Socio-Ecological Drivers and Consequences of Land Fragmentation

Under Conditions of Rapid Urbanization

by

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ABSTRACT

Land transformation under conditions of rapid urbanization has significantly altered the structure and functioning of Earth's systems. Land fragmentation, a characteristic of land transformation, is recognized as a primary driving force in the loss of biological diversity worldwide. However, little is known about its implications in complex urban settings where interaction with social dynamics is intense. This research asks: How do patterns of land cover and land fragmentation vary over time and space, and what are the socio-ecological drivers and consequences of land transformation in a rapidly growing city? Using Metropolitan Phoenix as a case study, the research links pattern and process relationships between land cover, land fragmentation, and socio-ecological systems in the region. It examines population growth, water provision and institutions as major drivers of land transformation, and the changes in bird biodiversity that result from land transformation.

How to manage socio-ecological systems is one of the biggest challenges of moving towards sustainability. This research project provides a deeper understanding of how land transformation affects socio-ecological dynamics in an urban setting. It uses a series of indices to evaluate land cover and fragmentation patterns over the past twenty years, including land patch numbers, contagion, shapes, and diversities. It then generates empirical evidence on the linkages between land cover patterns and ecosystem properties by exploring the drivers and impacts of land cover change. An interdisciplinary approach that integrates social, ecological, and spatial analysis is applied in this research. Findings of the research provide a documented dataset that can help researchers study the

relationship between human activities and biotic processes in an urban setting, and contribute to sustainable urban development.

Dedicated to My Family

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ACRONYMS AND ABBREVIATIONS

ADWR	Arizona Department of Water Resources
AMA	ADWR Active Management Areas
AWS	Assured Water Supply
CAP LTER	Central Arizona Phoenix Long Term Ecological Research
CRC	Colorado River Compact
DCDC	Decision Center for a Desert City
GFR	Grandfathered Groundwater Right
GIS	Geographic Information Systems
GMA/ the *Code*	Groundwater Management Act
GUI Permit	“General Industrial Use” Permit
GWSI	Groundwater Site Inventory
INA	ADWR Irrigated Non-Expansion Areas
LULC	Land Use and Land Cover
MW	Moving Window
NLCD	National Land Cover Datasets
RS	Remote Sensing
WIFA	Water Infrastructure Finance Authority of Arizona

Chapter 1

INTRODUCTION

1.1 Problem Statement and Research Objectives

Rapid urbanization has had significant impacts on Earth's systems, contributing to global climate change, land-use and land-cover (LULC) change, environmental pollution, and energy and water crises (Vitousek et al., 1997). Land fragmentation, especially on the periphery of rapidly urbanizing regions, is a global consequence of LULC change and has pervasive impacts on ecological systems and their feedback into social systems. Ecologists regard land fragmentation as one of the key factors in global biodiversity loss because it breaks up habitat, ecosystems, and land-use types into smaller parcels (Forman, 1995), and alters ecosystem structure and function. Yet few studies have explicitly explored how land fragmentation affects "socio-ecological" systems—those that involve the interaction of ecology, society, and economy (Berkes et al., 2003). Urban ecosystems are socio-ecological systems, and they now house half the world's population and collectively control, drive, and influence the ecosystems on Earth (Grimm et al., 2008; Grimm & Redman, 2004). This dissertation seeks to fill a knowledge gap in our current understanding of how land fragmentation affects urban ecosystems by posing the following question: *How do patterns of land fragmentation vary over time and space in the Phoenix metropolitan region, and what are the socio-ecological consequences of land fragmentation in this rapidly urbanizing desert city?* The specific research questions ask:

A. How has urban growth influenced and changed land fragmentation over time in the Phoenix metropolitan region?

A1. What were the spatial patterns of land fragmentation in 1992 and 2001?

A2. How have land-fragmentation gradients (fragmentation at different distances from the urban center) changed over time?

B. What are the major socio-ecological drivers of land fragmentation?

B1. What are the potential biophysical drivers of land fragmentation?

B2. How has historical decision making influenced land fragmentation?

B3. How do land and water institutions shape land-fragmentation patterns?

C. What are the socio-ecological impacts of land fragmentation on biodiversity in the Phoenix metropolitan region?

C1. How are land composition and land fragmentation related?

C2. What is the influence of land composition on bird biodiversity in metropolitan Phoenix?

C3. What is the influence of land fragmentation on bird biodiversity in metropolitan Phoenix?

D. How does the socio-ecological system contribute to urban sustainability?

D1. How do the socio-ecological implications of land fragmentation in urban settings contribute to sustainable urban development?

D2. What do the findings of this study suggest about policy for sustainable urban planning?

I focused on the greater Phoenix region for three reasons: it is one of the most rapidly growing urban areas in the US; it is a typical desert city facing major resources constraints (especially water) and uncertainty about the possible effects of climate change; and it is the focus region for the Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER) project (Fig. 1.1). For this dissertation research, I leveraged existing data and knowledge from this long-term National Science Foundation (NSF)-funded CAP LTER project, as well as institutional and water data from the ASU Decision Center for a Desert City (DCDC).

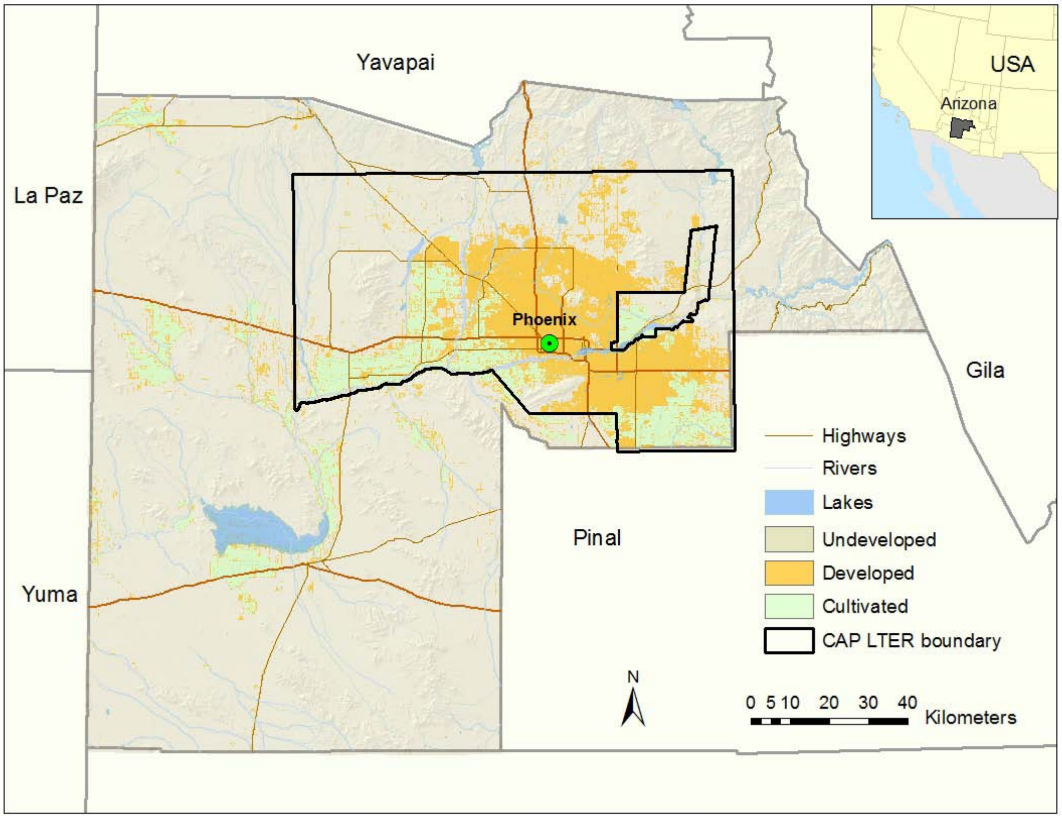


Fig. 1.1 Maricopa County land cover (2001) and CAP LTER site

To answer the research questions, I mapped temporal-spatial patterns of land fragmentation. Landscape metrics for calculating land fragmentation have been developed over the past decade (Li and Wu, 2004). These metrics are calculated based on LULC data, usually by using ArcGIS and Fragstats (Mcgarigal & Marks, 1995). They measure fragmentation patterns with such metrics as patch number, shape, diversity, and contagion. The selection of scales influences the results of land-fragmentation measurement. Therefore, I developed a method to select moving window scales that increases the accuracy of land-fragmentation analysis.

A limitation of existing land-fragmentation research is its overemphasis on pattern analysis at the expense of understanding process. Therefore, after conducting my own pattern analysis, I explored the consequences of land fragmentation by examining its effects on bird biodiversity. First, I examined the relationships between urbanization and levels of fragmentation, using percentage of land cover as an indicator of urbanization level. The hypothesis is that land fragmentation rises with increase in the percentage of developed land. I hypothesized, however, that once contiguous developed land becomes the dominant land cover, land fragmentation will begin to decrease.

Next, I considered biodiversity, using bird biodiversity as an indicator that is sensitive to habitat fragmentation. Biodiversity boosts ecosystem productivity and is directly affected by the presence and patch size of remnant native habitat (Chace & Walsh, 2004). I examined the impacts of fragmentation of native land (desert), cultivated land (farms and urban open space), and urban land (impervious surface) on bird biodiversity, using species abundance, richness, and evenness as metrics. My hypothesis was that in a complex urban ecosystem, land fragmentation will have varying effects on different groups of birds. For example, some native species negatively affected by fragmented native land might nevertheless appear in abundance in highly fragmented urban areas, because of enhanced food, water availability, and landscaping with native plants. This part of my study aimed to understand how land fragmentation affects bird species in an arid urban ecosystem, and to explore how to improve biodiversity in urban areas, especially the biodiversity of native bird species. Because scale of analysis and the fragmentation metrics used might affect study findings, I applied a multiple scale analysis, from 90 m by 90 m to 2470 m by 2470 m.

To better understand the socio-ecological drivers of land fragmentation, I selected four key drivers identified from fieldwork and existing literature:

- Topographic factors. Steep slopes and river valleys often preclude development while higher land with attractive view sheds may encourage high-end real-estate development and increase home values (Bourassa et al., 2004).
- Water institutions. Given the aridity of the US Southwest, provision of fresh water is a fundamental limiting factor of development (August & Gammage, 2006; Gober, 2005; Hanak & Chen, 2007). In Phoenix, agriculture tends to act as a bank for water rights, and once attracted development in farm areas.
- Land institutions. Phoenix's urban sprawl and fragmentation by residential, low-density development is fundamentally influenced by regulatory institutions, including lot size, zoning, and master plans (Dow, 2000; Lambin & Geist, 2006).
- Population. Nearly all land-use-change models include population dynamics because population growth typically leads to land conversion (Agarwal et al., 2001). In addition to growth rates, population characteristics shape land-use change. For example, development of isolated retirement communities has contributed significantly to peripheral growth in Phoenix (Gober, 2005; McHugh, 2007).

1.2 Theoretical Background

1.2.1 Urban Sustainability

Urban sustainability is a sub-concept of *sustainability*. The best-known definition of sustainability, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," was coined by the World Commission on Environment and Development (WCED, 1987) (Alberti, 1996). Others define sustainability as the simultaneous consideration of society, economy, and environment in decision-making (Adams, 2006). Some argue that sustainability is not value neutral, and that ethics and justice should be incorporated into working definitions. The STEPS (Social, Technological and Environmental Pathways to Sustainability) Centre, for example, defines sustainability as the goal of maintaining or improving ecological integrity, human well-being, and social equity for present and future generations.

Urban sustainability is the idea and practice of incorporating sustainability principles into the planning and functioning of cities. Theories of *urban political ecology*, *ecocities* (Register, 1987), *urban ecology* (Grimm et al., 2008), *urban social geography* (Knox, 2000[1982]), *urban ecosystems* (Pickett et al., 1997), *urban resilience* (Folke, 2006; Newman et al., 2009), *urban metabolism* (Kennedy et al., 2007), and *smart growth* (Transit-Oriented-Developed) (Porter, 1998) have influenced notions of urban sustainability from different disciplinary perspectives, approaches, and design principles. Sustainability has pushed for working, empirical solutions to urban-environmental challenges, from individual demonstration projects at the building or site level to city-level design, such as has been used in Vauban, Germany, the humane eco-city in Bogota, sustainable Seattle, and sustainable Manchester (Newman & Jennings, 2008). A key driver and outcome of these projects was a focus on environmental bench marks, indicators, and strategies.

Environmental concerns are an important component in the evolution of urban sustainability, and for cities in general. After the Industrial Revolution and the rise of rapid urbanization in the nineteenth century, cities were faced with a series of environmental problems, such as disease, unsanitary and crowded housing, and polluted air and water (Hall, 2002[1988]). Social scientists searched for the roots of the problems and tried to envision solutions. In the philosophy of *historical materialism*, Engels and Marx pointed out the relationship among human society and nature, and they were among the first to introduce "metabolism" as a metaphor of dynamic social-environmental change (Heynen et al., 2006). From Marxist perspectives, the development of capitalism associated with industrialization and urbanization was not only uneven, but also unsustainable.

In the 1920s, the influential Chicago School of sociology applied ecological principles to the process of urban development. However, "ecology" was a metaphor for the social and spatial morphology of the city. The theory used a "scale-hierarchic" ecosystems approach to explain the sorting of the city into distinct zones defined by land use and social characteristics (Soja, 2000; Dear, 2002). The Chicago School was not concerned with environmental issues *per se*, but used the metaphor of ecosystem processes to help explain the evolution of the modern North American City.

In response to the social and environmental horrors of the industrial city, Ebenezer Howard published the *Garden Cities of Tomorrow* in 1898 as an alternative, some say utopian, vision for urban life (Newman & Jennings, 2008). One of the first garden cities was Letchworth, completed in 1903 by Raymond Unwin and Barry Parker. Letchworth was followed by a number of similar projects, especially in the United Kingdom and the United States between the two World Wars. Based on the principle of “nothing gained by overcrowding,” these new developments were usually built on undeveloped land on the outskirts of cities, fuelling the rise of suburbia (Hall, 2002). In the same era, Frank Lloyd Wright’s idea of “Usonian Vision” also reflected anti-urban thinking. It was founded on an idealized vision of combining suburb and countryside, but neglected the social-economic context of urban life. After World War II, rampant suburbanization in the US departed from Wright’s vision, constructing giant roads and expanding urban areas along them (Hall, 2002). Low-density development was promoted as a remedy for urban environmental problems, but it generated new environmental problems such as land fragmentation, loss of agricultural and other working lands, high energy consumption, reliance on private transportation, traffic congestion, and air-quality problems.

Unlike the Garden City movement sparked by Howard’s 1898 book,, the City Beautiful movement during the first half of the twentieth century was concerned with controlling urban expansion even as it shared the Garden City movement’s interest in aesthetics, environmentalism, and moral order (Boone & Modarres, 2006). The Chicago Plan, designed in 1909 by Daniel Hudson Burnham, was a shining example of City Beautiful ideals, and served as the first comprehensive plan for the controlled growth of an American city. The rise of the City Beautiful movement corresponded with regional planning. The Regional Planning Association of America (RPAA) was founded in 1923, thanks primarily to the efforts of Clarence Stein, Benton MacKaye, and Lewis Mumford.

It raised concerns about the relationship between humans and nature, and emphasized that population should be distributed to utilize, rather than destroy, nature. “The conservation of human values hand in hand with natural resources” was a key principle (Hall, 2002). New York’s regional plan and the Greater London regional plan derived from this kind of thinking. London represented a successful example of regional planning using the greenbelt concept (i.e., a swath of undeveloped green space encircling a city) to limit urban growth.

In the last few decades, environmental issues in the city have been investigated from a number of different perspectives. In the 1980s, neo-Marxists argued that the root cause of longstanding socio-environmental injustice in the city was the capitalist mode of production and the flow of labor and capital. Political ecology picked up on these ideas and buoyed the environmental justice movement in the same decade (Boone & Modarres, 2006; Heynen, 2006; Short, 2006). In response to widespread low-density, suburban sprawl and associated environmental problems, the New Urbanist movement gathered steam during the 80s. It broke with traditional master planning to introduce such innovations as livable, pedestrian-friendly cities and mixed high-density land use with a diversity of buildings of types, sizes, and functions.

In the late 1980s, with the release of *Sustainable Development of the Biosphere* (Clark & Munn, 1986) and Our Common Future (WCED, 1987), sustainability science began to develop as an interdisciplinary science, serving as an intellectual umbrella for the study of human-environment problems (Turner, 2010). Changes in ideas about urban sustainability have reflected changes in two ecological concepts. The first is urban ecology. Urban ecology has undergone a significant transition in the last two decades, moving away from studying ecology *in* the city to studying ecology *of* the city (Pickett et al., 2001; Grimm et al., 2008). Cities need to be understood as ecosystems, albeit special ecosystems where social and ecological dynamics are tightly coupled (Redman et al., 2004). Thus, urban sustainability relies in part on the development and management of a sustainable ecosystem. The other ecological concept, resilience, is one of the Ten Melbourne Principles for sustainable cities (Newman & Jennings 2008). Like the concept of urban ecology, the concept of resilience has been applied to human-dominated ecosystems (Holling, 1973). Resilience is described as the capability of a system to absorb disturbance and still persist (Carpenter et al., 2001, Walker & Meyers, 2004). "Vulnerability and resilience constitute different but overlapping research themes embraced by sustainability science" (Turner, 2010), and building resilience is the analogous to reducing vulnerability.

Urban sustainability differs from traditional urban theories in many ways. First, it is problem-driven with a focus on solutions. Sustainability emphasizes that the status quo is unsustainable and threatens future survival. Unlike most traditional urban theories, which seek to explain the rules and characteristics of city development, sustainability is more like a development guide. Secondly, sustainability is strongly interdisciplinary. Traditional urban theories usually are based in one discipline. For example, the Chicago School, Neo-Marxism, and political ecology are based mainly in sociology or geography. Urban sustainability, however, requires an integration of different disciplines that can systematically understand coupled socio-ecological dynamics and formulate interventions that lead to desired pathways. This requires collaboration of scientists from various disciples, as well as policy makers, urban planners, and practitioners. Thirdly, urban sustainability tackles new levels of environmental concerns. Although environmental awareness is reflected in traditional urban theories, those theories are based on a quite limited understanding of the interactions between humans and nature, which are usually presented as dichotomies: growth vs. anti-growth, sprawl vs. sprawl control, pollution vs. protection. In contrast, sustainability seeks deep insights into human-nature interactions, recognizing that they form a complex dynamic system. Sustainability in general and urban sustainability in particular raises concerns about the environment to a new level. Finally, given that sustainability is concerned with problems that involve economy, society, and environment, a systems approach is necessary to understand the interactions among domains and the system that arises from the interactions.

1.2.2 Social-ecological systems framework and related theories

The Social-ecological systems (SES) framework is an organizing tool used by researchers to understand coupled social and ecological systems. The framework provides a way to analyze complex, dynamic systems. SES has been used by diverse groups of researchers. Early SESs included Pickett et al.'s (1997) human ecosystem framework and Grimm's (2000) conceptual scheme for integrating ecological and social systems in urban environments. Anderies et al. (2004) defined SES as "an ecological system intricately linked with and affected by one or more social systems," and generated a conceptual model of a social-ecological system. SES has proven especially useful to those studying *urban ecology* and *resilience*.

Over the last two decades, urban ecology has grown considerably. One reason for the growth of urban ecology in the United States is the National Science Foundation's commitment to funding the study of cities as ecosystems. This facilitated a key shift in urban ecology from studying ecology *in* cities to the ecology *of* cities, with the latter recognizing the city as a special, human-dominated ecosystem where social and ecological dynamics are tightly coupled (Pickett et al., 2001; Grimm et al., 2008). Urban ecology thus separated from ecology as a new discipline. Urban ecologists have described SES as "a conceptual framework for understanding the human dimensions of ecological change" (Redman et al., 2004) that considers the previous isolated "natural" and "human" systems as a single, complex social-ecological system (SES) (Fig. 1.2) (Redman et al., 2004).

