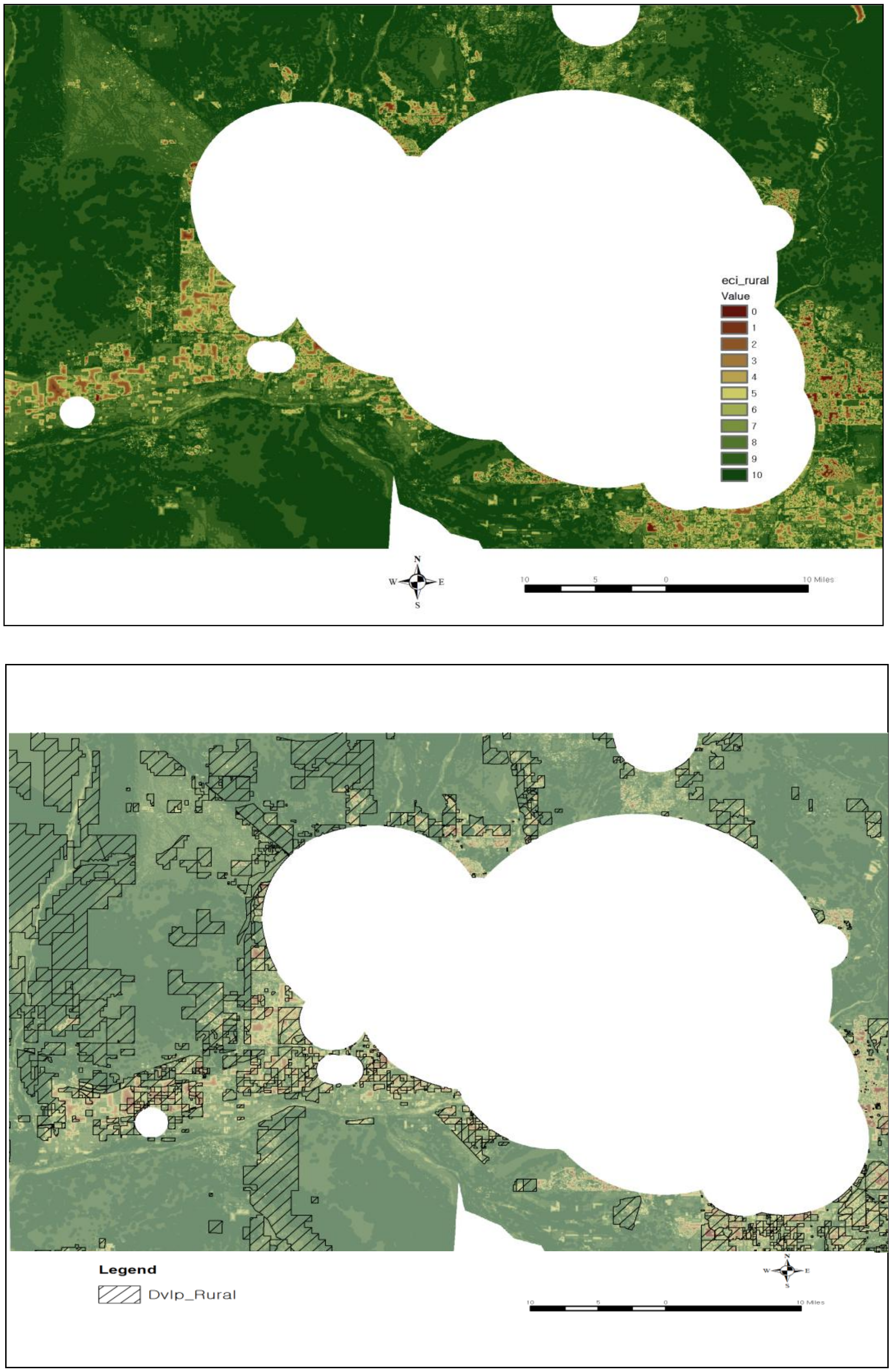


Figure 6.27 Relative ecological connectivity index map (top) and distribution of proposed urban development in rural zones (bottom)

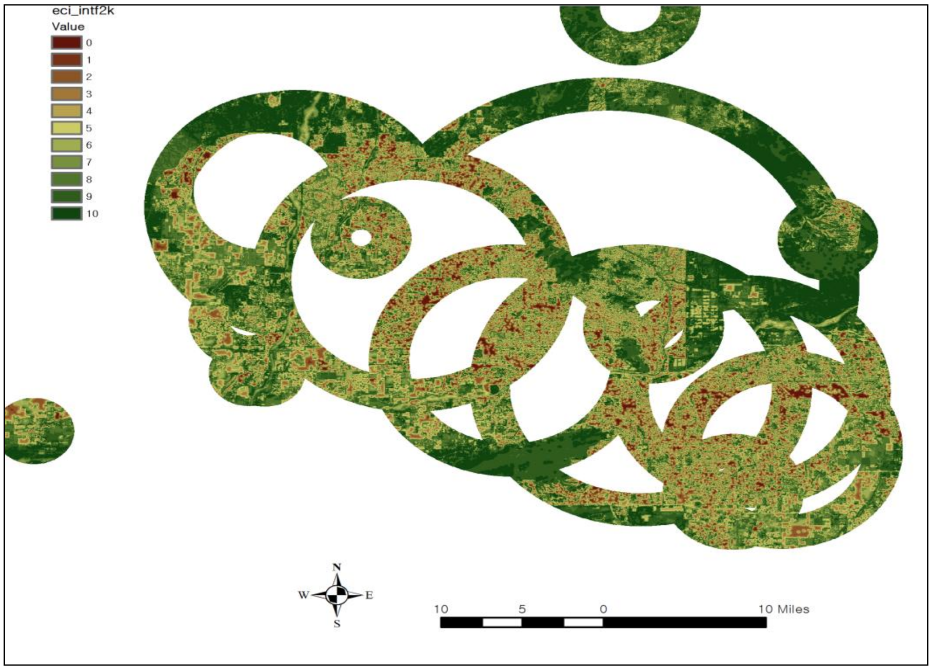


Figure 6.28 Relative ecological connectivity index map (top) and distribution of proposed urban development in interface zones (bottom)

6.7 Planning Implications

This study has meaningful implications regarding the integration of the ecological connectivity approach and planning dimensions of the approach. The possibilities for considering the notion of ecological connectivity in planning systems can be discussed in three parts: (1) prior to planning; (2) during planning processes; and (3) post-planning.

Prior to planning, landscape ecological connectivity values may be incorporated into development suitability analysis (or conversely conservation suitability analysis). It provides ecological information to the conventional planning practices with the reinforcement of landscape ecological connectivity conservation. In this regard, the ecological connectivity concept can contribute to guiding the urban plans to be allocated such that they minimize the destruction of higher ecological connectivity areas. While locating urban planning sites throughout the entire county landscape, planners need to conceive a big picture about how what they are planning individually would modify the existing connectivity pattern overall, and need to be conscious of precautionary preservation of regional ecosystem form and functions.

During the planning processes, ecological connectivity can help planners obtain site-context understanding. For example, McHarg developed and used the “Layer Cake” as an analytic concept to understand site system. Landscape ecological connectivity may be an addition to the top of the “cake.” In addition, the grid cell-based connectivity value information can be dissolved with other human land uses or land-based design. Through the localized planning solutions, not only the local ecological connectivity but also the regional connectivity can be conserved and maintained. The concept and approach of ecological connectivity, moreover, can help initiate the human community or neighborhood development with innovative and sustainable visions, such as conservative subdivision and open space subdivision development.

In the post-planning courses, the altered connectivity pattern due to an array of urban development can channel adaptive management strategies to effectively reconnect the remaining ecosystem patches. Hence, the connectivity concept can be useful in monitoring how piecemeal development causes micro-pattern change.