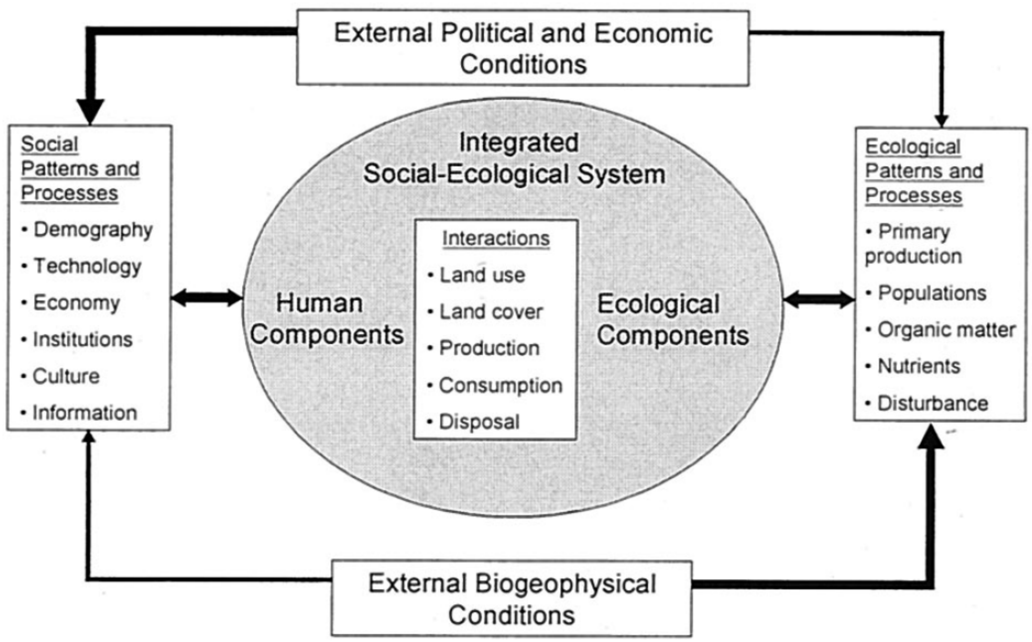


Fig. 1.2 Conceptual framework for long-term investigations of social-ecological systems (Redman et al., 2004)

Like urban ecology, resilience theory grew out of ecology, in the 1960s and early 1970s (Folke, 2006). An ecological definition of resilience is "the magnitude of disturbance that can be tolerated before a system moves into a different region of state space and a different set of controls" (Carpenter et al., 2001). Because hierarchies and adaptive cycles comprise the basis of ecological or social-ecological systems, Holling (1973) proposed a model of *panarchy* (Fig. 1.3). Panarchy represents a hierarchical structure as a nested set of adaptive cycles. The two major elements of panarchy are its adaptive cycles at different levels, and the connection between levels. Social-ecological systems are intertwined in adaptive cycles of exploitation, conservation, release, and reorganization. Resilience is defined as the capability of a system to undergo external disturbance and remain its functions and controls, and the threshold in the system change (Carpenter et al 2001, Walker and Meyers, 2004), and is consistent with the goal of sustainability (Holling, 2001). A resilient social-ecological system should have the following characteristics: when facing disturbance or external forces, the system has the high capability of self-organization and adaptation, and can absorb the changes and the external disturbance while maintaining the same state. The human ability to learn is an adaptive capacity that supports resilience. But human misunderstanding of problems may delay response to change or provoke inappropriate responses.

In principle, resilience could be measured by calculating system equilibrium over time. In reality, the complexity inherent in resilience makes it difficult to measure the resilience of an entire social-ecological system. Challenges include the measurement of interactions among fast or slow social and ecological variables, the determination of key variables (i.e., "rule of hand"), and the problem of how to deal with the upscale "revolt" effect, in which changes that originate at small scales may have large-scale spatial-temporal effects (Walker et al., 2006). Although several conceptual frameworks for resilience were developed as approaches (e.g., Berkes et al., 2003; Anderies et al., 2004), resilience remains hard to measure. Resilience may be a metaphor for sustainability, useful for case studies or practical assessment (Carpenter et al,. 2001). One way to understand resilience is by studying vulnerability.

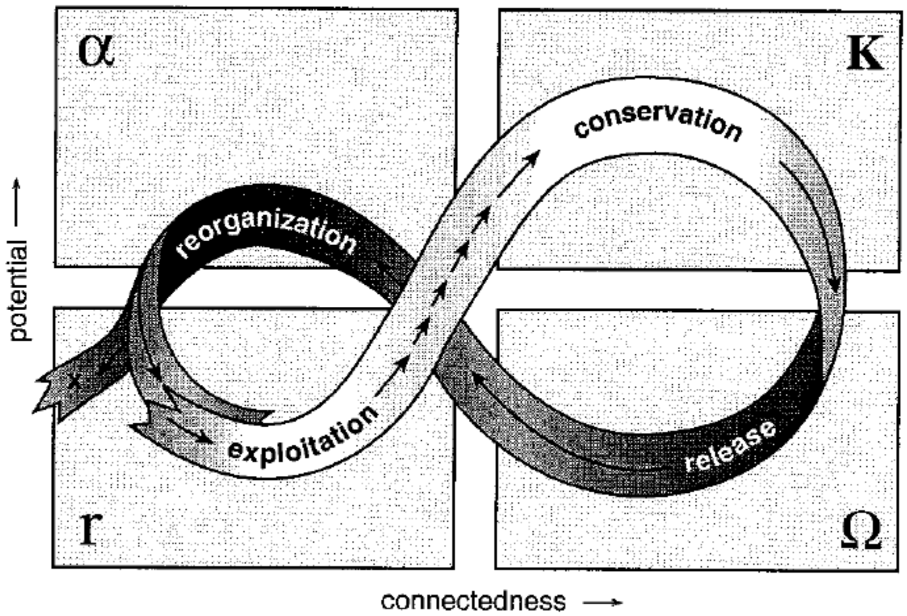


Fig. 1.3 Panarchy model of adaptive cycle and Panarchical connections between levels (Holling, 2001)

1.3 Research Framework

In urban sustainability studies, many research questions need to be answered through studying urban structures. Spatial analysis is a method that links human and natural systems by exploring pattern, pattern change, and pattern to process, and is the most prominent tool used urban social geography (Knox, 2000[1982]) and urban environmental studies. Social and ecological characters can be presented as patterns: e.g., land, biodiversity, demographic, pollution, housing, density, amenity, heat island. When social patterns are correlated with ecological patterns using geographic regressions, the process behind the patterns may be revealed. But to discover the drivers and consequences in urban SESs, we need go beyond spatial correlations. Thus, different methods such as surveys, archival analysis, and interviewing are needed. Urban environment studies within the framework of urban sustainability require a combination of different approaches and data.

One spatial phenomenon, land fragmentation, can be defined as ‘‘the breaking up of a habitat, ecosystem or land-use type into smaller parcels’’ (Forman, 1995). Over the past few decades, as land fragmentation has been recognized as having largely negative implications, researchers have conducted four kinds of studies. The first kind focuses on the *method* and *indices* for measuring land-fragmentation patterns (O’Neill et al., 1988; Dramstadt et al., 1998; Frohn, 1998; McGarigal & Marks, 1995; Lambin, 1999; Jaeger, 2000; Southworth et al., 2004). The second kind of study interprets complex landscape-structure and land-fragmentation *patterns*. Most studies of land fragmentation have concentrated on the fragmentation of natural habitat, especially forests (Burgess & Sharpe, 1981; Harris, 1984; Franklin & Forman, 1987; Skole & Tucker, 1993; Jorge & Garcia, 1997; Li et al., 2001; Millington et al. 2003; Tole, 2006). Driven by concerns about urban sprawl, some studies of natural-habitat fragmentation have been extended to urban areas (Kong & Nakagoshi, 2006; Irwin & Bockstael, 2007; Schneider & Woodcock, 2008). The third kind of study explores *drivers* of land fragmentation. Jaeger (2000) divided the drivers into human factors (such as the anthropogenic fragmentation caused by roads, railway lines, and extension of settlement areas) and natural factors (including fragmentation that creates natural barriers to animal migration. Most studies on the driving forces of land fragmentation have concentrated primarily on social drivers

(Lambin et al., 2001; Heim, 2001; Razin & Rosentraub, 2000; Tan et al., 2006; Munroe & York, 2003; Munroe et al., 2005; Nagendra et al., 2004; York et al., 2005, 2006). The fourth kind of study investigates the *impacts* of land fragmentation on social and ecological systems. Fragmentation disconnects landscape corridors, which affects biodiversity and ecosystem processes. Because many species are adapted to large rather than small patches of habitat, fragmentation usually decreases species richness (Vogelmann, 1995), forces species to migrate (Dyer, 1994), causes extinction (Wilcox & Murphy, 1985) and drives the global biodiversity crisis (McGarigal & Cushman, 2002). Fragmentation can not only change biological community structure, but also impacts ecosystem functions and services, such as microclimate changes (Saunders et al., 1991), agricultural and forest production, and native systems (Carsjens & van derKnaap, 2002; Rickenbach & Gobster, 2004; Kline et al., 2004). A limited number of studies have examined feedbacks from land fragmentation to human outcomes, including public-service provision costs (Camagni et al., 2002), outdoor recreation, and quality of life (Carsjens & van Lier 2002; Deller et al., 2001; Rickenbach & Gobster, 2003). In developing countries, land fragmentation often translates into a lack of basic infrastructure because of the high costs associated with providing services in disaggregated urban forms (Sudhira et al., 2004).

The above four categories of studies represent methodology, pattern, and process of land fragmentation. Given the high social and ecological costs of fragmentation, it is imperative to develop robust frameworks to improve understanding of the drivers and consequences of land fragmentation. Advanced measurements of the spatial variability of land fragmentation will help planners and policymakers to target resources to curb fragmentation rather than applying blanket approaches. Therefore, I adapted the LTER social-ecological framework (Collins et al., 2007) as a means to analyze the complex patterns and processes of land fragmentation (Fig. 1.4). Elements in red were the major concerns of my dissertation research.

Within the adapted framework, fragmentation provides the basis for understanding complex, dynamic socio-ecological systems. Case studies of land fragmentation and socio-ecological systems have been limited by one-way perspectives, examining either the impacts of social drivers on ecological structure and function, or vice versa. Much theoretical literature has been published on the need for examining the feedback relationships between social and ecological systems, but empirical studies are sorely lacking. Another limitation of land fragmentation studies, especially as they relate to ecosystem structure and functioning, is that urban systems have been underrepresented. Theoretically, the relationship between human disturbance and land-fragmentation pattern can be very different in urban than in remote rural or wild land areas. Fragmentation studies in non-urban areas (Lambin et al., 1999) have found that human disturbance tends to fragment the landscape and can lead to an increase in species *homogeneity*. Studies in and around cities have found similar patterns of species homogeneity from landscape fragmentation (Schneider & Woodcock, 2008), but Grimm and Redman (2004) question the generalizability of such findings. In urban areas, human activities may actually enhance preferable landscape and water availability, and provide new sources of food. Similarly, Williams et al. (2005) point out that in arid environments, urban plant diversity and abundance may actually be higher than in the surrounding deserts. Clearly, the links between land fragmentation and ecological structure and function in complex urban ecosystems deserve more careful study.

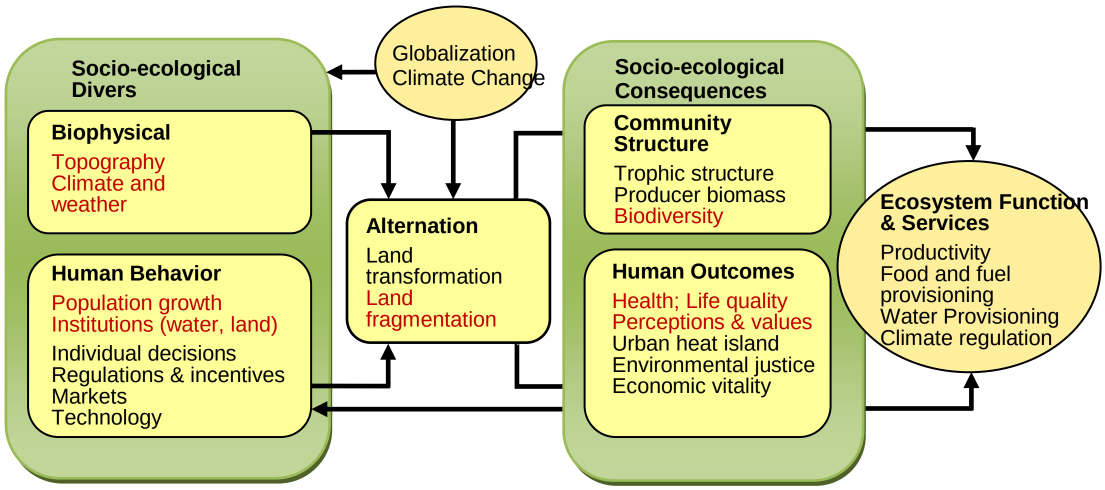


Fig. 1.4 Adapted socio-ecological framework for understanding land fragmentation

1.4 Study Area – Rapid Growth in the Phoenix Region

Growth and sprawl accelerated in the second half of the last century in the Phoenix metropolitan region (Grimm & Redman, 2004). The acceleration corresponds with rapid economic growth and expansion of population, city size, and employment. After World War II, population growth and the phenomenon of Rustbelt to Sunbelt migration (Vogel & Swanson, 1989) caused the population in the Phoenix metropolitan area to grow from 2.4 million in 1980 to 5.7 million in 2006. The huge migration from Rustbelt to Sunbelt was due not only to the decline of the industries in the Rustbelt, but also to Arizona's mortgage and loan policies and housing subsidies designed to attract people and facilitate economic development. These policies were consistent with growth-politics theories. Urban growth was also reflected by huge areas of land conversion. The urban area of Phoenix expanded from 17 square miles in 1950 to 515 square miles in 2005, and is surrounded by 24 growing municipalities (Heim, 2006). Land was initially converted primarily from farmland to residential areas, but recent developments are occurring on wild lands as well. (Grimm & Redman, 2004).

The expansion of urban development has resulted from competition for land among cities and developers, and has been leveraged by land institutions such as annexation, zoning, and legalization of sale or lease of state-trust land. Annexation allowed the areas of cities to expand rapidly, increased property tax bases, and incorporated wealthy regions (Luckingham, 1984). Annexation wars were waged among cities; one example is the battle for Ahwatukee among Tempe, Chandler, and Phoenix (Heim, 2001). Cities sometimes requested that developers annex land as part of municipal growth strategies. For example, Continental Homes requested annexation of Pima Ranch, and Avanti Mortgage Company of Phoenix requested annexation of 620 acres in 1987 to develop an indusial park (Heim, 2006). They gradually influenced the Phoenix City Council to approve annexation.

Highways development also reflects government support for urban growth, and it has pushed development across the valley’s east-west axis since the 1990s. Growth theories help explain some of Phoenix’s development, but growth was not the only force that shaped today’s Phoenix. Many factors, including globalization, environmental conservation, and the interactions of institutions and individuals have influenced Phoenix’s urban pattern, structure, and growth.

One reasons for the fast urbanization and suburbanization of Phoenix was emigration from the Rustbelt in the northeastern US to Sunbelt in the southern US after

WWII. The influx of Rustbelt refugees occurred during Phoenix's Fordist period, which was characterized by industrialized mass production. The postmodern spatial pattern of Phoenix is partly the product of systems of agglomeration around the semiconductor industry, represented by companies such as Intel, Motorola, and Honeywell. These high-technology industrial districts were distributed around the fringes of the metropolitan area. The transition from primary and secondary industries to the service industry, the rise of smaller-scale flexible production and deindustrialization, and resulting economic restructuring allowed Phoenix urban area to sprawl in a nomadic and unbounded way. Urbanization merged more than 24 cities into a large urban region and formed the metropolitan Phoenix area. The merging of the cities gradually generated a multicenter urban pattern. The central business district (CBD) in Phoenix lost its dominant role.

During the past fifty years, immigration to the area has fueled rapid population growth in Metropolitan Phoenix; the growth has been associated with the extensive development of residential areas. Incomers have played an increasingly significant role in shaping urban structure. Middle- and upper-class people started to build their own "privatopias," (e.g., gated communities), at the edge of the city, pushing the boundaries of the city outward into undeveloped desert areas. However, this expansion has not been rational in the way that modernism proposed. Modernism is characterized by rational growth; a typical example is the Chicago School's theory of natural growth around the city core. Phoenix did not grow outwards from a central core. It is a desert city where water is particularly important to people. The water-rights doctrine of prior-appropriation in the southwestern US, which allows people to buy and sell water rights, was a crucial underlying factor that shaped the city's form. Another factor was the Federal Highway

Act of 1956, which resulted in large-scale expansion of freeway construction. Throughout Phoenix's history, urban development has happened in the areas where transportation and water are available—contrary to theories of rational growth.

Immigration created a Phoenix with ethnic pluralism, a typical characteristic of postmodernism and a prominent feature of the contemporary urban development process. However, the mix of nationalities, cultures, and races in Phoenix has also generated another characteristic of postmodernism–a polarized city with injustice (Stefanov et al., 2004). With the emergence of social problems, environmental problems also aroused people's attention. An example can be seen from landscape pattern: the multicenter urban sprawl and chaotic, leapfrog development increased land fragmentation, exposing Phoenix to many environmental problems, such as water shortage, urban heat island, and loss of native species.

1.5 Research methodology and dissertation structure

1.5.1 Advanced land fragmentation methodology

A research methodology for efficient analysis of land fragmentation is described in Chapter 2. I evaluated the effect of moving window (MW) size on observed fragmentation spatial patterns at a regional level, and proposed a method to identify an effective MW size using Simpson's diversity index. To test the robustness of the proposed method, I demonstrated its use in six cities in the Phoenix metropolitan area that have substantial variation in land composition and configuration. Then I explored the effects of gradient observation scale and the role of scale in removing noise. I compared and discussed two popular approaches to measuring urban-to-rural fragmentation gradients—concentric ring- and transect- based approaches—highlighting the usefulness of each approach in an extensive and rapidly urbanizing region. This study provides a new method for selecting window size, offers insights on scale effects, and provides guidance on gradient scale selection to achieve the best representation of land-fragmentation patterns for urban analysis.

1.5.2 Fragmentation gradient analysis

Using the method for effective land-fragmentation analysis that I developed, I created a fragmentation gradient in the Phoenix Metropolitan Area from 1992 to 2001. Fragmentation gradient is the mean fragmentation value at distances from the urban center, and it measures the intensity of urbanization (high in center and low on periphery). The land-fragmentation analysis was based on the National Land Cover Datasets (NLCD) of 1992 and 2001. I selected the Central Business District (CBD) in Phoenix as the urban center, based on classic urban economic growth theory (Alonso, 1964). To examine the land fragmentation gradient, four transects passing through the urban center across the region were applied. The study also evaluated the accuracy of NLCD data by comparing it with parcel data.

In Chapter 4, I describe how I applied the research methods I developed to five southwestern US cities for a cross-site comparative study. I compared different urban forms and land-fragmentation patterns in arid regions undergoing rapid urbanization.

1.5.3 Land fragmentation and socio-ecological drivers

Various drivers shape land fragmentation in Phoenix. For example, basin-and-range topography provides ample flat land for easy development, but steep, abrupt hills and mountains act as barriers to contiguous development. Micro-climate variations in the desert make development at higher elevations desirable. Extensive public and tribal lands contribute to leap-frog development. Decisions by policy makers can influence land patterns through local tax controls, expansion of public services, and lot-size requirements. Water institutions allow lands with senior water rights to develop much more quickly than others. In order to explore the power of such drivers, beyond the pattern analysis, I examined social and topographical drivers of land-fragmentation change, such as urbanization, population dynamics, transportation, and institutional factors. Because water provisioning plays a pivotal role in the development of cities in desert environments, I focused especially on evaluating water policies and how they drive land-fragmentation patterns in Phoenix. I conducted a statistical analysis of the relationship between distribution of wells and degree of land fragmentation, and compared results within and outside the Active Management Area (AMA). The Groundwater Management Act (GMA)-created AMAs are zones where groundwater use is restricted in order to maintain aquifer levels. Results of my evaluation are discussed in Chapter 5.