More important, the landscape ecological connectivity concept may be utilized as a communication vehicle to increase sustainability within planning sites and also to connect to other local planning sites. The local efforts to conserve ecological connectivity may bring active citizen participation within the cities and create unintended cultural benefits such as city revitalization. If the methodologies and approaches of landscape ecological connectivity can be more refined to the extent of influencing emerging planning paradigms, such as landscape urbanism (Waldheim, 2006), ecological urbanism (Mostavi and Doherty, 2010), or landscape ecological urbanism (Steiner, 2011), it will allow improving quality of habitat, quality of space, and quality of life simultaneously.

6.8 Conclusion

This study quantified landscape ecological connectivity using indicator species and GIS-based modeling technique. The relative landscape ecological connectivity maps represented a generous view of ecological connectivity in an urban setting. This study proved the pre-established research propositions: the landscape ecological connectivity values increased as urban density decrease. This finding supports the author's previous study that investigated the same research questions but utilized landscape metrics method (Park, 2010). The negative correlation between landscape connectivity and urban density, however, was not evident in the special area of the interface zone, which has a large proportion of higher connectivity areas and at the same time under high development pressure.

Even though this study took an inclusive approach to cover all types of urban desert habitats as spatial connectivity units, it is likely that the landscape connectivity-urban density relationship vary depending on individual habitat class. For example, cultivated grass habitats tend to be better connected in urban zones whereas desert grasslands seem more connected in the less urbanized areas.

This study adequately accounts for the second proposition as well, that the areas most likely influenced by the municipality's proposed developments will be distributed near the boundaries of the scaled zones rather than the inner cities or outlying deserts. The fragmentation likelihood due to urban development projects was even more marked on the periphery over the urban centers. These results imply that more attention should be paid to the edge areas of already developed lands.

Although the study utilized a circular shape for zonal classification, it is also possible to use different shape of geometry to describe idealized urban form, such as oval, square, or lobed structure (See Snellen et al. 2002 and Bierwagen, 2005 for urban form diagrams and examples). If asymmetric or irregular shapes can be technically applied to this type of analysis, it may capture more realistic urbanization density pattern. However, the landscape ecological connectivity pattern revealed in this study presumably will likely be the same, despite the change in urban structure.

This study proposes that landscape ecological connectivity could be better understood when it is combined with cultural landscapes. In this regard, the notion of landscape ecological connectivity needs to be considered in conjunction with current and future urbanization. Certainly, conserving ecological connectivity for a particular species is very important to protect the population and dispersal capacity. However, a more holistic point of view for ecological connectivity can contribute not only to regional biodiversity, but also to our ability to predict changes that land use causes in urban habitats. This may be a coarse approach relative to conventional ecological connectivity research and practice in conservation biology and landscape ecology, but it would help integrate ecology into urban planning, especially in urbanized or urbanizing areas like Phoenix.

The introduction of planning instruments that place more emphasis on regional ecology, such as landscape ecological connectivity, is very indispensable at this point, given the fact that this region is expected to double in population by the year 2050 to approximately 12 million people. It is obvious that the population increase will be accompanied by further development of transportation systems, increases in barrier effects, decreases in landscape matrix quality, and changes in metapopulation dynamics, but nothing has yet been well understood.

As mentioned in section 6.7, the study outcomes provide an insight into urban and regional planning in the Phoenix metropolitan area. The conservation of landscape ecological connectivity can promote the continued existence of urban desert species in this region, and thus serve as an important strategy to gauge urban biodiversity. At the same time, the study of landscape ecological connectivity contributes to instigating ecological planning or biodiversity planning in Phoenix, or at least to undertaking wiser land use planning than the contemporary planning practice. This study informs urban planning toward more carefully planned city design and planning and suggests that urban planning practices need to be sensitized by, and respond to, ecological processes. The innovative change in the urban planning framework advocating landscape ecological connectivity could not only effectively deliver various environmental benefits that the connected landscape provides, but ultimately leads to landscape sustainability in the urban region.

CHAPTER 7

DISCUSSION

This study addressed ecological patterns and urban dimensions both at county and metropolitan levels. The two different scales have their own research goals and inquires within the individual framework, but are also relevant to each other for the following reasons. First, the overall intention in the two studies relates to integrating ecological landscapes with cultural landscapes characterized by urban development. The understanding of the county-level landscape pattern focusing on ecosystem loss and fragmentation can provide an overall picture about the impact of various magnitudes of urbanization processes, which in turn can scale down to urbanized areas where human activities more actively occur and thus have more effects on urban habitat patches. With regard to landscape connectivity, the county-scale analysis provides descriptive conclusions focusing on the connectivity tendency to be influenced by county-wide urbanization, while the metropolitan-scale analysis provides spatially explicit landscape connectivity measures which can be useful to landscape planning that typically involves selection of potential areas from many alternative areas based on some conflicting criteria.

Second, the two studies facilitate analytical hierarchy processes in formulating planning problems. Due to the different extent and scale, Maricopa County and urbanized metropolitan-Phoenix may have different planning issues with different priorities occurring at each level of the political ladder. However, since the Phoenix metropolitan areas are embedded in Maricopa County, many issues at both scale influence and be influenced by each other. Obviously, it requires comprehensive thinking that considers the collective impact of sporadic site-scale development on the regional landscape, or conversely, reflects the site implications of regional urban plans. In this respect, it is necessary to have flexibility and efficacy in planning across the scales from site planning to urban, suburban, and rural planning.

Third, the county- and metropolitan-scale studies provide useful information for future planning efforts especially in identifying fine-grained ecologically important areas in land planning. Even though the county-level study addressed temporal change of landscape pattern and the metropolitan-level study attempted to explore spatial landscape gradient effects, both studies emphasize the important principles of ecological approaches in understanding a place, its nature and its patterns.

Even though the methodologies employed in county and metropolitan studies may need to be refined for actual implementation, they provide an initial effort for landscape ecological planning (Ahern, 1999) or sustainable land planning (Leitão and Ahern, 2002) to better integrate landscape ecology and landscape planning.

Furthermore, interdisciplinary practices among ecosystem management, urban planning, and landscape architecture need to be implemented beyond the individual traditional boundaries. To practice landscape ecological planning more effectively, it is also necessary to develop a new framework where ecological science and planning issues are well integrated. This study suggests landscape ecological connectivity as a promising language facilitating communication among stakeholders, recognizing planners' role in maintaining ecological properties and dimensions of a sustainable landscape. This approach has implications in modifying the heavily urbanized places to improve sustainability and wildlife habitat, and in turning the tide of urban development toward more sustainable development, offering more opportunities for habitat protection.

CHAPTER 8

CONCLUSION

This study explored landscape pattern change in response to proposed urban development plans at the county scale and then measured landscape ecological connectivity at the metropolitan scale. The desert shrub lands appeared to be a major type of ecosystem in this region but are expected to experience a tremendous amount of land transformation to urban use in the near future. The urban croplands will also be dramatically influenced by the future urbanization, if the proposed urban developments are materialized in the real landscape. Suburban and exurban residential developments can provide an alternative opportunity to create urban green spaces that can serve as potential habitats for urban biodiversity but more innovative approaches are needed for biodiversity conservation and planning.

The landscape ecological connectivity analysis demonstrated the negative correlation between connectivity values and urban density. The indicator species approach was used to look at urban desert landscape and demonstrate the relative connectivity values at the landscape level. This study diagnosed the Phoenix metropolitan landscape as fragmented for a certain large species, but not as degraded as wastelands that cannot sustain urban biodiversity. In the urban modification gradient analysis, the interface areas defined as “in-between” areas of different urban density were expected to have the largest loss of higher connectivity due to future urbanization.