1.5.4 Land fragmentation and consequences on bird biodiversity

Chapter 6 describes my study of the effects of fragmentation on bird biodiversity. Bird data from 51 CAP LTER monitoring sites were applied. The sites (30m × 30m square plot per site) were randomly selected within the CAP LTER study boundary, and birds had been monitored in four seasons each year since 2000. Diversity indices were calculated using the PAST program (Hammer et al., 2001). Based on Blair's (1996) classification, I grouped all species of birds observed in metropolitan Phoenix into "urban avoiders" (native bird count decreased in urbanized area), "urban adapters" (native bird count increased in urbanized area), and "urban exploiters" (exotic birds). The relationships between land fragmentation and overall bird diversity were analyzed separately for the three land types. For each bird group, a correlation was made between bird diversity and land fragmentation and composition. Land composition was linked with fragmentation to investigate which land class might cause the highest land fragmentation. I also considered scale effects at the habitat and landscape levels (Chace and Walsh, 2004), and examined the buffer area with a side length gradually increasing from 90 m to 2490 m around the sites.

Chapters 2 through Chapter 6 close the loop of the theoretical socio-ecological framework, and link the biotic structure and patterns with human behavior and outcomes. Chapter 7 summarizes study findings and the contributions of this research project.

In summary, my research aimed to contribute to sustainable governance of socio-ecological systems by augmenting our understanding of socio-ecological dynamics in an urban setting, by making a case-study of land fragmentation. The research systematically examined the dynamic fragmentation patterns in the greater-Phoenix region, using a series of indices that reflect land patch numbers, contagion, shapes, and diversities over ten years (1992-2001). It then found empirical evidence of the links between land fragmentation and ecosystem properties by exploring the drivers and impacts of fragmentation. The method was extended to five southwest US cities for a cross-site comparative study of patterns and process of fragmentation. Water policies were evaluated as a potential driver of land fragmentation in arid regions. Research results provide a documented dataset that can be used to understand the relationship between human activities and biotic processes in an urban setting, and thereby contribute to urban sustainable development.

Chapter 2

METHODOLOGICAL ADVANCES IN THE SPATIAL ANALYSIS OF LAND FRAGMENTATION

2.1 Introduction

Fragmentation disconnects landscape corridors, affecting biodiversity and ecosystem processes. Because many species are adapted to large rather than small patches of habitat, fragmentation usually decreases species richness (Vogelmann, 1995), forces species to migrate (Dyer, 1994), and drives the global biodiversity crisis (Jorge & Garcia, 1997; McGarigal & Cushman, 2002). Besides its implications for biodiversity, fragmentation impacts agriculture and forest production, native systems (Lawrence, 1988; Carsjens & van Lier, 2002; Carsjens & van der Knaap, 2002; Rickenbach & Gobster ,2003; Kline, Azuma, & Alig, 2004), public service provision costs (Camagni, Gibelli, & Rigamonti, 2002), outdoor recreation, and quality of life (Deller et al., 2001; Rickenbach & Gobster, 2003; Sudhira, Ramachandra, & Jagadish, 2004). Given the high social and ecological costs of fragmentation, it is imperative to develop robust methods for analyzing land fragmentation, especially in metropolitan areas that are highly heterogeneous and growing rapidly. Advanced measurements of the spatial variation of land fragmentation will assist planners and policymakers in targeting resources to curb fragmentation where it is highly detrimental rather than applying blanket approaches.

Over the past few decades, landscape metrics have been developed to interpret the characteristics of complex landscape structure and land fragmentation. Recent development of FRAGSTATS (McGarigal & Marks, 1995) has increased application of landscape metrics because it can calculate more than forty landscape metrics and is compatible with geographic information systems (GIS) and remote sensing software. A common approach to characterizing fragmentation is to average fragmentation metrics over an entire area. However, this method may lead to incorrect interpretations of the causal dynamics of fragmentation (Herold, Scepan, & Clarke, 2002) because averaging does not account for spatial variation (McGarigal & Cushman, 2002). Moving window (MW) analysis, in contrast, uses a window at a selected scale to move across the landscape one cell at a time, calculate the specified metrics within the window, and assign the value to the center cell of the window (McGarigal & Cushman, 2005). Fragmentation gradient analysis may be used in combination with the MW analysis providing information about the directionality and location of fragmentation. Fragmentation gradients are generally analyzed by a series of equal-width concentric rings around the city enter, or a transect passing through the city center with a "gliding box" (Gustafson, 1998) moving along the transect. Urban-to-rural fragmentation gradients illustrate intensity of urban sprawl, a key dynamic in metropolitan socio-ecological systems (e.g. Jensen, 1979; McDonnell et al., 1997; Irwin & Bockstael, 2007; Keys, Wentz, & Redman, 2007).

Using a case study of the Phoenix metropolitan area, this study addresses the major methodological issues in moving window and gradient analyses of land fragmentation. First, we propose a method to explore a MW size that improves the effectiveness of fragmentation analysis. Second, fragmentation gradient analysis is conducted at a certain scale of resolution, hereafter called "observation scale", which is determined by the width of the concentric rings or the size of gliding box. We examine the effects of observation scale on urban-to-rural fragmentation gradient analyses and evaluate the choice of concentric rings versus transects. These issues are raised because every analyst makes these selections when conducting a MW and gradient analysis, yet often the criteria for choice is not explicit and the selection consequences on fragmentation results are not adequately taken into account.

Most research on landscape structure tests various window sizes over several runs and makes a decision based on visual inspection and intuition. Without a theoretically determined window size, there is a significant difference in the MW sizes selected based on empirical trials—for instance, Langanke et al. (2005) used a 0.44 km^2 round MW in a regional study in northern Germany, Kong and Nakagoshi (2006) selected a 0.79 km^2 round MW for Jinan city in China, Bielecka (2007) applied a 1 km^2 MW for identification of landscape diversity of the whole of Poland, Tole (2006) adopted a 0.02 km^2 square MW in Jamaica's Cockpit Country, UK, and Buyantuyev et al. (2010) chose a 0.11 km^2 square MW for a study of Phoenix city in USA. Clearly, fragmentation results are sensitive to the selection of the window size (Openshaw, 1984; Eiden, Kayadjanian, & Vidal, 2000; Wu, 2004; Berling-Wolff & Wu, 2004). Therefore, it is necessary to explore an approach of finding a MW size that can provide a clearly recognizable land distribution pattern. Eiden (2000) raised the hypothesis that the optimal window size for a given landscape should be indicated at the point with the greatest range of number of classes the MW detected. Land fragmentation is defined as the breaking up of land use type into smaller parcels (Forman, 1995). Continuous areas of the same land class form land "patches"—the basic components that all fragmentation metrics are derived from (Sudhira et al., 2004), so land types are the very essential precondition for fragmentation. Therefore, we agree with Eiden et al. (2000)'s logic that the suitable MW scale should allow identifying both single type and sufficient mixed types of land for a better measurement of fragmentation variation, making a broad spectrum of fragmentation level observable. We develop a process to find the effective MW size by evaluating the diversity of number of land classes a MW can capture.

Selection of MW size is not the only important choice for fragmentation gradient analyses; the adoption of an observation scale also affects the observed fragmentation gradients. Similar to the MW selection, analysts have adopted a wide range of ring widths and sizes of gliding boxes. Examples include 7-km concentric ring applied in a Phoenix study (Keys, Wentz, & Redman, 2007), 1-km concentric rings in a comparative study of 25 cities worldwide (Schneider & Woodcock, 2008), a 15 km × 15 km gliding box in a study of Phoenix (Luck & Wu, 2002), a 4 km × 4 km gliding box in a study of Chengdu, China (Schneider, Seto, &nWebster, 2005), and a 5 km × 5 km gliding box in a study of Guangzhou, China (Yu & Ng, 2007). For the goal of providing a guideline in choosing an appropriate scale for effective analysis, in this article we analyze the impact of observation scale for both concentric ring and transect methods on fragmentation gradients.

2.2 Methods

2.2.1 Study area and dataset

The Phoenix metropolitan area consists of twenty-six municipalities located primarily in Maricopa County, Arizona. The basin and range geology of the Sonoran Desert has ample flat and easily developable land, and urban areas have expanded quickly here, especially in the Post World War II era (Grimm & Redman, 2004). With a population of 4.4 million, the Phoenix metropolitan area is ranked twelfth in population in the United States and is an exemplar of a fast-growing urban region in the US. Southwest. Although growth in the Phoenix metropolitan area has been explosive in the post-War period, the pattern of growth and land use is highly varied among the incorporated cities in the region due to their individual histories, locations with the region, institutions, and social-ecological contexts (Gober, 2005).

The primary data source for our analyses is the 30-m resolution USGS National Land Cover Datasets (NLCD) for 1992 and 2001. We use these data to derive land cover change information and fragmentation analyses for the county. The NLCD is compiled from Landsat satellite Thematic Mapper imagery with a 30 m / pixel spatial resolution and supplemented by a relatively small number of aerial photographs as well as various ancillary data for ground truthing. The NLCD 1992 data for this region has an accuracy rating of 82 percent to 85 percent at Anderson Level I (Wickham et al., 2004).

Because we focus on human impacts on landscape structure, we classify land cover types into three categories: “Developed” characterized by a high percentage (30 percent or greater) of constructed materials such as asphalt, concrete and buildings; “Undeveloped” characterized by water, barren, forest, shrub land, herbaceous upland, woody wetlands and emergent herbaceous wetlands; and “Cultivated” characterized by herbaceous vegetation (75 percent or greater) that has been planted or is intensively managed for the production of food, feed, fiber, or is maintained in developed settings for specific purposes such as parks and golf courses (Fig. 2.1).

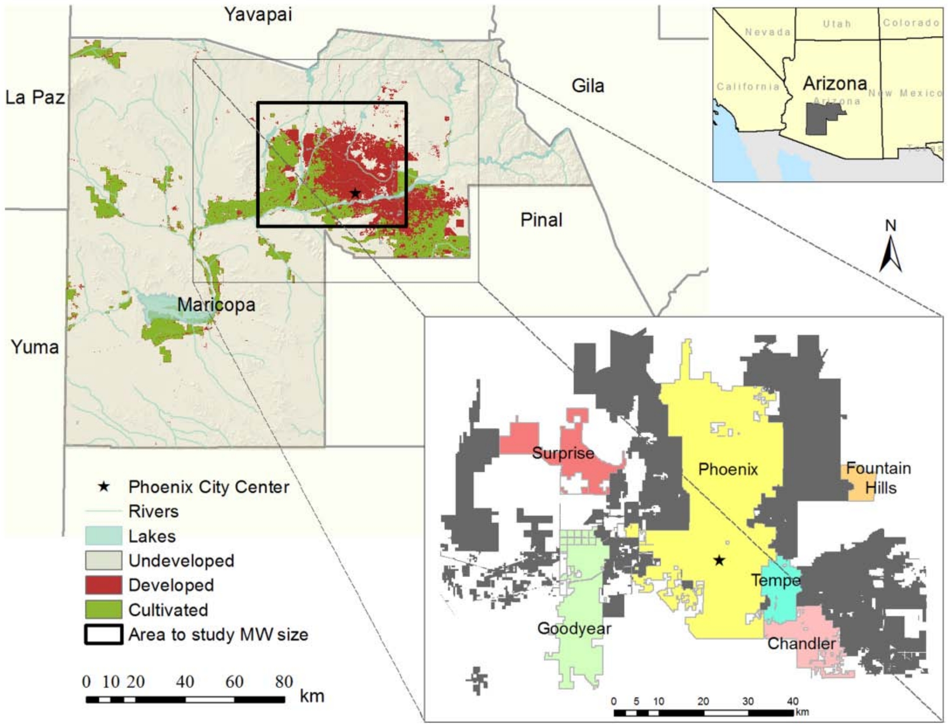


Fig. 2.1 Land cover of the Phoenix metropolitan area using reclassified NLCD 1992 and the selected incorporated areas, Maricopa County, Arizona

2.2.2 Effective MW size identification for spatial fragmentation analysis

Eiden et al. (2000) argued that the optimal MW size occurs with the greatest range of land classes detected (Fig 2.2). We develop a method for detecting the size whereby the highest diversity of land classes are detected for all the "observations," which means each time the MW calculates the fragmentation metrics within the window. To characterize the diversity of number of land classes within each MW observation, we apply the complementary form of Simpson's index (Simpson, 1949) on the number of land classes. Here, the Simpson's diversity index (D) is described as:

$$D = 1 - \sum_{i=1}^{n} p_i^2 \ .$$

Where p_i equals the percentage of the number of land classes value on the total observations at a specific MW size, n equals to the number of p_i values. The highest D value represents a maximum diversity of number of land classes, i.e. the effective MW size.

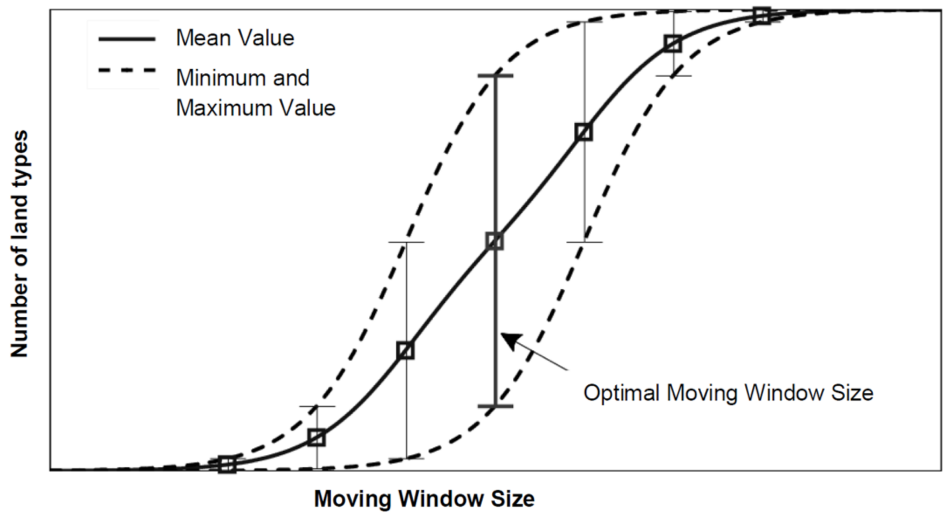


Fig. 2.2 Concept of the optimal moving window size by Eiden et al. (2000)

The proposed method of effective MW size is especially appropriate for studying regional urban areas where fragmentation characteristics are typically non-uniform and variable across space. We chose a 60 km by 50 km extent centered over the core urban area that delineates an urban to rural region in order to empirically test the MW sizes (Fig. 2.1). In the sample urban to rural landscape in Phoenix, a series of MWs with side length of 90 m to 2370 m are tested to find the most effective MW size based on the highest Simpson's diversity index.

In order to test this approach in different landscapes, six cities in the Phoenix metropolitan area are selected for further study. These cities are selected along an urban to rural gradient representing cities with differential urban density and developed land uses. Phoenix (1250 km^2) is the biggest city and is the core of the metropolitan area. Tempe and Chandler are selected along the southeast urban-rural gradient. Located only 9 km from the center of Phoenix, Tempe (103 km^2) has 93 percent of its area developed. Chandler (152 km^2) is adjacent to Tempe but extends into the urban-rural fringe. Developed and cultivated land together count for 98 percent of area, and only 2 percent of vacant land interspersed within the city. In contrast, Surprise (190 km^2) and Goodyear (303 km^2) are located further from the urban core and contain less developed land: Surprise has 18 percent developed and 66 percent undeveloped land; Goodyear's land area is only 10 percent developed and 59 percent undeveloped. Fountain Hills (47 km^2) is a smaller city with a near absence of cultivated land. 99.6 percent of the area is developed and undeveloped land. These cases provide smaller tests of effective window size within a metropolitan region.

2.2.3 Selection of observation scale and approaches in the gradient analysis

In gradient analysis, a major challenge is how to identify the variation of gradients with strong fluctuations. Observation scale needs to be big enough to smooth out the noise to illustrate the fragmentation trends. The observation scale creates an averaging effect, since any fluctuation where the wavelength is smaller than the observation scale will be attenuated. Since fragmentation fluctuation is not one simple wave, the wave at the smallest scale is formed by the minimum mapping unit (i.e. cell value of the fragmentation metrics), and the numerous waves form a bigger wave at a larger scale. We can explain how the window filters the small scale variation through the example in Fig. 2.3. To simplify the waves at different scales, we assume that the fragmentation fluctuation is the superposition by only two scales of waves, $\sin(2\pi x / l_1) + 0.3\sin(2\pi x / l_2)$

which are shown in Fig. 2.3A. The large scale example has a wavelength of $l_1 = 10\,km$ and small scale example has a wavelength of $l_2 = 1\,km$. In order to remove the disturbance of the small scale fluctuation, we can set the observation size, the width of the rings or the side length of the gliding box, between the wavelengths of the two scales. Setting the wavelength at 2 km (Fig. 2.3B) demonstrates that small scale fluctuation has been filtered out but the desired large scale variation is retained.

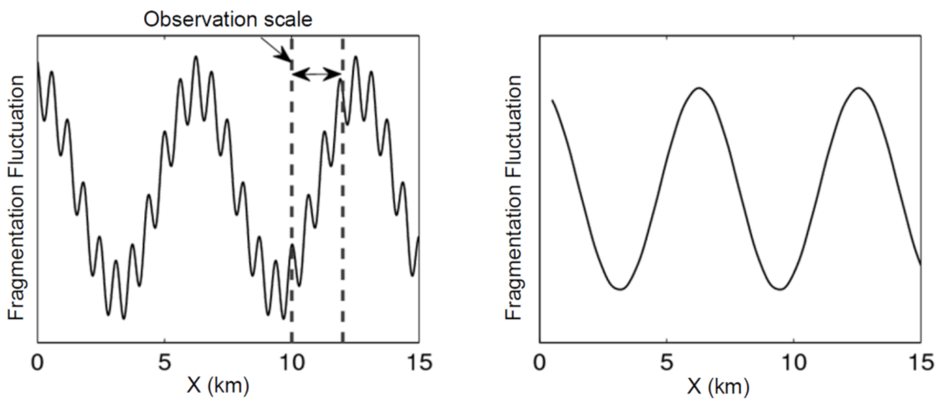


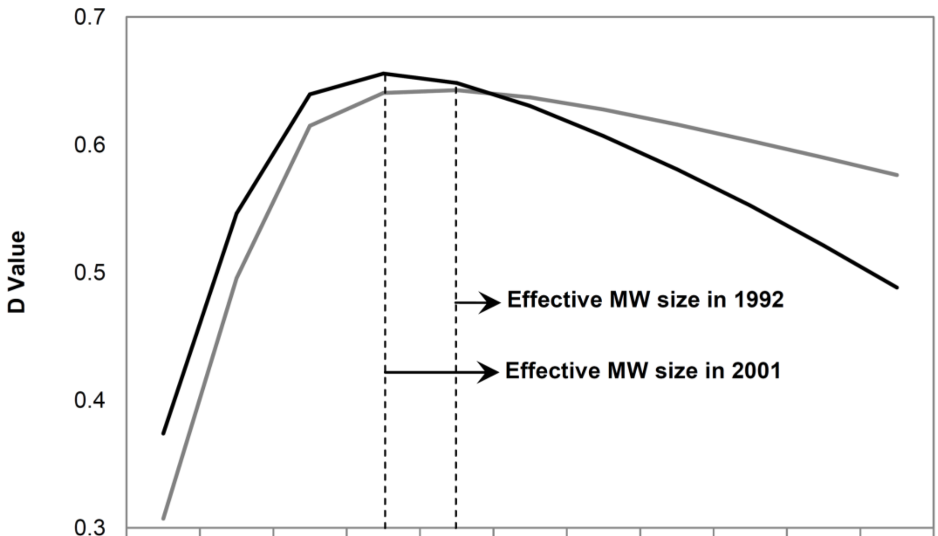
Fig. 2.3 Concept of appropriate observation scale which is able to filter unwanted disturbance from fragmentation variation

Fragmentation gradient analysis is based on the fragmentation pattern obtained from MW analysis, thus observation scale only affects the filtering or averaging, but not composition and configuration. We use two scales to investigate this averaging effect: 5 km and 1 km wide rings radiating out from Phoenix's city center, approximated by Phoenix City Hall. These two scales are selected based on the commonly used scales in recent regional studies. Similarly, we test the observation scale effect on the transect approach. A 15 km width transect band was clipped to traverse the main urban core of the Phoenix metropolitan area to the remote desert using a gliding box of 15 km × 15 km versus a 15 km × 1 km box. To make the concentric rings and transect approaches comparable, the gliding box of 15 km × 15 km moves 5 km each time, calculating fragmentation every 5 km along the gradient, while the 15 km × 1 km box moves 1 km each time to match the interval of 1 km rings. This selection of the two approaches may be based on a theoretical question: for instance, if directionality of fragmentation is the major concern, a transect may be the most appropriate choice while if one is interested in the overall gradients of fragmentation from the city center, concentric rings may the best choice.

2.3 Results

2.3.1 Effects of MW size on land fragmentation spatial pattern analysis

We propose that the effective MW size should be selected using Simpson's Diversity index as an indicator of variation of land classes. In Fig. 2.4, Simpson's diversity index rises and falls with increasing MW size. In 1992, the effective window size indicated from the highest D value is 930 m × 930 m, and for the 2001 image, it is 690 m × 690 m. The variation of the effective MW sizes between the two years is potentially due to the enhancement of fragmentation levels in 2001, creating a more complex spatial heterogeneity. The results infer that a well-defined peak of D value suggest a more specific MW size, while flatter D curves suggest a range of MW sizes are appropriate. In the case study of metropolitan Phoenix, for both 1992 and 2001, a MW size between 450 m to 930 m is effective in presenting land fragmentation pattern.



	90	210	450	690	930	1170	1410	1650	1890	2130	2370
1992	0.31	0.50	0.61	0.64	0.64	0.64	0.63	0.62	0.60	0.59	0.58
2001	0.37	0.55	0.64	0.66	0.65	0.63	0.61	0.58	0.55	0.52	0.49

Fig. 2.4 CONTAG metrics based on different MW sizes from 90 m × 90 m to 2370 m × 2370 m in the year 1992

To understand the change in number of land classes, we present histograms of the land classes captured with different MW sizes in 2001 (Fig. 2.5). At the smallest extreme with the 90 m × 90 m MW, 75.87 percent of the observations can only capture one of the three land classes when the window moves over the landscape (Fig. 2.5A). Because all landscape metrics are calculated based on thematic land classes, the small MW does not capture the spatial relationships among different land classes, and thus results in the same fragmentation value for most of the landscape. At the largest extreme of 2370 m × 2370 m, 66.69 percent of observations capture three classes (Fig. 2.5C). Large windows result in an overall increase of most fragmentation metrics and loss of fragmentation variation. At the effective 690 m × 690 m size, the observations for one, two and three land classes become nearly evenly distributed (Fig. 2.5B), capturing the greatest diversity and producing the best distribution of land fragmentation.

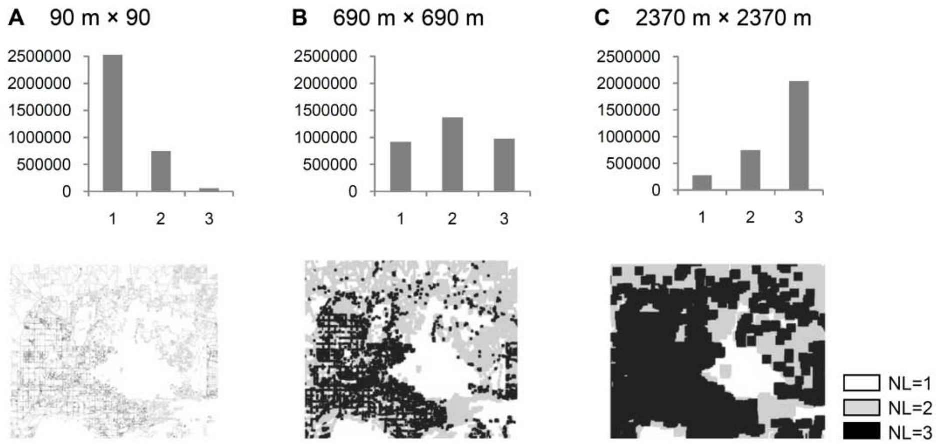


Fig. 2.5 The relation of MW sizes and D value of number of land classes for the sample area in the year 1992 and 2001

(NL = number of land classes)

To verify the effectiveness of the determined MW size using the proposed method, a contagion (CONTAG) fragmentation analysis with different size of MW is given in Fig. 2.6. We found that MW sizes result in similar fragmentation pattern but different contrast across the landscape. In Fig. 2.6, it can be seen that in most areas of the map, large and small MW sizes do not capture the variation of CONTAG fragmentation. For example, in the center of the figure where fragmentation level is low, 90 m × 90 m (first panel) and 2370 m × 2370 m (last panel) MW sizes both fail to show the detail of CONTAG variation. Since detection of fragmentation requires a large enough area to be observed, a small MW size (such as 90 m × 90 m case) is not capable of detecting the fragmentation. On the other hand, very large MW can average the fragmentation detail out, blurring the fragmentation map, as is the case of 2370 m × 2370 m MW size. The effective window size 690 m × 690 m, however, clearly shows the variation detail. One can see that the gray levels have the richest distribution in the box area among the different MW sizes.

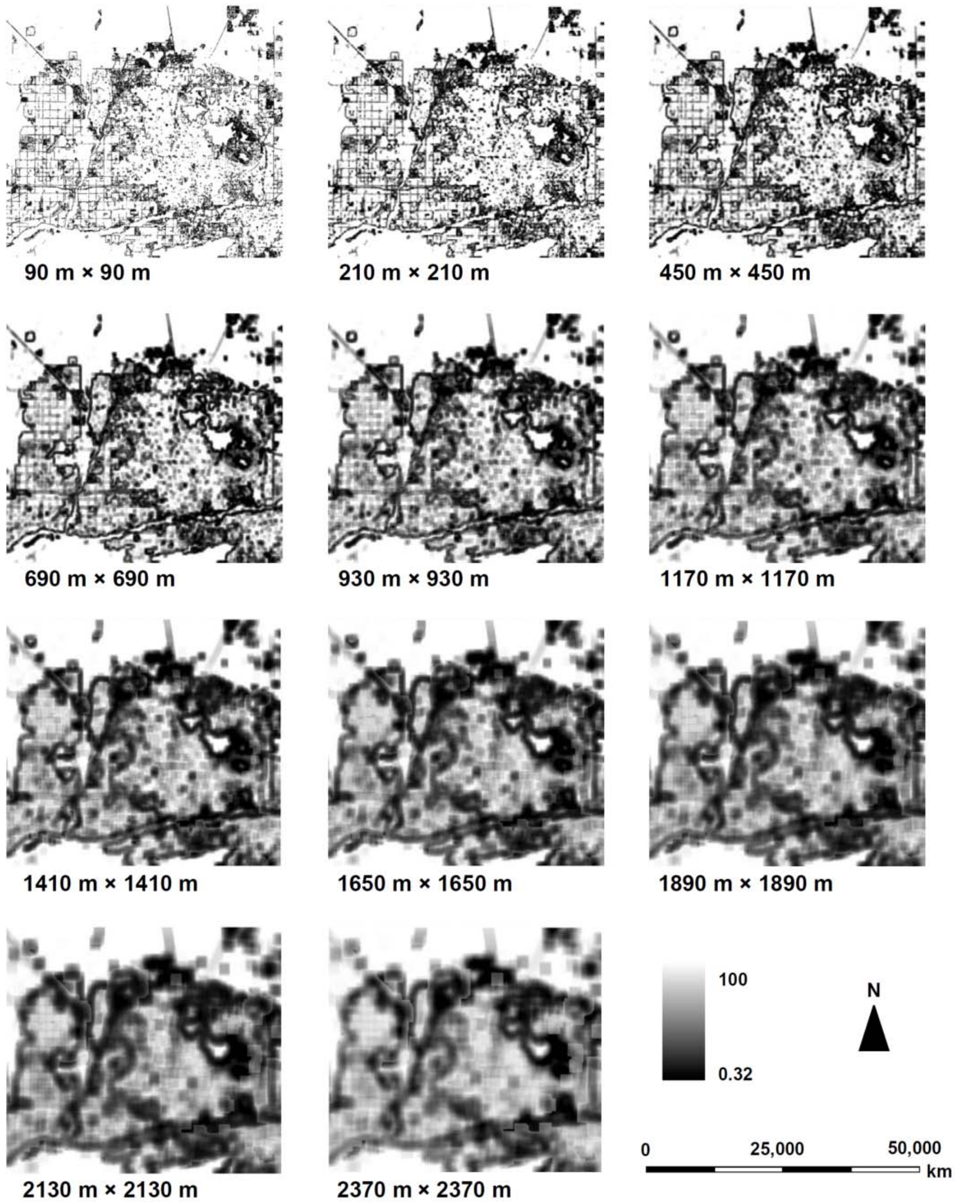


Fig. 2.6 Examples of the number of land classes captured by three of the tested MW sizes

In order to test this approach in different landscapes, results of MW analysis for the six small cities are shown in Fig. 2.7. Four of the six cities have smaller effective MW sizes than the regional metropolitan area while two have larger effective MW sizes. A closer look at the six cities helps to understand the relationship between the effective MW sizes and landscape pattern.

Smaller MW sizes are suggested for the cities of Fountain Hills (Fig. 2.7A), Surprise (Fig. 2.7B), Chandler (Fig. 2.7C) and Goodyear (Fig. 2.7D). Note that all four cities are located on the fringe of the Phoenix metropolitan region. Fountain Hills is a city dominated by a mixture of developed and undeveloped land. Its landscape is the most fragmented among all cities, leading to a very small effective MW size of 90 m. Chandler consists mostly of developed and cultivated land. It has an effective MW size of 450 m. Surprise is situated at the urban fringe, and is farther from the urban center than Chandler with a mix of the three land classes and complex fragmentation variation, with an effective MW size of 450 m. Goodyear is a city expanding into desert with development and cultivated land in the north. Expansion of transportation and cultivated land causes increased fragmentation in the desert in the south resulting in an effective window size of 690 m. One highly fragmented city has a very small effective MW, two cities have similar effective MW sizes, slightly smaller than the regional optimum, and the last one's optimum is similar to that of the entire metropolitan region.

Phoenix (Fig. 2.7E) and Tempe (Fig. 2.7F) have larger effective MW sizes than the metro as a whole. Phoenix has a nearly contiguous area of developed land stretching from the urban core to the northern and southern desert fringes resulting in a bigger MW size of 1650 m. Similarly, Tempe is dominated by one land class of developed area with an extremely uniform landscape resulting in the largest effective MW size of 2850 m.

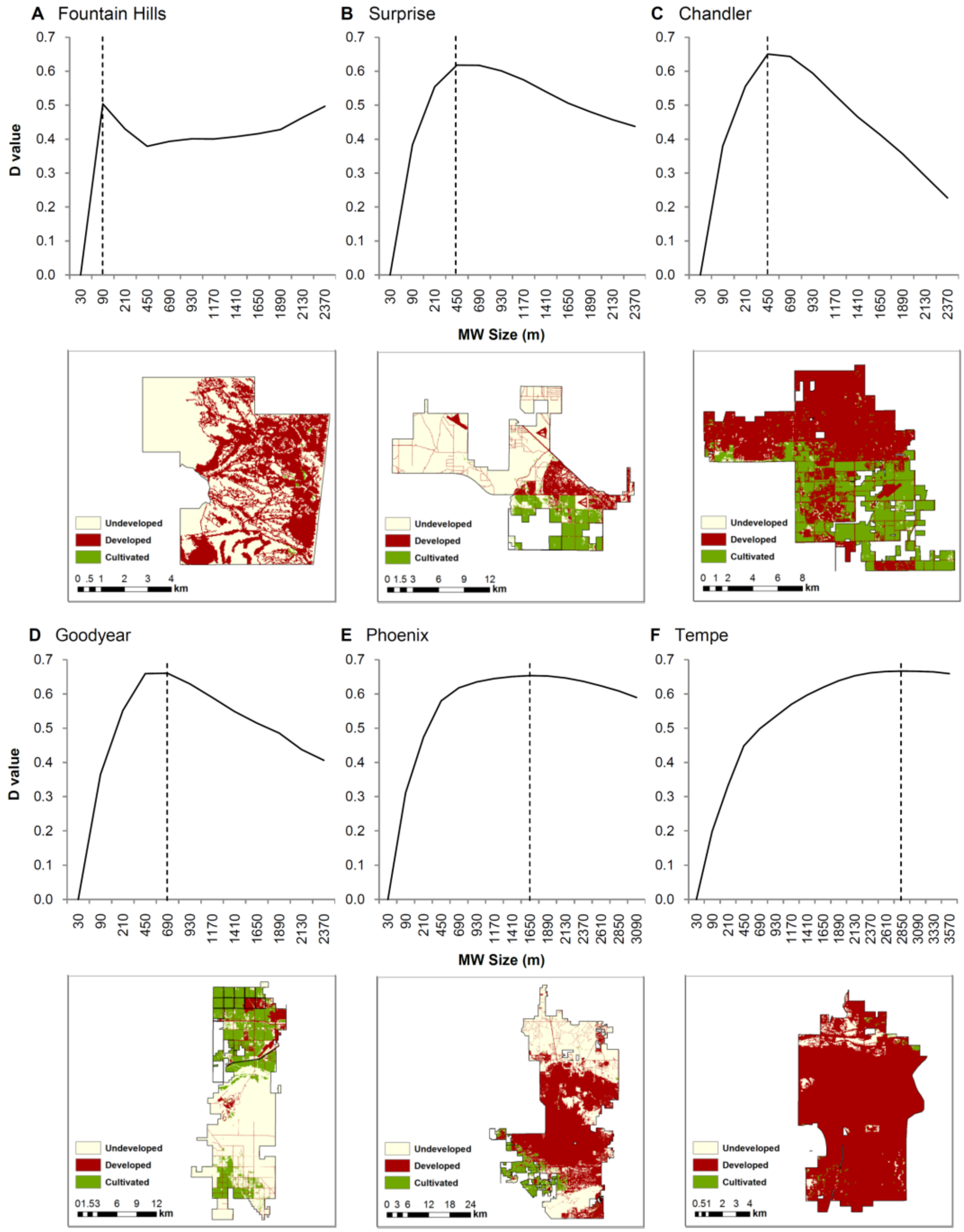


Fig. 2.7 The relation of MW sizes and D value of number of land classes for six cities in the Phoenix metropolitan area in the year 2001

2.3.2 Effects of fragmentation gradient observation scale and two gradient analysis approaches

To evaluate the scale effect of fragmentation gradient analysis we apply the effective metropolitan MW size of 690 m × 690 m. In Fig. 2.8A and 2.8C, a 15 km × 15 km box effectively filters the small-scale spatial noise much better than the 15 km × 1 km box. The movement of the peak fragmentation outward from the city center during the period 1992 to 2001 can be more easily observed in Fig. 2.8A. Fig. 2.8B and Fig. 2.8D represent the comparison of ring widths of 5 km and 1 km. The smaller scale of 1 km causes more fluctuation in the results. However, with less noise compared to that in the transect, the peak of fragmentation is still visible with the 1 km rings.

Next, we compare the fragmentation gradients using concentric ring- and transect-based approaches. We focus on the comparison of the transect approach with the gliding box of 15 km ×15 km (Fig. 2.8A) and the ring approach with the ring-width of 5 km (Fig. 2.8B). The selected observation scales are shown as appropriate from the previous scale effect study. First, the transect approach is capable of capturing directional information that is relevant to understanding processes where fragmentation is uneven across a landscape, e.g. urban growth along a river or interstate highway. The ring approach better captures the overall level of fragmentation as distance from the city center increases. For example, Fig. 2.8B indicates that the highest level of fragmentation changed from 10 km to the city center in 1992 to 40 km to the city center in 2001, and fragmentation grew the fastest at 40 km from the city center. Fig. 2.8A using the transect method shows that the fragmentation peaks spread outwards at both sides of the city center, and the fastest growing area is on the east side at 150 km. Average fragmentation levels in the remote west are considerably higher than in the remote east, indicating a development trend towards the west. This is due partially to the western parts of the county having more expanses of flat land and fewer mountains, which facilitates agriculture. Second, concentric rings have a stronger averaging effect. The rings incorporate radial moving directions and average the fragmentation values in each ring over the whole angular direction. Transects, however, have only one moving direction and average the fragmentation values in a defined gliding box along the transect. Furthermore, the concentric rings applied different scales in detecting fragmentation. They have larger areas and hence their averaging effect is enhanced with increasing distance from the city center. Therefore, the transect method has larger ranges and higher fluctuations of fragmentation values than the concentric rings method. As seen from Fig. 2.8, the CONTAG ranges from 60.98-99.98 in 1992 and 55.76-100 in 2001 in Fig. 2.8A, and ranges from 66.22-98.04 in 1992 and 65.67-95.74 in 2001 in Fig. 2.8B. The fluctuation of CONTAG value decreases 18.41 percent in 1992 and 32.03 percent in 2001 when shifting from the transect to ring approach. As the rings continue moving outwards, the increasing area further smoothes out the CONTAG values and reduces fluctuations. This effect may indicate that the transect is more effective at capturing fragmentation variation than the concentric ring approach due to the unchanged scale of the transect far from the center.

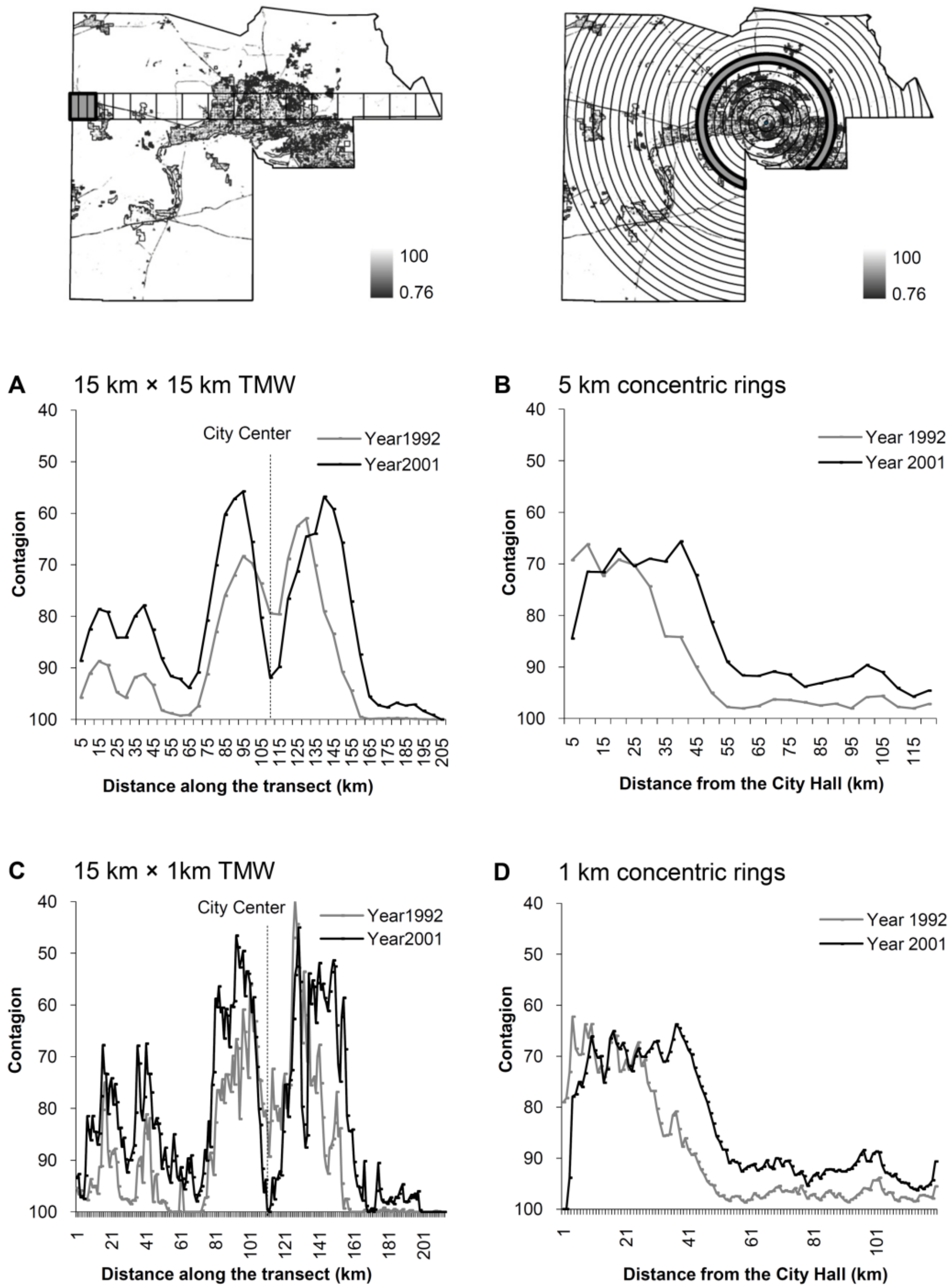


Fig. 2.8 Comparison of the effect of observation scales and two fragmentation gradient methods

2.4 Discussion

MW analysis is a useful tool for capturing the spatial variation of landscape patterns for regional studies. Intuitively one might think that smaller windows give more information on variation of the fragmentation in all cases. However, if the window size is too small, and nearly equal to the cell size, it can catch only one land class without any fragmentation, or only capture fragmentation at the edges of two land classes. However, if the window is too big, it always captures all land classes, and the coverage of the window is nearly the whole landscape wherever it moves. The increase of MW creates more overlapped areas in each calculation, thus it gradually loses the capability to present small to medium scale fragmentation variance. Therefore, very large and very small MWs are not desirable for capturing land fragmentation. We proposed an efficient MW size based on capturing the maximum diversity of land classes for different window sizes.