The concept and the modeling method regarding landscape ecological connectivity must be further discussed in more detail on actual areas, but it may contribute to reducing cost and time involved in the early planning stage of identifying potential habitat areas that may conflict with anthropogenic demands.

Maintaining and securing connectivity can be the important first step to understanding the ecology of city. Connectivity can be a planning strategy to make more sustainable landscape. The methods for quantifying landscape connectivity illustrated in this research can be used an effective tool to conserve as many urban habitats connected to wildlnad as possible.

Overall, this study provides an understanding of the impacts of human activities on ecosystem pattern and landscape ecological connectivity in the Phoenix urban region. The underlying ideas and approaches of this study can result in more informed landscape ecological planning that allows the planners to draw up potential areas for connectivity conservation. To do so, urban planners need to think more about processes that are affected by the quality of a landscape, and developers need to be more normative and recognize the regional ramification of local planning. To reflect the site-scale conservation values to the full potential for urban biodiversity, however, more powerful planning tools and frameworks compatible with conservation objectives will be needed.

These challenges and issues which were not fully addressed at the county and metropolitan scales need to be explored in future research. The prospective research direction on the continuum of this study is two-fold: one is related to scaling-up, and the other is to scaling-down.

The scale-up study will examine the impacts of urban morphology on regional or mega-regional landscape connectivity. In other words, the degree of landscape connectivity can be correlated with the size and form of urban settlements. There have been long debates about which urban form is desirable to biodiversity and other ecological processes. Some advocate for compact city forms, while others argue that urban and suburban sprawl is rather helpful. If we regard the notion of landscape ecological connectivity as a proxy to estimate urban biodiversity, the connectivity analysis can be excellently tied in figure out favored urban patterns. Furthermore, the landscape connectivity pattern can be considered as relating to the formation of urban networks at the mega-region scale. Understanding how landscape pattern plays a role during the course of the evolution from metropolis to mega-region would enhance the knowledge of the implications of associated environmental and ecological consequences.

Scaling down to local levels, it may be a great opportunity to capitalize upon large-scale master-planned residential development for urban green spaces creation. This is based on an assumption that maintaining tiny green patches in residential areas can have cumulative effects in urban ecological connectivity. The need for this kind of research can be found in the importance of its critical role for site-scale biodiversity conservation and ecology-grounded community planning. Given the outlook that future development of Phoenix area will continue to spread through the landscape, making human spaces ecologically sustainable can be an alternative to ecological loss and fragmentation. There are a growing number of plans for mid- to large-scale master-planned community developments across the Phoenix region, as the master-planned community historically has been a major type of residential development in Phoenix (Forsyth and Crewe, 2007). Based on the author's preliminary study (Park, 2011), the majority of modern planned communities are situated on the urban fringe and thus are geographically very close to neighboring ecological sources, such as state or regional parks. Besides, significant amount of the lands within the planned community boundaries are either vacant or set aside from housing development temporarily or semi-permanently. Since the housing density is relatively low in such planned communities largely consisting of single family homes, even individual dwelling units have larger lot sizes compared to traditional types of residential development. All these landscape features shown in recently built planned communities have room for increasing and maintaining landscape ecological connectivity for the future community development to come. Hence, timely studies need to be conducted at community or neighborhood scale that highlight green open spaces' potential for ecological connectivity. Although the consolidation of various communities' general plans represents a desired outcome, rather than a predicted one, investigating the optimal composition and configuration of urban green spaces accrued by urban development can contribute not only to creating sustainable community per se but also to regional landscape health.