In this paper, Simpson's D index (Simpson, 1949) is selected to measure the diversity. Simpson's D index, along with Shannon's diversity index (Shannon & Weaver, 1949) is the most popular diversity indices frequently employed to quantify landscape composition (Nagendra, 2002). But Simpson's index is more intuitive than Shannon's index with its statistical meaning (McGarigal & Marks, 1995). Both metrics evaluate the evenness and richness of diversity. However, Shannon's index emphasizes richness, while Simpson's index emphasizes evenness (Peet, 1974; McGarigal & Marks, 1995). Shannon's index is preferable when a component has a relatively small number (DeJong, 1975). However, in land fragmentation analysis, a rare-portion land type usually has small effects on the overall land fragmentation, thus evenness is more likely to be the major factor in selecting the MW scale and Simpson index is thus selected for this study.

Using this approach, we find that a 690 m × 690 m moving window is the effective size for capturing land fragmentation in the sample region of Phoenix metropolitan area. At a sub-metropolitan level, the effective MW size depends on the percentage of each land class within the sample area, whether or not a single land class dominates the landscape, and the overall fragmentation of the study sites. Since Tempe is covered largely by one land class, a larger MW is needed to increase the identification of two and three classes. In cases with a single land class dominating the landscape, large MW sizes are most likely needed. MW is also influenced by the overall fragmentation level of the landscape. Both Chandler and Phoenix are cities where developed area is more than fifty percent. Unlike Phoenix, the highly fragmented pattern of Chandler results in a smaller effective MW size than Phoenix. In cases with high land fragmentation evenly distributed across the whole landscape a smaller MW is needed. Generally, low fragmentation area results in a big MW size, and high fragmentation results in a small MW size. In the case of region with pockets of high and low fragmentation, the effective MW balances the uneven distribution of fragmentation, which is illustrated by the Phoenix metropolitan area with an effective size of 690 m. The greatest advantage of MW analysis versus an average value for the whole area lies in its ability to detect the difference of fragmentation distribution. For cases without an obvious peak D value, such as Tempe or Fountain Hills, there is little variation in fragmentation across the landscape, thus it may be a case where MW is not an appropriate analytical tool.

Effective MW sizes are potentially correspondent with the scale of fragmentation, such as the mean size of patches. Using the case studies of six cities, we examine the correlation between effective MW sizes with the overall landscape fragmentation of each city. We chose two metrics for measuring the size of patches: Largest Patch Index (LPI), which is the percentage of the landscape comprised by the largest patch, and Mean Patch Size (MPS), which is the average patch size of all land classes. Our findings demonstrate that the effective MW sizes are positively and strongly correlated with the two patch size metrics: LPI (r = 0.906, p = 0.013) and MPS (r = 0.894, p = 0.016). It is potentially possible to develop a model using sufficient sample areas, involving fragmentation indices such as patch size, percentage land cover, as well as other variables that may affect the choice of MW. This paper hopes to inspire further studies and model development on the MW selection.

Selection of the scale of observation in the gradient analysis impacts landscape metrics and fragmentation pattern. Generally, larger observation scales have a stronger averaging effect, smoothing the observed fragmentation, which results in a blurred image of the CONTAG results. As the width of the transect is reduced to the minimum mapping unit, the gliding box nears cell size leading to more observable fluctuation in fragmentation.

From our comparison of the concentric ring and transect methods for land fragmentation gradient analysis, some general conclusions can be drawn. Although both methods can effectively capture and measure fragmentation gradients to the city center, the ring method averages all the directions, while the transect method provides better directional information, helping the researcher understand in detail how and why urban growth happens. In addition, due to the strong averaging effect of the rings, to avoid distortion of the results, a monocentric symmetric urban configuration is most appropriate for this approach; otherwise, an area with higher fragmentation level could be masked by lower levels averaged in the rest of the area within the ring, resulting in a biased fragmentation evaluation. In contrast, the transect is more flexible in capturing uneven development characteristics, and more sensible for long-range directional fragmentation assessment.

2.5 Conclusion

This article highlights methodological issues in the spatial pattern and gradient analysis of landscape fragmentation. It provides a theoretical basis and a new methodology for the selection of effective MW size using Simpson's Diversity index based on the hypothesis that effective MW size captures the greatest diversity of land classes. We applied the method to the metropolitan Phoenix region and its sub-metropolitan region as case studies. Results from the Phoenix case study find that 690 m × 690 m is an effective MW size. At the sub-metropolitan scale, if we exclude the extreme cases of Tempe and Phoenix and Fountain Hills, which are highly dominated by one land type or small and highly fragmented, the range of effective MW is from 450m to 1km. This range provides a rough reference when selecting a suitable MW size for other regional-level landscapes.

Finally, we evaluate and compare the performance of two common gradient analysis methods—concentric rings and transects—providing guidance for researchers in selecting the appropriate method and scale. For the gradient analysis, city form is a critical factor that needs to be considered when choosing ring- versus transect-based approach. Most fragmentation analyses treat the city as monocentric (Von Thünen, 1966 [1826]; Alonso, 1964). However, polycentric forms (Papageorgiou & Casetti, 1971), "leapfrog" development over green space and open land (Razin & Rosentraub, 2000) and "edge cities" (Mieszkowski & Mills, 1993), necessitate new approaches for measuring fragmentation. Scholars have explored the use of road networks instead of city centers for multi-centered urban areas (Irwin & Bockstael, 2007) or a wind rose concentric ring approach to examine the growth distances in different directions.

For analysts interested in assessing overall fragmentation in a landscape, our study proposes methodological advances to empirically develop an effective window size, appropriate observation scale, and gradient analysis method selection. It provides an approach to this complex selection issue, while recognizing that there is no universal solution. We expect our results to stimulate further study through empirical testing and further theoretical and methodological development.

Chapter 3

LAND FRAGMENTATION DUE TO RAPID URBANIZATION IN THE PHOENIX METROPOLITAN AREA: ANALYZING THE SPATIOTEMPORAL PATTERNS AND DRIVERS

3.1 Introduction

Rapid expansion of the Phoenix Metropolitan Area exemplifies the dominant US Southwest urban growth pattern of the past six decades (Luckingham, 1984; Wu et al., 2011). Even with the current housing market downturn that began in 2007, Phoenix continues to grow in population and remains the sixth largest city in the nation. Aggressive real estate development, especially since the Second World War, has resulted in large scale, low-density residential development in the Greater Phoenix area (Heim, 2001; Gober & Burn, 2002; Keys et al., 2007; Roach et al., 2008; Buyantuyev & Wu, 2010; Redman & Kinzig, 2008). One consequence of this development is increasing land fragmentation, which may include subdivision of land into discrete land uses, conversion from native to designed land cover, or development in a non-contiguous or “leap-frog” pattern (Irwin & Bocksteal, 2007; Clark et al., 2009; Heimlich & Anderson, 2001; Theobald, 2001). Such landscape patterns significantly alter ecological functions and processes (Turner et al., 2001; Alberti, 2005) with important consequences on ecosystem services, including the loss of habitat and wildlife corridors, decreases in agricultural and forest productivity, as well as reduction and elimination of culturally-significant open spaces and natural amenities (Burchell et al., 1998; Dale et al., 2005; Carsjens & van der Knaap, 2002; Schipper 2008).

In this paper, we analyze and characterize the rapid urbanization trend in Phoenix with a specific focus on land fragmentation patterns. The paper has two primary objectives: (i) to assess the applicability and accuracy of National Land-cover Database (NLCD)—a widely used land-cover dataset—to detect and measure urban growth and land fragmentation patterns in the relatively tree-less desert biome of the US Southwest; and (ii) to quantify and categorize the spatiotemporal patterns of land fragmentation. We conclude with a short discussion on drivers of changes in land use, land cover, and fragmentation in Phoenix.

3.2 Study Area and Methods

3.2.1 Study area

The urbanized area of Greater Phoenix extends 120 kilometers from east to west and 60 kilometers north to south, encompassing a population of 4.2 million. There are 26 cities within the Phoenix Metropolitan Area, but the City of Phoenix is the dominant municipality (Fig. 3.1 Map of Study Site). The Phoenix Metropolitan Area (hereafter Phoenix) is situated in the Sonoran Desert and has a mean annual precipitation of 180mm. Large supplies of surface water diverted from the Salt, Verde, Gila and Colorado Rivers, as well as regulated groundwater pumped from local aquifers, have made possible irrigated agriculture, industrial production, and lush vegetation relative to background flora. However, all sources are considered under risk in the face of climate change (Gober, 2010; Bolin et al., 2010). While 60% of the land in Maricopa County is still covered by deserts, the urban built-up areas has dramatically expanded from 3% of the total land in 1955 to almost 20% in 2001, mostly at the cost of agricultural and desert land. The expansion is continuously radiating outward, except where constrained by natural barriers, such as South Mountain or federally protected American Indian reservations.

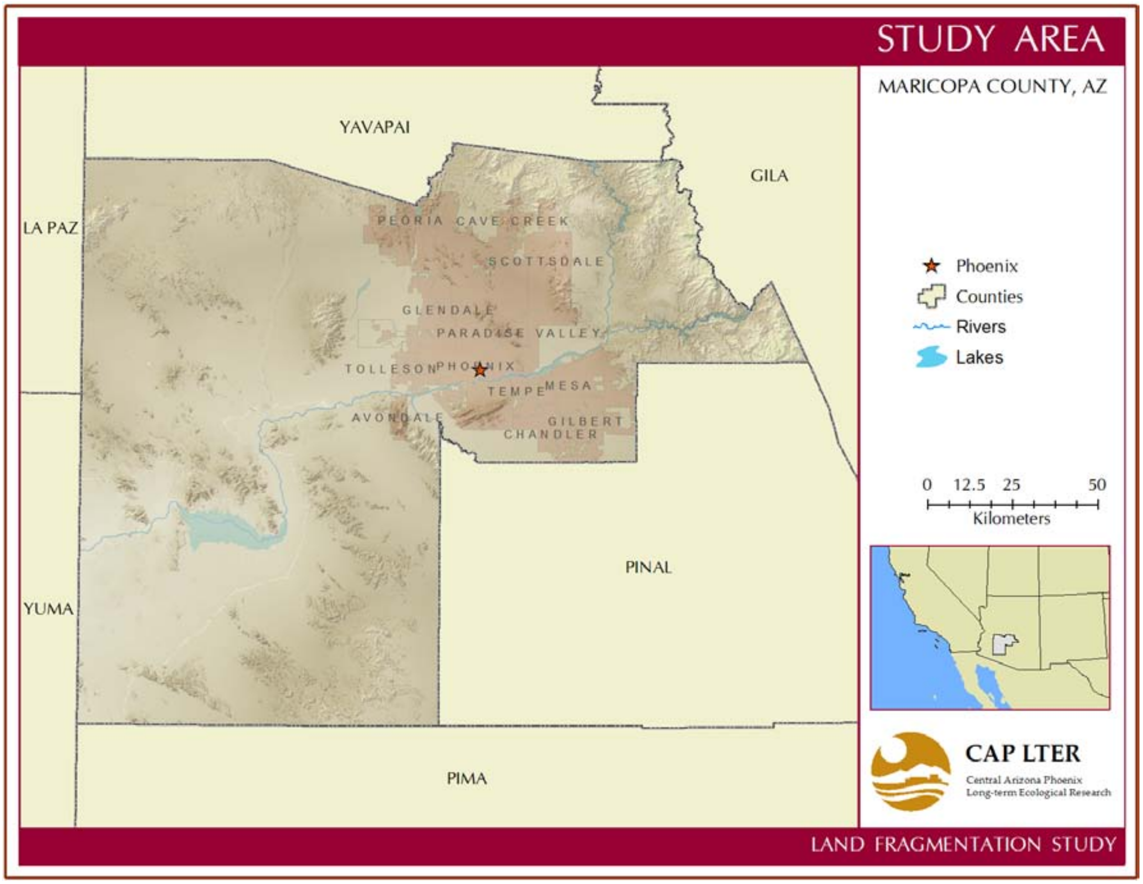


Fig. 3.1 Study area

Land conversion and fragmentation is most acute at the metropolitan fringe. Communities such as Cave Creek, Queen Creek, Buckeye, and Fountain Hills have undergone significant land-use and land-cover over the last decade. To capture these and other fragmentation hot spots, we selected a set of transect windows using east-west, north-south, northeast-southwest, and northwest-southeast orientations that run through the central city of Phoenix. The extent of the study area matches that of the Central

Arizona – Phoenix Long Term Ecological Research (CAP LTER) project (Grimm & Redman, 2004).

3.2.2 Methods and Data

This study combines land-cover data, landscape metrics, gradient analysis, and socioeconomic data. The major source of land-cover data is the National Land-cover Database (NLCD), which provides seamless coverage for the United States. NLCD was the first nationwide initiative that provided consistent land-cover inventory for the US and it has been widely used in studying urbanization (Vogelmann et al., 1998; Burchfield et al., 2006) and landscape fragmentation (Heilman et al., 2009; Riitters et al., 2002). Due to problems arising from differences in source data and classification systems of NLCD 1992 and 2001 (for details, see Homer et al., 2007), we “retrofitted” 1992 land-cover classes to match 2001 classes (Fry et al., 2009). After we generated land-use maps for 1992 and 2001, we validated these maps based on expert knowledge of scientists in the CAP LTER.

The most common method to analyze land fragmentation is to apply landscape metrics on land-cover maps extracted from remotely sensed data, which can identify and describe landscape patterns that are generally not directly observable to human eyes. As demonstrated in several previous studies (Cushman & McGarigal, 2002; Seto & Fragkias, 2005; Wu et al., 2011), landscape metrics can quantify and characterize the spatial patterns observed at a landscape based on the shape, size, number, and other spectral signatures of land parcels or patches captured in remote sensing data. Unlike in the past when detection and analysis of land-use and land-over change were often considered a cumbersome task, increasing availability of land-cover data derived from remotely sensed images have made it easier in recent years to study and corroborate the dynamic nature of urbanization (Batisani & Yarnal, 2009; Dietzel, Herold, Hempfill, & Clarke, 2005; Thapa & Murayama, 2000; Vogelman et al., 1998; Yang & Lo, 2002) and to detect urban land fragmentation patterns (Bhatta, Saraswathi, & Bandyopathyay, 2010; Luck & Wu, 2002; Munroe, Croissant, & York, 2005; Schneider & Woodcock, 2008; Ward, Phinn, & Murray, 2000).

The reliability of NLCD data for measuring characteristics of exurban development has been questioned with evidence from temperate forests in the eastern USA, where satellite images with moderate resolutions are found to be too coarse to detect low-density settlement (Irwin & Bockstael 2007). In the case of arid regions of the southwestern USA, however, we hypothesize that NLCD, specifically the 2001 NLCD, provides sufficient accuracy of low and medium-density development for the relatively treeless landscape of the region and the explicit considerations of impervious surface in the 2001 NLCD, which improved the accuracy of the dataset for urban areas (Homer et al., 2004; Stehman et al., 2003).

3.2.3 Testing the accuracy of NLCD

To validate the accuracy of NLCD, we used two highly detailed, geocoded land-use maps collected from the Maricopa County Assessor's Office parcel data (MCPD) of 2001 and the Maricopa Association of Governments land-use coverage (MCLC) data of 2000. MCPD is based mainly on the County Tax Assessor's Data, which systematically organizes land-use categories with detailed property descriptions. Boundaries of all private and public parcels, which number more than 1 million, are digitized and classified under one of the 2,092 "property use codes." Using sensitivity analysis (Batty & Howes, 2001), we checked the distribution of parcels to ensure that MCAPD is a reliable reference, mainly to eliminate the possibility of errors resulting from the conversion of this vector data to a raster format in the accuracy assessment. MAGLC is derived from aerial photographs and it has 46 major land use categories (see Appendix A for supplementary information covering general description of all the dataset used in the study, land use classification system, and sensitivity analysis).

After reprojection (UTM Zone 12, WGS 1983), the MAPD and MCLC dataset were resampled to 30m x 30m cell size to match with the resolution of NLCD. The MAPD with its 2,092 property use codes and MCLC with its 46 land-use categories were subsequently reclassified into six land-use classes matching NLCD classification: developed, high intensity (DHI), developed, medium intensity (DMI), developed, low intensity (DLI), open space or very low intensity (VLI), transportation (TRP), and undeveloped (UND) (see Appendix A). Only those land-cover categories with more than 5% impervious surface were considered “developed”, which is consistent with Irwin & Bocksteal (2007). We overlaid the land-cover map created from the 2001 NLCD and the reference map (i.e., MAPD) and generated an error matrix by calculating the total cell numbers intersected in both (Congalton & Green, 1993). We also compared the accuracy of NLCD with the MCLC dataset.

3.2.4 Measuring land fragmentation and spatial heterogeneity

We selected two methods to analyze urban growth patterns and their spatial heterogeneity: (i.) average fragmentation for the whole landscape at the class level to reflect landscape composition, especially its relationship to density; and (ii.) fragmentation distribution along the transects at the landscape level to capture landscape configuration (Cushman & McGarigal, 2002). The transect methodology was applied to detect fragmentation along the urban-rural gradient, as well as the directionality of urbanization patterns. We weighed the benefits of using a full coverage moving windows analysis (Riitters et al., 2002) in the transect analysis (Luck & Wu 2002; Yu & Ng, 2007). We applied the same size transect block of 15 km × 15 km across the study area, in which the block moves along the transect overlapping at 5 km intervals and generate a mean value for the center pixel to be used for the fragmentation analysis (Fig. 3.2).

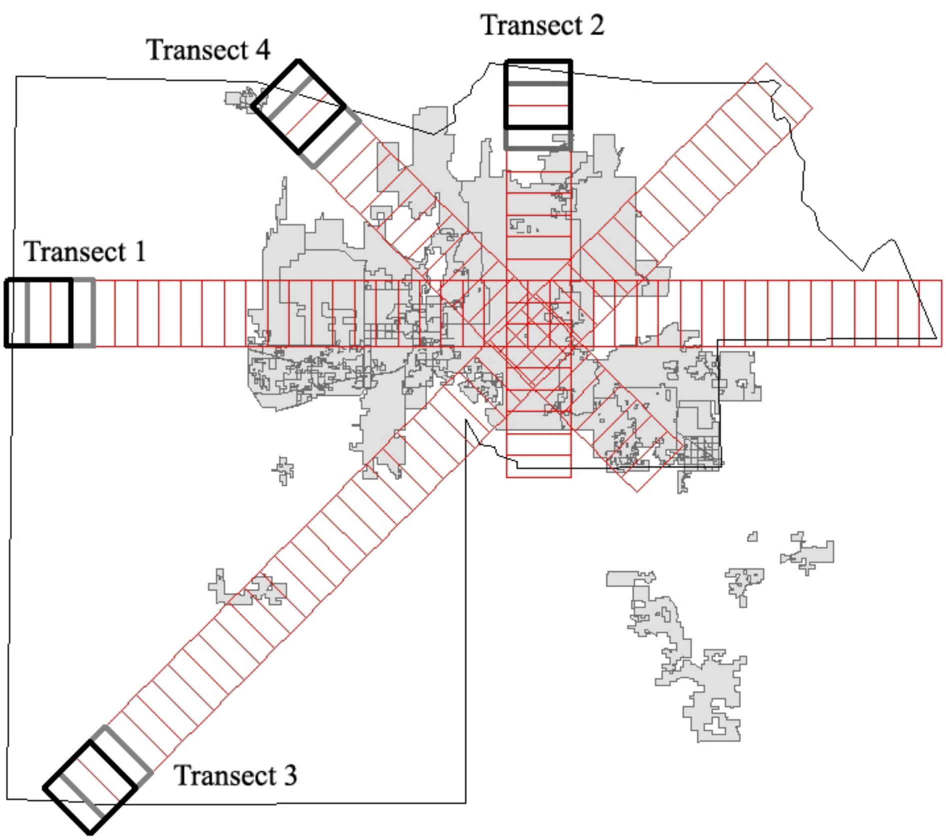


Fig. 3.2 Using four transects through the urban center area

(The measures were calculated along the transects with a 15km × 15km overlap moving window. The window moves 5 km each time)

Since we are interested primarily in the spatiotemporal patterns of urbanization, we re-classified the six NLCD classes into two: developed and undeveloped[1]. We rasterized the land-cover map with a cell size of 30m for analysis in FRAGSTAT, which is a landscape pattern analysis program (McGarigal et al., 2002). We also considered the sensitivity of both the resampled cell size and the sensitivity of landscape metrics (Saura & Martinez-Millan, 2001; Wickham& Ritters, 1995). To be consistent with the Irwin & Bocksteal study (2007), we also chose the same suite of landscape pattern metrics reflecting area, density, shape, edge, and spatial relationship of the land types and selected two to three metrics for each of these categories. Selected landscape metrics for this study were patch density, mean patch size, mean perimeter-to-area ratio, contrasting edge ratio and contrasting edge proportion between developed and undeveloped land, mean dispersion, contrast weighted edge density, and contagion (see Table 3.1 for descriptions). The increase of patch number, density, edge, complexity of the shapes, and dispersions can indicate an increase in land fragmentation. Lower patch sizes and contagion values exhibit a disconnected land use area, and higher fragmentation. The contrasting edge ratio and proportion are normalized by the length of like edges and by the sum of like edges and contrasting edges, as shown in Table 3.1. When measuring the landscape fragmentation metrics of each developed land type (e.g., high density development), we define the "focal land use" to be the developed land type at that density, and "contrasting land use" to be "undeveloped" land. When measuring the fragmentation metrics of undeveloped land, we define the "focal land use" as the "undeveloped" land,

[1] Developed - characterized by a high percentage (30 percent or greater) of constructed materials such as asphalt, concrete and buildings; "undeveloped" - characterized by water, barren, forest, shrub land, herbaceous upland, woody wetlands and emergent herbaceous wetlands.

and “contrasting land use” to be “all developed,” in which different density land development are aggregate to one land type.

Table 3.1 Land fragmentation metrics

Pattern measure	Definition	Explanation
Class area (km^2)	$\sum_i a_{ik}$	a_{ik} = area of patch i with land use k; Units = km^2
Percentage of landscape	$\frac{\sum_i a_{ik}}{A}$	A = total landscape area (km^2); Units = %
Number of patches	n_k	n_k= total number of patches in land use k
Patch density	$\frac{n_k}{A}$	Same definitions as above; Units= $1/km^2$
Mean patch size	$\frac{\sum_i a_{ik}}{n_k}$	Same definitions as above; units = km^2
Mean perimeter-to-area ratio	$\frac{\sum_i \frac{I_{ik}}{a_{ik}}}{10^6 \cdot n_k}$	l_{ik} = total perimeter length of patch i with land use k; units = m/m^2
Contrasting edge ratio	$\frac{e_{kj}}{e_{kk}}$	E_{kj}=total length of edge shared between cells with the focal land use k and contrasting land use j; e_{kk} = total length of edge shared between cells with the focal land use k
Contrasting edge proportion	$\frac{e_{kj}}{e_{kj} + e_{kk}}$	Same definitions as above; varies between 0 and 1
Mean dispersion	$\frac{\sum_i p_{iik}}{n_k}$	p_{jik} = proportion of cells of contrasting land use j that are within a specified distance of cell i with focal land use k; n_k = total number of cells with land use k; varies between 0 and 1
Contrast weighted edge density (CWED)	$\frac{e_{kj} \cdot d_{kj}}{100A}$	Same definitions as above; d_{kj} = edge contrast weight, here d_{kj} = 1 units = m/hectare
Contagion (CONTAGION)	$\left[1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left[(p_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]\cdot\left[In(p_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]}{2\ln(m)}\right]100$	P_i =proportion of the landscape occupied by patch type (class) i; g_{ik} =number of adjacencies (joins) between pixels of patch classes i and k based on the double-count method; m =number of patch classes present in the landscape, including the landscape border if present.

All the measures are computed based on raster data with 30 m × 30 m cells

Metrics 1 and 2 are the area of land type and its percentage of landscape. They provide basic information for urban sprawl. Metrics 3 and 4 are number of patches and patch density. They measure the fragmentation degree from the patch number aspect. Increased patch number and density generally represent an increased fragmentation. Metrics 5 and 6 are mean patch size and mean perimeter-to-area ratio, and they focus on size and shape of the patches. If the total area of a land use type keeps the same or increases, a decrease of mean patch size of this class type indicates an increase in the fragmentation. Perimeter-area ratio is a simple measure of shape complexity. An increase of the value indicates a more complex patch shape or the decrease in patch size with a constant shape.

3.3 Results and discussions

3.3.1 Accuracy of NLCD for the US Southwest

At the outset of this study, we hypothesized that the NLCD would accurately capture urbanization and sprawl in the US southwest, mainly because of sparse vegetation coverage in the region, which minimizes the chances of misclassification of low-density settlements as vegetation classes, such as cultivated land, forest, or grassland. Similar to the Irwin & Bockstael's study (2007) in Howard County, Maryland, we tested this hypothesis by comparing NLCD with the highly detailed MCPD based on "Tax Assessor Data" and contrasted both datasets to check how NLCD performed in each of the land-use classes. The summary results are presented here in an error matrix (Table 3.2).

Table 3.2 Comparison of 2001 NLCD land-cover and Maricopa County parcel data

Land-use Codes	Actual land-use*	No. of developed cells from County Parcel 2001	No. of developed cells in 2001 NLCD#	% labeled developed by 2001 NLCD	Irwin and Bocksteal (2007)	MCLC accuracy
1	Developed, High Intensity (DHI)	6411511	4446419	69.35	83	85.11
2	Developed, Medium Intensity (DMI)	3766422	2769014	73.52	62	95.46
3	Developed, Low Intensity (DLI)	7355092	5900874	80.23	26	66.43
4	Open space, Very Low Intensity (VLI)	10640799	7064870	66.39	8	63.14
5	Transportation	27315	25721	94.16	80	82.42
6	Undeveloped	27800940	2432922	8.75	6	3.38

* Developed categories have at least 5% impervious surface and these categories are based on the percentage of constructed materials, such as buildings, asphalt, concrete, etc.

Grid cells are 30 x 30 m

As reported in Table 3.2, we compared the accuracy of NLCD with both the 2001 MAPD as well as the 2000 MCLC. The primary focus of this table is to show a comparison of number of cells identified as “developed” cells in the MAPD and the percentage of those cells accurately identified in the NLCD. In sum, the results support our claim that the 2001 NLCD recognizes “low density land-use” category in Phoenix at a much higher rate than what the Irwin & Bocksteal study (2007) reported for the same category in Maryland. In this case, 80% of the “developed, low intensity (DLI)” areas and 66% of the “open space, very low intensity (VLI)” areas were correctly identified, compared to 26% and 8% respectively found in Maryland. Thematic accuracy is consistently high across all other land-use classes as well, suggesting that the overall accuracy of NLCD is satisfactory for arid regions with sparse vegetation. Our comparison of NLCD to the MCLC dataset also reaffirmed the accuracy of NLCD data for Phoenix, showing 66% and 63% for DLI and VLI respectively, reconfirming the satisfactory accuracy level of NLCD.

3.3.2 Spatial and temporal patterns of land fragmentation and spatial heterogeneity

Table 3.3 reports the results of fragmentation metrics applied to land-use maps generated from the NLCD 1992 and 2001 dataset. In this table, all residential and non-residential developed land-use types are grouped as “developed” category and all other land-use types with no footprints of residential properties, such as deserts, agricultural lands, and forests are categorized as “undeveloped.” To capture and differentiate the exact nature of fragmentation patterns that occurred among different urban land-use types and their spatial variations across the study area, the “developed” land-use category is further disaggregated into three distinct types: high density, low-mid density, and very low density. As indicated in the changes reported in the “class area pattern measure” and the “percentage of landscape measure” in the table, quite a significant conversion and modification in land-use/cover types occurred between 1992 to 2001, corresponding mainly with the expansion of urbanization at the urban-rural fringe.

The analysis shows a rapid increase in the area of “medium” to “very low density” development from 1992 to 2001, indicative of suburban sprawl and exurbanization. The decrease of patch density and the increase of mean patch size of overall development, except very low density development, potentially capture “in-fill development” in Phoenix (Heim, 2001). The decrease of mean perimeter to area ratio for the “all development” indicates that the patch shape tends to be less complex. A comparison of the results among various land-use type that fall under “developed” category – ranging from the high to very low-density developed areas – indicates that high density areas are experiencing a decrease of land fragmentation, while most metrics for low-density development indicate an increasing level of fragmentation from 1992 to 2001. The differences are especially clear in contrasting edges and dispersion metrics. Contrasting edge ratio dramatically increased by 355.87%, and mean dispersion (1 km) increased by 119.93% during the ten years.

If we focus on one year and compare the three developed land types, the most obvious phenomenon, as we expected, is when the developed area changes from high, to mid-low, and to very low density; the fragmentation is shown increasing, especially in year 2001, and it is corroborated by most of other fragmentation metrics, such as patch size, contrasting edge and dispersion. Low-density development, which typically happens on the urban-rural fringe, contributes to an increasing level of land fragmentation in undeveloped areas. For both developed and undeveloped area, the growth rate of the mean dispersion measured within 5 km distance is not as high as the mean dispersion within 1km, suggesting that the urban growth is penetrating into undeveloped areas mostly within 1 km of the existing developed area. This finding suggests that development is occurring in a more contiguous rather than "leap frog" fashion.

Table 3.3 Aggregate land-use pattern measures

Pattern measures	Developed														
	All Developed			**High density**			**Low-Mid density**			**Very low density**			**Undeveloped**		
	1992	**2001**	**% change**	**1992**	**2001**	**% change**	**1992**	**2001**	**% change**	**1992**	**2001**	**% change**	**1992**	**2001**	**% change**
Class area (km^2)	1380	2200	59.46	476	110	-76.92	758	1469	93.96	146	621	325.23	22444	21624	-3.66
Percentage of landscape (%)	5.79	9.23	59.46	2.00	0.46	-76.92	3.18	6.17	93.96	0.61	2.61	325.23	94.21	90.77	-3.66
Number of patches	20459	9227	-54.90	43041	6551	-84.78	15464	9580	-38.05	9611	20336	111.59	12283	6001	-51.14
Patch density ($1/km^2$)	1.00	0.39	-61.44	1.81	0.27	-84.78	0.65	0.40	-38.05	0.40	0.85	111.59	0.52	0.25	-51.14
Mean patch size (km^2)	0.07	0.24	253.57	0.01	0.02	51.64	0.05	0.15	213.09	0.02	0.03	100.97	1.83	3.60	97.20
Mean perimeter-to-area ratio (m/m^2)	1086.24	890.46	-18.02	1095.12	794.19	-27.48	1067.14	856.83	-19.71	1035.15	840.35	-18.82	1050.24	762.73	-27.38
Contrasting edge ratio *	0.22	0.35	63.25	0.35	0.03	-91.08	0.12	0.17	40.01	0.23	1.04	355.87	0.01	0.03	156.85
contrasting edge proportion *	0.18	0.26	46.71	0.26	0.03	-88.31	0.11	0.15	34.13	0.19	0.51	174.17	0.01	0.03	152.12
Contrast weighted edge density (m/hectare)	7.56	18.53	145.14	3.99	0.10	-97.62	2.46	6.53	165.41	0.84	11.91	1319.77	7.56	18.53	145.14
Mean dispersion ($1km^2$) *	0.24	0.31	29.39	0.33	0.10	-68.47	0.18	0.20	14.21	0.28	0.61	119.93	0.01	0.03	114.14
Mean dispersion ($5km^2$) *	0.36	0.39	8.69	0.42	0.17	-58.89	0.31	0.29	-3.98	0.46	0.67	44.72	0.02	0.04	79.94

***** For “Alldeveloped” land use measures, focal land use= developed, contrasting land use=undeveloped;

For “High density (Low-Mid density, Very low density) developed” land use measures, focal land use= High-density (Low-Mid density, Very low density) developed, contrasting land use=undeveloped;

For Undeveloped, focal land use= undeveloped, contrasting land use=developed, and the calculation is based on two land types only

Because the scale and thematic resolution of land-cover data can strongly influence the evaluation of landscape pattern and fragmentation (Wu, 2004; Buyantuyev et al., 2009), we considered a set of transects with different orientations and consistently applied them with two fragmentation metrics: contrast weighed edge density (CWED) and contagion (CONTAG) metrics. We applied a 450 × 450m (210m radius) square moving window analysis for the whole area. The results are raster data of land fragmentation distribution. To test the fragmentation gradients to the city center, based on the spatial fragmentation map, four transects at eight directions through the urban center area were selected, and measures were calculated each time for a 15 km × 15 km block, which moves 5 km each time along the transects (Fig. 3.3).

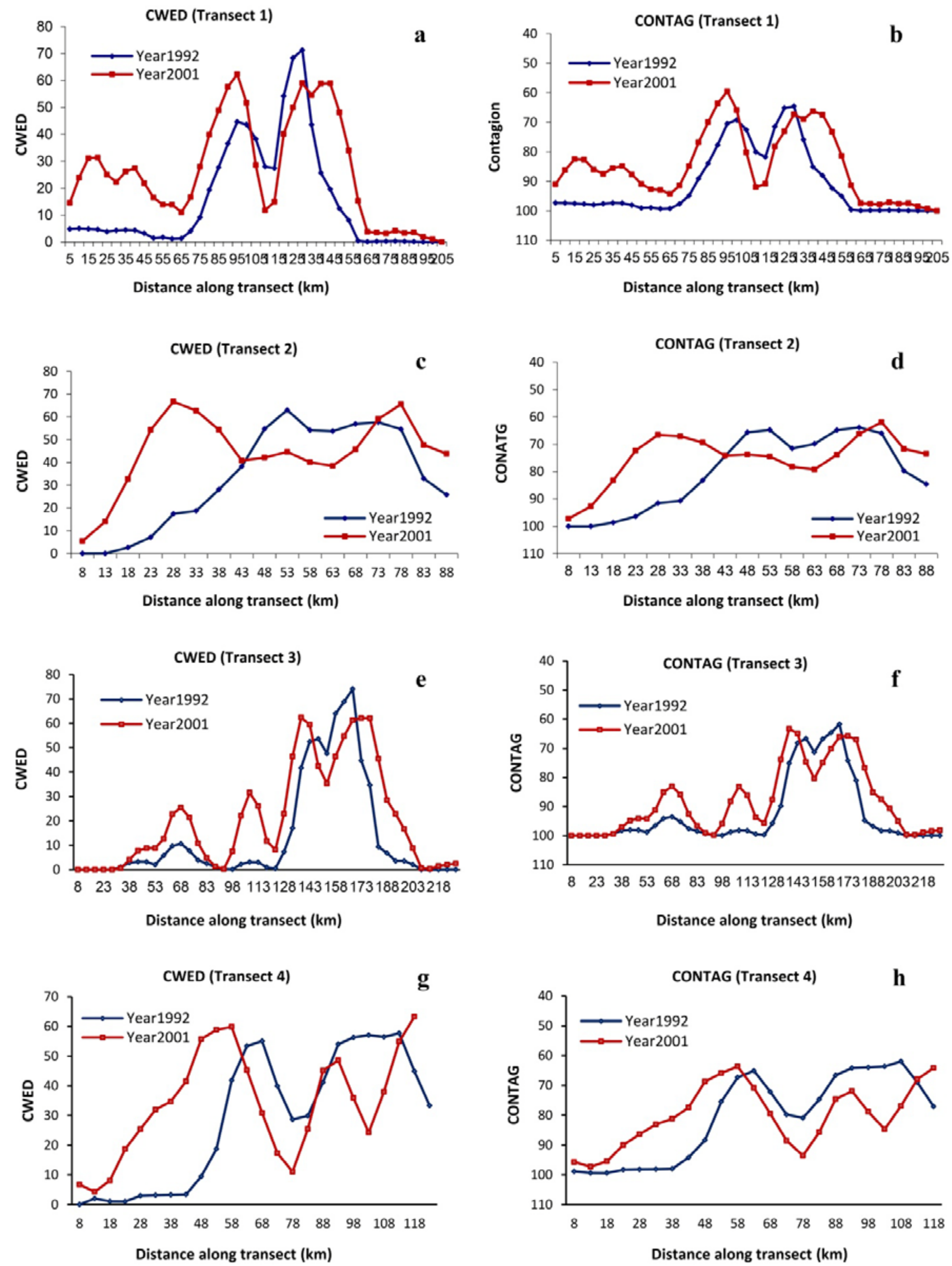


Fig. 3.3 Spatial patterns of land fragmentation

Figure 3.3 illustrates land fragmentation along the urban-rural gradient covered in the four transects using two metrics: CWED and CONTAG. All of transects indicate that land fragmentation reaches the highest point at the urban-rural fringe and subsequently decreases to the lowest point at both the city center area and the remote undeveloped areas. Comparing the fragmentation change between 1992 and 2001, two peaks observed at both sides of the city center in these transects confirm what previous studies have claimed: higher fragmentation levels are generally associated with the low-density developed areas (Theobald, 2001; Dale et al., 2005; Clark et al., 2009). All of the four transects indicated that the peaks of fragmentation are shifting outwards around 10 km from city center. Fragmentation grew the fastest at 30-40 km east to the city center (Table 3.4). Transect 1, with an east-west orientation, shows a similar gradient fluctuation as transect 3, which has a southwest-northwest orientation. They both show a rapid increase of fragmentation at 30 km east of the urban center. Transect 2 has a similar gradient as that of transect 4. They exhibit a rapid increase of fragmentation between 1992 and 2001 at 35-40 km north of the urban center. As transects 2 and 4 travel through both urban and rural areas, the overall fragmentation level is higher than that of transects 1 and 3.

Table 3.4 Results of landscape metrics

Transect	Metrics	Distance from city center to the fragmentation peak on one side (km)			Distance from city center to the fragmentation peak on the other side (km)			Distance from city center to the location where fragmentation increased the fastest from 92-01
		1992	2001	shifting from 92-01	1992	2001	shifting from 92-01	
1	CWED	20	20	0	15	15	0	30
	CONTAG	15	20	5	15	25	10	30
2	CWED	10	35	25	10	15	5	35
	CONTAG	10	35	25	10	15	5	35
3	CWED	15	25	10	15	20	5	30
	CONTAG	5	15	10	15	20	5	30

4	CWED	20	25	5	15	35	20	40
	CONTAG	20	25	5	25	35	10	40

These transects can be used to explore relationships between land fragmentation and sprawl, and the potential drivers of suburbanization. Low density residential areas, consisting mainly of single family dwellings are strongly associated with higher levels of fragmentation. Similarly, the asymmetric "peaks" and "valleys" in the fragmentation curve characterizes urban-rural fragmentation gradients, confirming that the greatest fragmentation areas are located at the urban-rural fringe. It forms a distinct "monocentric" pattern centered on Phoenix, with expansion of development creating a continuously dense urban center and a highly fragmented rural area. During 1992-2001, the urban core of the regions shows decreased fragmentation, while rural areas witnessed increased fragmentation. The peaks of fragmentation are shifting outwards from city center during the study period, indicating the ongoing urbanization consistently fragments undeveloped areas on the urban-rural fringe. Fragmentation grew the fastest north and east of Phoenix city center, and particularly in several valley cities, such as Scottsdale, Fountain Hills, Apache Junction, and Mesa. Exploration into the potential drivers of these changes, to which we now turn, can help explain past land fragmentation patterns and predict the future trends and directions of land fragmentation.