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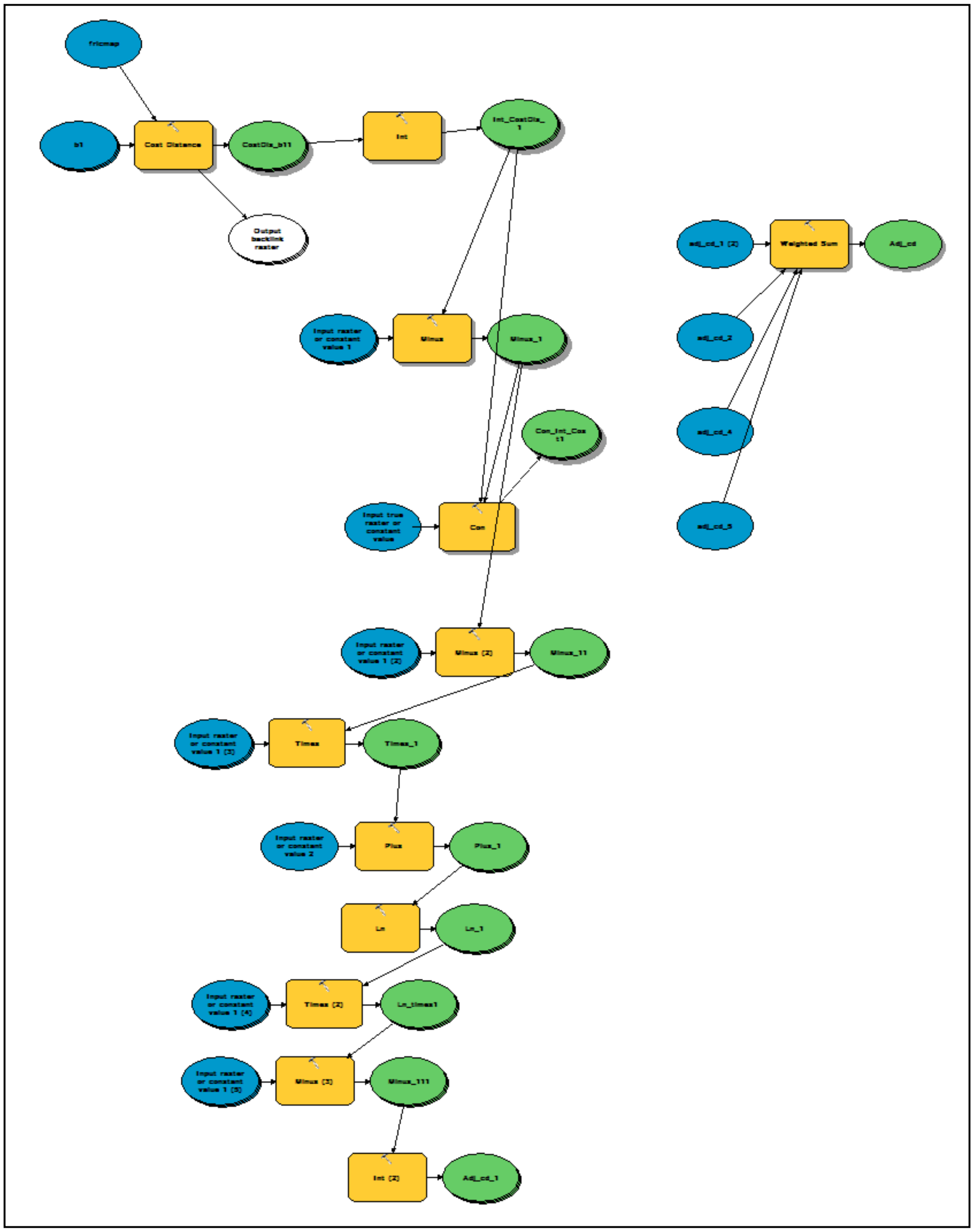
APPENDIX I