3.3.3 The drivers of Phoenix's rapid urban growth

The pattern of land fragmentation in Phoenix is the result of a combination of biophysical and social processes, particularly urban population dynamics, water provisioning, transportation, institutional factors, and topography. During the study period (1992 and 2000), Phoenix grew in population from 2,272,582 to 3,199,440 (41%

increase), mainly from an influx of new migrants attracted by booming economic opportunities in the valley. Recent estimates put the population of Metropolitan Phoenix at 4.4 million (US Census Bureau, 2010). Much of the valley is “master-planned” for low intensity, single family residences, but there has also been infilling of high density residential development (e.g., multistoried apartments, condominiums) in the urban core areas of Phoenix. Until the recent slump in the housing market, single family housing in the fringe expanded aggressively, driven by rampant speculation (Gober & Burns, 2002).

The rapid development of several peripheral cities in Phoenix particularly between the 1980s through 2006 occurred mainly through aggressive acquisition and annexation of formerly agricultural and desert lands. Population growth aside, the drivers of this land-use change pattern can only be explained by examining the historical land-use legacy of this area. First of all, it is important to note that rapid urbanization of this desert city is not possible without ensuring adequate and reliable water supply. Water provision has played a key role in settlement patterns in this area, starting from the prehistoric Hohokam civilization, which built extensive canals for irrigated agriculture in the valley, sustaining a permanent settlement for nearly a thousand years (Redman & Kinzig, 2008). Modern development is largely dependent on water diverted from the near and distant rivers, including the Salt, Gila, Verde and Colorado. The first modern settlement was established in 1870, using many of the ancient Hohokam canals for irrigation, and the city gradually expanded outward with the growing demand for agricultural lands, particularly cotton farms (Gober, 2005; Redman & Kinzig 2008).

In 1911, the Bureau of Reclamation built the Roosevelt dam to provide water for the growing agricultural activities in the valley (Luckingham, 1984). Growth in population and agricultural production led to a continuing search for “new” water sources, including Colorado River water transported in the Central Arizona Project canals, begun in 1973, and concerted efforts in ground-water pumping (Glennon, 2009). Since the passage of the Arizona Groundwater Management Act in 1980, reliance on groundwater has been curtailed, but it is unlikely that safe yield from groundwater will be achieved by the stated goal of 2025 (Gober et al., 2010). Water sources for residential development have come largely from retirement of agriculture, which reduced its water use from 1.3 million acre-feet in 1985 to 0.7 million acre-feet in 2005 (Gober et al., 2010). Assured Water Supply Rules (1994) associated with the Groundwater Management Act require developers to supply “100 years assured water” for all new residential developments outside of municipal water provision boundaries, which many achieve by purchasing farmland with senior water rights (Heim, 2001). The 100 years of assured water, however, is not iron-clad as state legislation allows exemptions for smaller developments and relaxed rules for municipal water providers that spend funds on water conservation and education (Hirt et al., 2008). Purchasing agricultural lands that have senior water rights is a common means of securing water supplies for development in Phoenix. In the past six decades, a significant increase in the total urban area at the expense of desert and agricultural lands has been the major land-use/cover change trend. In the 1950s, the urban area was only about 3% of the total land, while the desert was 82% and agriculture area was 14%. By the late 1990s, the urban area increased to 18% and the desert and agricultural lands decreased to 66% and 11% respectively (Redman & Kinzig, 2008).

Historically, government employment opportunities, especially with the military, played an important role in the local economy with the establishment of four military bases around Phoenix (Koning, 1982). This also followed with rapid growth in both defense contracts and electronic industries, from Honeywell and Lockheed Martin to Intel, accompanied by a great deal of real estate development to accommodate the changing economic opportunities. Public expenditures on services (e.g., freeways, better school system, public health, efficiency in potable water supply) and favorable economic incentives (i.e., low tax burden, pro-growth policies) have also kept pace with the population growth and increasing demands for rural homes and lifestyle (Gober, 2005). Another important factor that accelerated this process of exurbanization is amenity-driven migration. Phoenix, along with several Sunbelt cities, has championed growth based on amenities preferred by retiree populations, which include mild winters, the year-round sunshine, and the proximity of "wilderness" (Gober, 2005; Rudzitis, 1999). Relocation decisions of baby boomers are influenced by socio-economic factors as well, including low tax burdens, inexpensive housing markets, and excellent health services (Duncombe et al., 2003; Glaeser & Tobio, 2007).

The dominant form of urban living and accessibility in Sunbelt cities is based on the automobile (Glaeser & Kahn, 2003). Automobile exhibits a key characteristic of exurbanization in Phoenix. Public transportation system including the recently built light-rail system is concentrated in the city center; hence, life without automobile is almost impossible in Phoenix. Like the railroad, Phoenix did not construct a major transcontinental freeway until relatively late when Interstate-10 was completed in 1990s. Automobile dependence combined with a lack of freeways led to traffic congestion and fueled expansion of the state highway system in the 1990s, looping around the city and pushing development outward, especially to the east, southeast, and north (Gober, 2005).

This expansion of highway and freeway network during the 1990s was imminent with the rapid economic growth occurring in the area at that time, which saw major urban growth taking place in relatively smaller cities at the periphery, such as Buckeye, Chandler, Peoria, Sun city, Fountain Hills, and Surprise. These cities developed very aggressively in the recent years than others which already had several established settlements in the post-World War II period through the 1990s (e.g., the city of Phoenix, Tempe, and Scottsdale). This is also the reason why these growing cities in the periphery were hit the hardest by the recent housing market bubble burst, leaving many empty houses and apartment complexes. Real estate developers, well supported by the local growth policies, have been very aggressive in pursuit of “opportunities for capital gains” (Heim, 2001), often resulting in exurban expansion on desert and farmland creating significant spatial heterogeneity in land-use patterns within the valley.

Spatial heterogeneity in the valley is also tied closely tied to local topography and institutional factors. The basin and range topography with isolated mountains in Phoenix has created opportunities for residential development to expand into the foothills and jump over the mountains (many of which are held by public entities). Phoenix is surrounded by the Tonto National Forest, four military bases, large city mountain parks, and state trust land, which act as barriers in continuous urban growth. Growth onto Forest Service or city park land is unlikely, but conversion of state trust land has been relatively common (Gammage, 1999). Indian reservations also act as local growth controls. In Phoenix, urbanization skipped over Indian communities to the eastern reach of Mesa and Scottsdale and the city of Fountain Hills, leaving rural landscapes on Indian community land in between (Gober, 2005). There has also been a tough competition among the valley cities for new lands to develop their territories. Annexation allowed area cities, especially Phoenix, to expand rapidly, increase property tax bases, and incorporate middle-class and wealthy regions (Luckingham, 1984). In some cases this has led to "annexation wars" such as the battle for Ahwatukee by Tempe, Chandler, and Phoenix, won by the latter during an emergency midnight city council meeting (Heim, 2001). Similar annexation conflicts erupted between Gilbert, Mesa, and Chandler in the southeast valley, illustrated by the debacle surrounding annexation of Williams Air Force Base (Lang & LeFurgy, 2007). Much of the conflict surrounding growth and annexation of undeveloped land in the Phoenix valley is associated with the growth imperative of the cities and emergence in the 1990s of numerous "boomburbs," cities with double digit growth, over 100,000 in population, and an increasingly voracious appetite for city expansion (Lang & LeFurgy, 2007).

Topographic variation also influences microclimates and creates aesthetically pleasing and valuable scenic views, which encourages residents and developers to move farther out into the foothills and mountains. Differences in elevation from the northern uplands to the southern floodplains can also be linked to microclimatic variations and general socioeconomic differentiations within the valley; the cities at the higher gradients, such as Scottsdale and Paradise Valley, generally have relatively cooler temperature and higher per capita income in comparison to the floodplains, such as South Phoenix, which has also been "a stigmatized zone of racial exclusion and economic marginality" (Bolin et al., 2005).

3.4 Conclusions

Urbanization is driven by a variety of factors, and in this paper we briefly examine the roles of population dynamics, water availability, institutions, transportation, and topography. In Phoenix, water provisioning institutions drive the conversion of agricultural lands and the increased fragmentation on the urban fringe. Explosive population growth during the study period resulted in exurbanization and increased fringe fragmentation, but also decreased fragmentation and a shift from low to medium intensity development in the suburbs. Topography, especially the foothills and mountains, draws high income residents closer to fringe areas and open spaces for view-sheds and cooler microclimates in the northeast valley, while low income residents remain in stigmatized areas with higher temperatures and increased exposure to environmental hazards in the floodplains near the Salt River. Public land sales lead to increased urbanization, while Indian land holdings restrict growth in the region particularly to the south. These factors affect the overall shape, rate, and pattern of urbanization.

During the study period, Phoenix's growth has been characterized by exurbanization and increased fragmentation on the fringe coupled with infill development and decreased fragmentation in the suburban areas. These two factors generate an overall monocentric pattern with continued growth outward in all directions, although institutions and topography pull and push urbanization, leading to increased fragmentation and agricultural conversion in the northeast valley while urbanization has been restricted to the south of the city by Indian communities.

Our study also illustrates that NLCD is a reliable data source for measuring land use in the southwest, even in low-density environments. This offers a real advantage given that NLCD are free and provide comparable data for large regions of the country. Unlike studies in the mid-Atlantic, within the relatively treeless desert biome of the southwest NLCD accurately captures peri-urban development. NLCD compared favorably to locally available datasets from the local government on land use. We encourage future research that tests the accuracy and usefulness of NLCD in biomes similar to and different from Phoenix's.

In addition to our test of NLCD, this work illustrates the relevance of combining qualitative analyses of social-ecological drivers with fragmentation analyses. It is imperative that scholars continue to work to understand the processes and reasons for observed patterns in addition to technically advancing spatial and fragmentation analyses. By analyzing the drives of observed urban fragmentation patterns, we move toward an improved understanding of cities, urban geography, and urbanization.

Acknowledgements

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Appendix: Supplementary Information

A. Data description

General descriptions of the dataset used in this study are below. These are based on the metadata files provided by the respective agencies

*NLCD 1992 and 2001***.** Produced by the United States Geological Survey (USGS), National Land-cover Database (NLCD) is the first nationwide initiative to provide consistent and seamless land-cover inventory for the United States (refer to Vogelmann et al. 2001 for details). Available for the year 1992 and 2001, NLCD consists of vector files derived from Landsat Thematic Mapper (TM) satellite imagery taken during the early to mid 1990s with 1992 as the oldest collection data and is available for the 48 contiguous states at 30-meter resolution. NLCD 1992 has 21 different land-cover classes and the accuracy of NLCD 1992 at the Anderson Table Level I for the eastern United States is found to be between 70 to 83 percent (Stehman et al. 2003). NLCD 2001 on the other hand is considered to be more accurate and consistent than NLCD 1992. Accuracy estimates across mapping zones ranged from 70% to 98%, with an overall average accuracy across all mapping zones of 83.9% (see Homer et al. 2004 for details). It has 26 land-cover classes and also provides both imperviousness and canopy data.

Originating Agency: US Geological Survey (USGS)
Projection and Units: the Albers Conic Equal Area projection, meters
Datum: NAD83
Primarily based on the early to mid-1990s Landsat TM data with 30-meter spatial resolution and its 21 land-cover classes scheme is applied consistently over the United States.
For more info on NLCD classification: http://www.epa.gov/mrlc/classification.html or

*2001 The Maricopa County Assessor's Office Parcel Data (MCPD) files***.** In these vector files delineating geo-coded private and public parcels, there are 2092 "property use code" (PUC) under 9 major categories (i.e., single family residential, multifamily residential, commercial, industrial, institutional, transportation, utilities, and open space). This dataset has detail information about parcel lot size, livable space, property address, property use codes, and so forth. Parcels are linked to the 2001 Tax Assessment Database containing 1,101,319 records and each parcel is assigned to one of those PUCs.

B. Data generation

Originating Agency: the Maricopa County Assessor's Office
Projection and Units: Arizona State Plane (Central)- Feet
Datum: NAD83
Digitization: 2009
Additional consideration and remarks:

The MCPD shows that the majority of parcels fall between 600 m^2 to 900 m^2, which is common for the Phoenix Metropolitan Area, where extensive, single-family residences dominate the landscape. In this study, sensitivity analysis (Batty & Howes, 2001) was carried out, which helped analyze the distribution of all the parcels and their size (see Figure I below). We carefully examined the MCPD to avoid potential bias propagation in the accuracy assessment of NLCD in our study. We were aware that when converting this vector data into a raster dataset by rescaling to 30m x 30m cell size to match with NLCD, some parcels with low impervious surface may be erroneously reported as "developed" categories if the majority of parcels are below 30m in size. In this case, the possibility of such cases propagating error in the accuracy assessment is low.

Fig. I: Distribution of parcel sizes

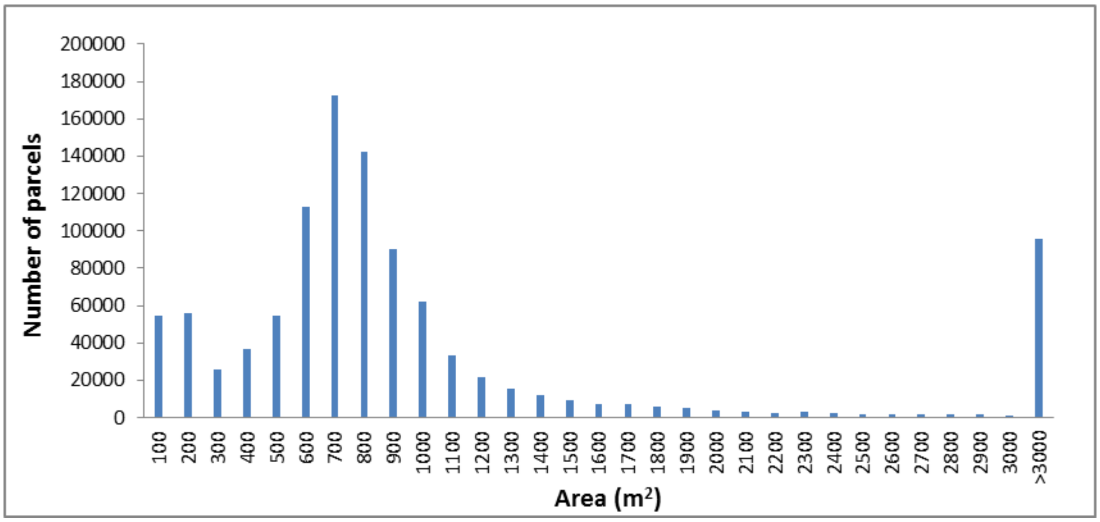


Table I: Distribution of parcel in percentiles

Percentiles

	Percentiles						
	5	10	25	50	75	90	95
Weighted Average area (Definition 1)	1071.00	2115.00	5907.00	7643.00	10577.00	36262.00	69504.00
(Sq m)	99	196	549	710	983	3369	6457
Tukey's Hinges area			5907.00	7643.00	10577.00		

*2000 MAG land-use data***.** These vector files are from the Year 2000 Land-use Coverage Project, which was created as a joint effort of the Maricopa Association of Governments (MAG) and MAG member agency staff. In the original dataset, land-use components are classified into 46 land-use categories, derived from aerial photographs and other existing ancillary data. These 46 land-use categories were also reclassified into 6 major land-use categories to match the focus of this study.

Data generation
Originating Agency: the Maricopa Association of Governments
Projection and Units: Arizona State Plane - Feet
Datum: NAD83
Date Created: 2000

II. Land-use Classification Scheme

"Developed" Land-use*	Land-use code	MAG Land Parcel	Descriptions for MAG Property use codes
Developed, high intensity	**11**	Multiple family	Apartments, condominiums, town houses
	12	Commercial	Office building Groceries, supermarkets, pharmacies, convenience stores, warehouses Shopping centers, stores, strip center, Hotels, motels, resorts, restaurants Theater, bars, night clubs, race tracks Banks, auto-services, gas station, utilities
	13	Industrial	Manufacturing, industrial parks, warehouses Salvage, raw materials extracting processing Heavy equipments storing and repairing
	14	Institutional	Schools, libraries, research institutes Hospitals, clinics, dental, animal shelters Airports, firefighting and military facilities Municipal storage lots, government facilities Prison, community services
Developed, medium intensity	**21**	Mixed (0.5 to 5 acre lots)	One or more duplexes, triplexes SFR, SFR + duplex, etc (Density > 7 du/ac)
	22	Single family 5-7 du/ac	One residence per parcel (5-7 2 du/ac)
Developed, low intensity	**31**	Single family 2-5 du/ac	One or more residence (density 2-5 du/ac)
	32	Mobile home/campers	Mobile homes, mobile home sites, campers
Open space (very low intensity)	**41**	Single family <2 du/ac	One residence per parcel (density < 2du/ac) Residence < 5 ac
	42	Agriculture	Crops, plant nurseries and green houses Livestock
	43	Open space	Parks, Golf Courses Residential recreation centers
	44	Cemetery	Cemetery, Mortuary, Crematorium
Transportation	**51**	Roads and parking lots	Freeways, railroads Parking garage, parking lots
Undeveloped	**61**	Undeveloped	Forest, exempt, Indian lands, barren lands, state ownership
	62	Water	Canals Recreation lakes
	63	Vacant	Vacant, non developable open space

* The 2001 NLCD includes four "developed" categories that vary in terms of percentage of "constructed materials": <20% (developed open space, including large-lot, single family), 20-49% (low-intensity, single family), 50-79% (medium intensity, single family), and 80-100% (high-intensity, multifamily and commercial/industrial). Developed include those with 5% minimum impervious surface.

Chapter 4

LAND FRAGMENTATION UNDER RAPID URBANIZATION:

A CROSS-SITE ANALYSIS OF SOUTHWESTERN CITIES

4.1 Introduction

Over the last five decades, residential low density development at the urban fringe has fragmented the American landscape (Clark et al., 2009; Downs, 1998; Mieszkowski and Mills, 1993; Walker et al., 1997). Exburbanization, the development of land outside the urban core (York & Munroe, 2010), sprawl, extensive or excessive urban development (Irwin & Bockstael, 2007), and ‘leap-frog’ development, discontinuous development (Heim, 2001) fragment socio-ecological systems, leading to a number of negative consequences. Fragmentation isolates habitats by destroying crucial corridors, (Alberti & Marzluff, 2004; Dale et al., 2005; Grimm et al., 2008; Wang, 2001), increases costs for public service provision (Camagni et al., 2002), decreases agricultural (Carsjens & van der Knaap, 2002) and forest productivity (Kline et al. 2004; Rickenbach & Gobster, 2003), and reduces or eliminates culturally-relevant open spaces and natural amenities (Deller et al., 2001; Schipper, 2008). Development of greenfield sites and conversion of farmland and wildlands to subdivisions while central city lots and brownfields lie vacant, underscores the inefficiencies that accompany such growth (Boone & Modarres, 2006).

Despite the profound consequences of land fragmentation on socio-ecological systems, extant research on fragmentation is limited in a number of ways. First, the vast majority of land fragmentation studies focus on pattern analysis. Measuring the degree and characteristics of fragmentation is a worthwhile goal, but greater attention to the causal processes that lead to observed patterns is necessary (Irwin & Geoghegan, 2001).