MODEL BUILDER DIAGRAMS

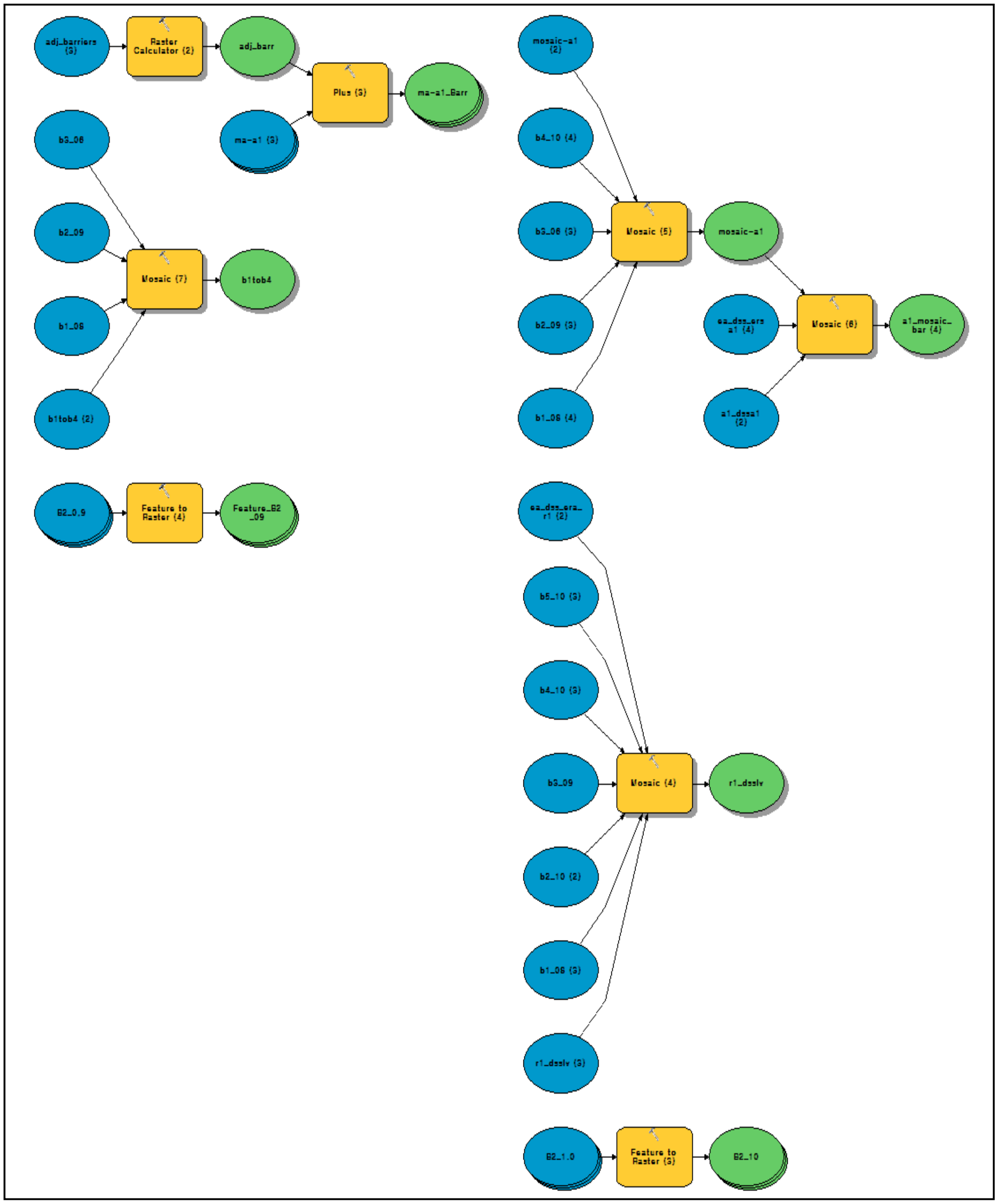
Appendix I. Model Builder Diagrams

(A) Friction Layer



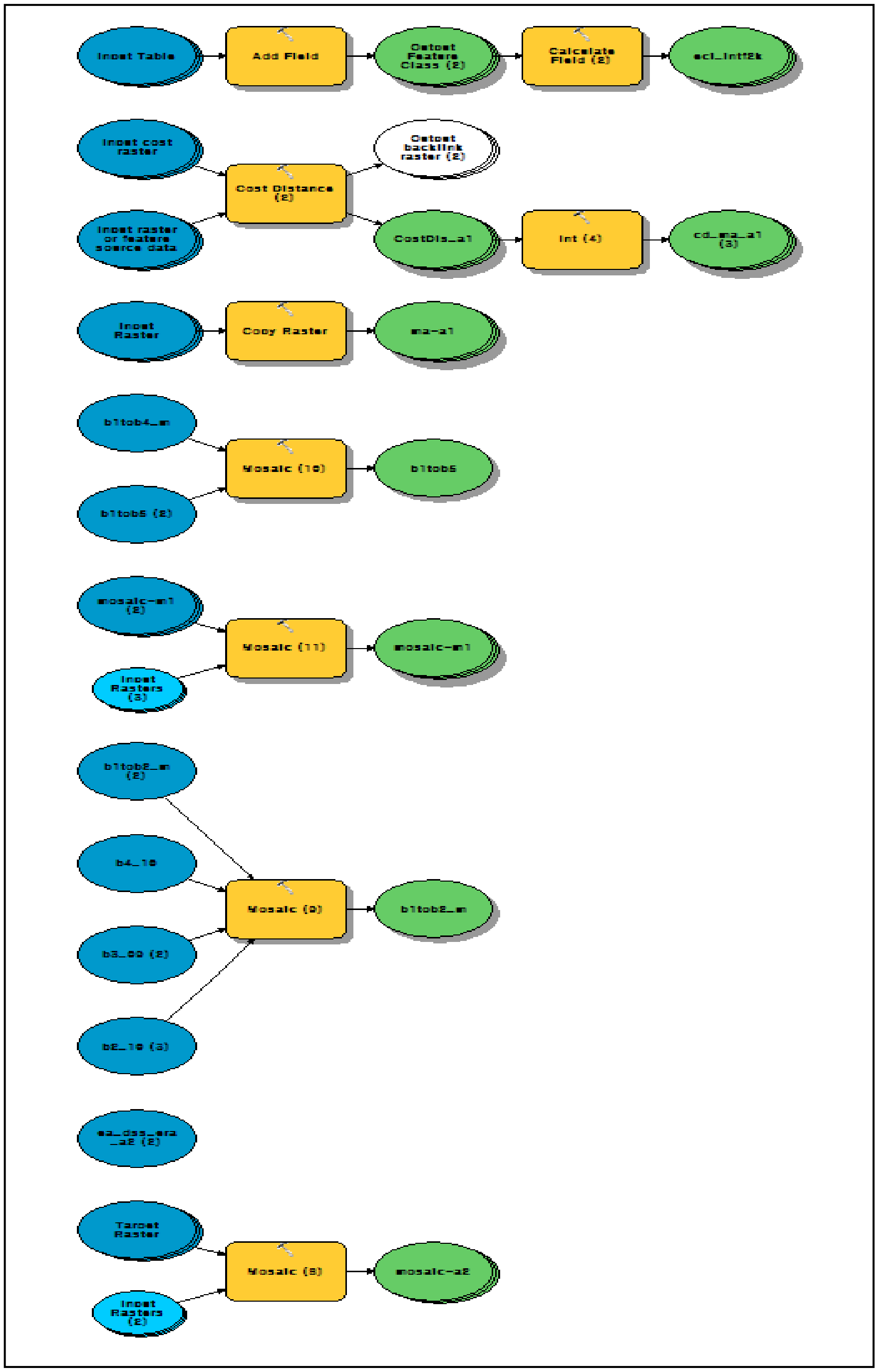
Appendix I. Model Builder Diagrams (Cont'd)

(B) Barrier Effect Index Layer



Appendix I. Model Builder Diagrams (Cont'd)

(C) Matrix Affinity Layer



Appendix I. Model Builder Diagrams (Cont'd)

(D) Adjusted Cost-Distance Layer