Second, land fragmentation research typically begins from two perspectives – an ecological and principally landscape ecological perspective, and from a land use, especially planning, perspective – with very little overlap between the two literatures. As a result, the methods and analyses employed tend to focus on either the ecological or planning consequences of land fragmentation. For best management practices, as well as to better comprehend coupled natural-human systems, there is a clear need for an integrated socio-ecological framework that improves understanding of the drivers and consequences of land fragmentation (Jenerette & Wu, 2001). Finally, most land fragmentation studies are single cases. The case study approach allows researchers to use specialized data sets and draw on local expert knowledge. However, the use of non-standard data, especially land use and land cover classification systems, makes comparisons across sites problematic. As such, there are relatively few comparative studies of land fragmentation. In this study we set out to reconcile these shortcomings by measuring land fragmentation using a common land cover classification scheme across five urban areas in the US southwest, and employ expert knowledge to compare the role of biophysical and social drivers in the land fragmentation process. We adapt a socio-ecological framework, developed as part of the *US LTER Decadal Plan* (Collins et al., 2007), to study the complex, interrelated processes of landscape change, land fragmentation, land use decision-making, and the socio-ecological consequences of fragmentation (Fig. 4.1).

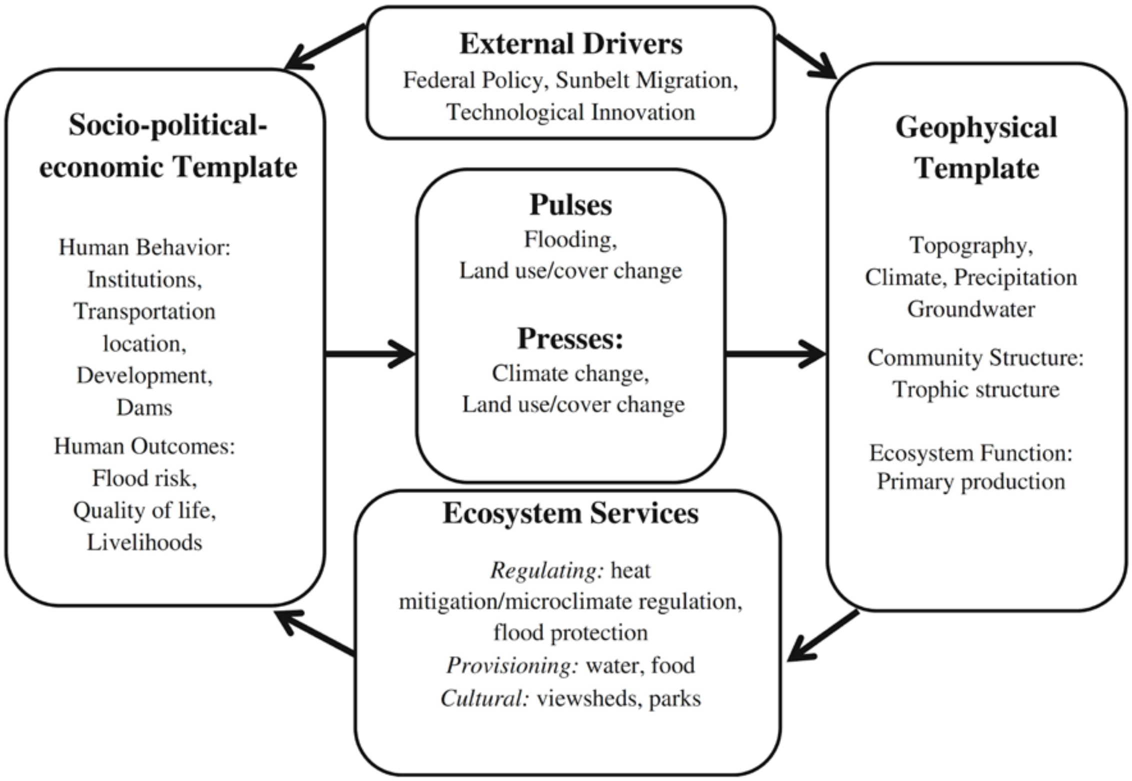


Fig. 4.1 Integrated socio-ecological system

The framework links biotic structure and function with human outcomes and behavior. In this study we focus on five drivers of land fragmentation patterns: water provisioning, urban population dynamics, transportation, topography, and institutional factors-these factors are components within the socio-ecological system or external drivers. For the purpose of our study, land fragmentation is conceptualized as press and pulse events, meaning that some changes, events, or impacts continue over time “pressing,” while over perterbations are discrete “pulsing” events (Ives & Carpenter, 2007). Many studies evaluate these press and pulse events as causes or drivers of socio-ecological changes, but in this study we unpack how processes within the socio-ecological system generate land use/cover change leading to the observed landscape fragmentation. Topography makes up part of geophysical template affecting the potential for residential, industrial, and commercial development, flooding risks, and biodiversity, including plants that make up the observed land cover. Water provisioning is an ecosystem service, partially determined by the geophysical template's climate, precipitation, and topography, but the distribution of water use and provisioning across the landscape is affected by human decisions, most notably water law and dam building. Transportation affects land use decision-making through the location decisions, but also through technological innovation such as the invention and adoption of rail road and automobile technologies, an external disturbance. Institutions affect water provisioning and also directly impact land use through economic development, zoning, and planning, and federal military and land management policies. Urban population dynamics are influenced by Sunbelt migrations and employment opportunities, particularly employment associated with military and military support industries, which are based on federal policies. The socio-ecological framework integrates social and ecological drivers allowing us to focus on system-wide impacts and the interrelationships of multiple factors and processes. It also provides a systematic approach for cross-site comparison.

We selected five southwestern cities for our study – Phoenix, Albuquerque, Las Cruces, Fort Collins, and Manhattan, KS—which are associated with the Central-Arizona Phoenix, Sevilleta, Jornada, Shortgrass Steppe, and Konza Prairie Long Term Ecological Research Sites (Map 1). Each of the sites in the LTER network maintains long-term data. More importantly, the projects have cultivated long-standing research commitments from biophysical and social scientists to analyze and understand the changing socio-ecological dynamics of their sites. This depth of experience and the development of research and social networks through the LTER enhance the ability of our team to conduct cross-site research. We chose to take a regional approach with a focus on the US southwest because of the characteristic rapid growth, emerging new geographies of exurbanization, and comparable biophysical properties related to arid and semi-arid climates (Travis, 2007).

Comparative analysis depends on accessible, comparable data. In recent years, the greater availability of land-cover data derived from remotely sensed images has made it easier to study urban growth and sprawl (Dietzel et al., 2005; Stefanov et al., 2001; Vogelman et al., 1998; Yang & Lo, 2002; Wang et al., 2001) and to detect urban land fragmentation (Luck & Wu, 2002; Wu et al., 2009). Landsat images have been used in some cross-site studies to study urban land-use fragmentation (e.g., Luck & Wu, 2002; Schneider & Woodcock, 2008; Seto & Fragkias, 2005; Wu et al., 2009). In this study, we use remote sensing images, landscape metrics, gradient analysis, and socioeconomic data to analyze the effects of five drivers – water, population dynamics, transportation, topography, and institutions – on the spatial and temporal patterns of land fragmentation. We selected three land fragmentation metrics that capture different aspects of fragmentation: patch density, edge density, and Shannon's Diversity Index. Patch density is defined as the number of patches divided by the total landscape area[2]; patch density is intuitive and useful for cross-city comparisons (Schneider & Woodcock, 2008). Edge density is defined by the length of an edge, the boundary between two different patches, divided by the total landscape area[3]. Edge density is a straightforward metric and provides information about the lengths of edges between dissimilar uses, which sometimes creates conflicts within urbanizing areas, i.e. agricultural uses and residential

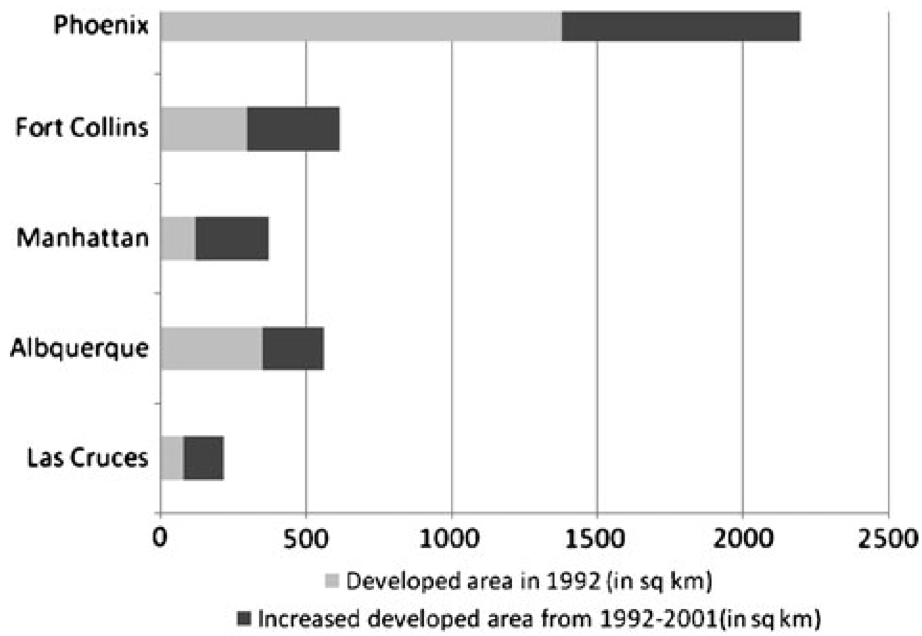
[2] The unit for patch density is number of patches per hectare.
[3] The unit for edge density is meters per hectare

use, and may provide important habitat for species that prefer edge environments. In addition to these two common, simple metrics, we use Shannon's Diversity Index (SHDI), which provides a measure of rare patch types on the landscape and is widely used in community ecology (McGarigal & Marks, 1995). SHDI increases as the number of different patch types increases and the proportional distribution of area among patch types become more equitable. SHDI reflects the basic aspects of heterogeneity including: configuration, composition and sensitivity to low-abundance classes (Díaz-Varela et al., 2009). These three metrics provide information about density of patches, length of edges, and the heterogeneity of patch types-distinct dimensions of landscape fragmentation (Fig. 4.2).

Selection of the drivers is based on expert knowledge from investigators at each of the sites and from knowledge of existing literature. Given the aridity of the US Southwest, provision of fresh water – as precipitation, surface and groundwater, and delivered through infrastructure – is a fundamental limiting factor of development (August & Gammage, 2006; Gober, 2005; Hanak & Chen, 2007). In addition to household, commercial, and industrial uses, the provision of irrigated water and groundwater withdrawals has permitted extensive and intensive agricultural production, which often precedes urban land use development and contributes to land fragmentation (Jenerette & Wu, 2001; Keys et al., 2007). Agriculture also acts as a "bank" for water rights, and since farming consumes more water than residential land use, it ensures a water supply for future development. Nearly all land use change models include population dynamics as population growth typically leads to land conversion (Agarwal et al., 2002). In addition to growth rates, population characteristics shape land use change.

For example, development of isolated retirement communities has contributed significantly to peripheral growth in Phoenix (Gober, 2005; McHugh, 2007). From expansion of suburbs to clearing of forests, transportation is a key land conversion factor. One of the best ways to predict land change is the development of new transportation corridors. This is especially the case when combined with an understanding of existing land uses (Iacono & Levison, 2009; Yang, Li, & Shi, 2008). Prediction of land use change also improves by incorporating topographic characteristics (Clarke & Gaydos, 1998; Silva & Clarke, 2002). Steep slopes and river valleys often preclude development while higher land with attractive viewsheds may encourage high-end real estate development and increase home values (Bourassa et al., 2004). The ability to build in certain locations nevertheless is limited by regulatory institutions, especially zoning and master plans (Dow, 2000; Lambin & Geist, 2006). However, in the southwest, land use development can also be directly or indirectly influenced by the availability of water and the institutions that govern its delivery. An expansive view of institutions that extends beyond traditional land use planning is therefore necessary to understand the role of regulatory agencies on fragmentation. While land use change models incorporate other drivers, the participants of agreed that these five drivers are particularly pertinent to urbanization in the US Southwest.

A



B

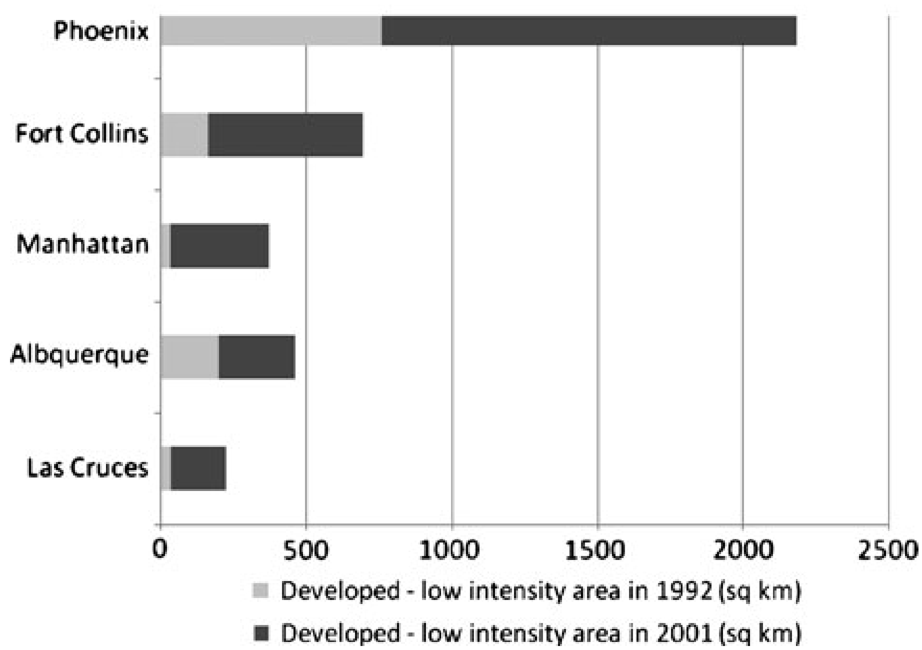


Fig. 4.2 A. Developed land-use between 1992 – 2001 (based on the two land-use classes analysis), B. Changes in the “developed – low intensity” land-use categories between 1992 and 2001

4.2 Data and methods

The five chosen sites share some common characteristics and important differences. All are relatively treeless, with the exception of Manhattan, which has experienced woody encroachment from the hilly uplands onto the grasslands and rangelands, a major ecological concern (Briggs et al., 2002). There is variation in precipitation levels at the five sites, but all use diversion of surface water through major dam infrastructure and reservoirs to provide necessary irrigation water for agriculture, which has fueled urban expansion at all sites. The three desert sites – Phoenix, Albuquerque, and Las Cruces – receive less than 300mm of rain on average, while Fort Collins and Manhattan receive approximately 380 and 890 mm. Population grew very rapidly in all but one site, Manhattan, which experienced a small decline during the study period (Table 4.1). However, the magnitude of the variables varies across the sites, creating a useful gradient for examining socio-ecological drivers of land fragmentation in the southwest.

Table 4.1 Study sites at a glance

	Study sites				
	Phoenix	**Albuquerque**	**Las Cruces**	**Manhattan**	**Fort Collins**[1]
County/counties	Maricopa	Bernalillo, Valencia, and Socorro	Dona Ana	Riley, Geary, Pottawatomie, and Wabaunsee	Parts of Larimer (only area below 1,830m or 6,000 ft), and Weld
Area coverage (sq km)					
Study site	23,890	23,015 Bernalillo: 3,028 Socorro: 17,221 Valencia: 2,766	9,881	6,962 Riley: 1,611 Geary: 1,047 Pottawatomie:2233 Wabaunsee: 2071	12,345 Larimer: 6,822 Weld: 10,417
Est. population[2]					
1992	2,272,582	568,935	141,228	125,123	337,772
2001	3,199,440	647,497	176,536	116,368	453,794
Change	926,858	78562	35,308	-8757	116022
Growth ratio	41%	14%	25%	-7%	34%
Population density (sq km)					
1992	95	25	14	18	20
2001	134	28	18	17	26
Precipitation 1983 to 2008 (mm)[3]					
Average annual	198.16	255.65	293.71	804.77	404.08
St. dev.	92.65	71.09	90.52	193.29	92.40
Sample (No. of years)	19	26	24	26	25

In this study, the SGS site covers the whole area of Weld county and only the parts of Larimer (below 1,830 m) county; however, all parts of Larimer county is included in this table for convenience

Source: US Census Bureau (2010)
Source: Ecotrends (2010)

To measure land fragmentation, we employ the National Land Cover Database (NLCD) for 1992 and 2001, compiled from Landsat Thematic Mapper (TM) images, which provides seamless coverage for all sites (Homer et al., 2004). NLCD was the first nationwide initiative that provided consistent land-cover inventory for the US and it has been widely used in studying urbanization (Vogelmann et al., 1998) and landscape fragmentation (Heilman et al., 2009; Riitters et al., 2002). The dataset does have limitations for land fragmentation analyses, especially in detecting peri-urban and exurban development (see for example Irwin and Bockstael, 2007; Ward et al., 2000). At the outset of this study, however, we hypothesized that the NLCD would accurately capture peri-urban development in arid environments where tree canopy is sparse. We compared NLCD to tax assessor data, similar to Irwin and Bockstael's (2007) study in suburban Maryland. In Phoenix, NLCD performed relatively well with a 66% accuracy rate for exurban areas and 81% rate for peri-urban, much better than the 8% and 26% respectively found in Maryland. Because of NLCD's performance in Phoenix and its coverage of all five sites, we opted to use NLCD. To simplify comparisons, we regrouped the land-cover classes into seven categories: developed urban (higher intensity), developed (lower intensity), agriculture, forest, deserts/undeveloped, grass/shrubland, and water (Appendix)[4]. For each site we generated two maps for 1992 and 2001, validated by local collaborators at each site, which were reclassified for further pattern analysis and quantification of land fragmentation using landscape metrics (Table 4.2).

4 These are the most common categories for the Southwest and the Midwest, and these were agreed upon by all collaborators in our workshop specifically organized to come up with the common dataset and methodology. It is important to note that NLCD 1992 and 2001 originally had different classification scheme, and hence, their land-cover categories were slightly different, which were subsequently retrofitted to make them consistent (Homer et al. 2004). In our study, we used the retrofitted land-cover classes and data.

To analyze urban growth patterns and their spatial heterogeneity, we weighed the benefits of using a full coverage moving windows analysis (Riitters et al., 2002) and a transect analysis (Luck & Wu, 2002; Yu & Ng, 2007). The transect methodology was selected due to the linear form of many of the sites and our wish to detect directionality of urbanization patterns. We selected two methods to analyze spatial heterogeneity: i.) fragmentation metrics at the class level to reflect landscape composition; and ii.) fragmentation metrics at the landscape level to capture landscape configuration (Cushman & McGarigal, 2002) (Fig. 4.3 and 4.4). To ensure consistency and uniformity across the five study sites, we applied the same size transect window of 15 km × 15km. These windows move along the transect overlapping at 5 km intervals and generate a mean value for the center pixel that is used for the fragmentation analysis.

At two consecutive workshops, we identified the five socio-ecological drivers described above that affect decisions on land use and cover and consequent fragmentation patterns. At a third workshop, we analyzed the relative importance of the five socio-ecological drivers across the five sites and identified causal explanations of differing patterns and degrees of fragmentation. Each of the drivers was ranked from high to low in explanatory power using an iterative expert analysis with local scientists and drawing on relevant literature for each of the sites (Table 4.3).

Table 4.2 Changes in the area covered by each land-use category in the study sites

Land-use	Phoenix			Albuquerque			Las Cruces			Manhattan			Fort Collins		
	1992	2001	% change	1992	2001	% change	1992	2001	% change	1992	2001	% change	1992	2001	% change
Developed, high density	622	774	24%	150	99	-34%	44	25	-43%	89	31	-65%	137	82	-40%
Developed, low-density	757	1425	88%	199	461	132%	35	191	446%	31	341	1000%	161	534	232%
Agriculture	1722	1445	-16%	103	215	109%	211	373	77%	1379	934	-32%	3300	3770	14%
Shrubs/grassland	1234	1167	-5%	93	143	54%	48	9	-81%	4927	4768	-3%	8347	7263	-13%
Forest	396	304	-23%	2660	2833	7%	79	59	-25%	334	711	113%	56	173	209%
Undeveloped	18992	18612	-2%	19845	19297	-3%	9454	9211	-3%	3	9	200%	67	294	339%
Water	83	78	-6%	71	73	3%	9	11	22%	203	171	-16%	211	163	-23%
Total Area	23806			23120			9879			6966			12278		

Area in km^2. The numbers in parentheses are the percent change (1992-2001) within the particular land-use category

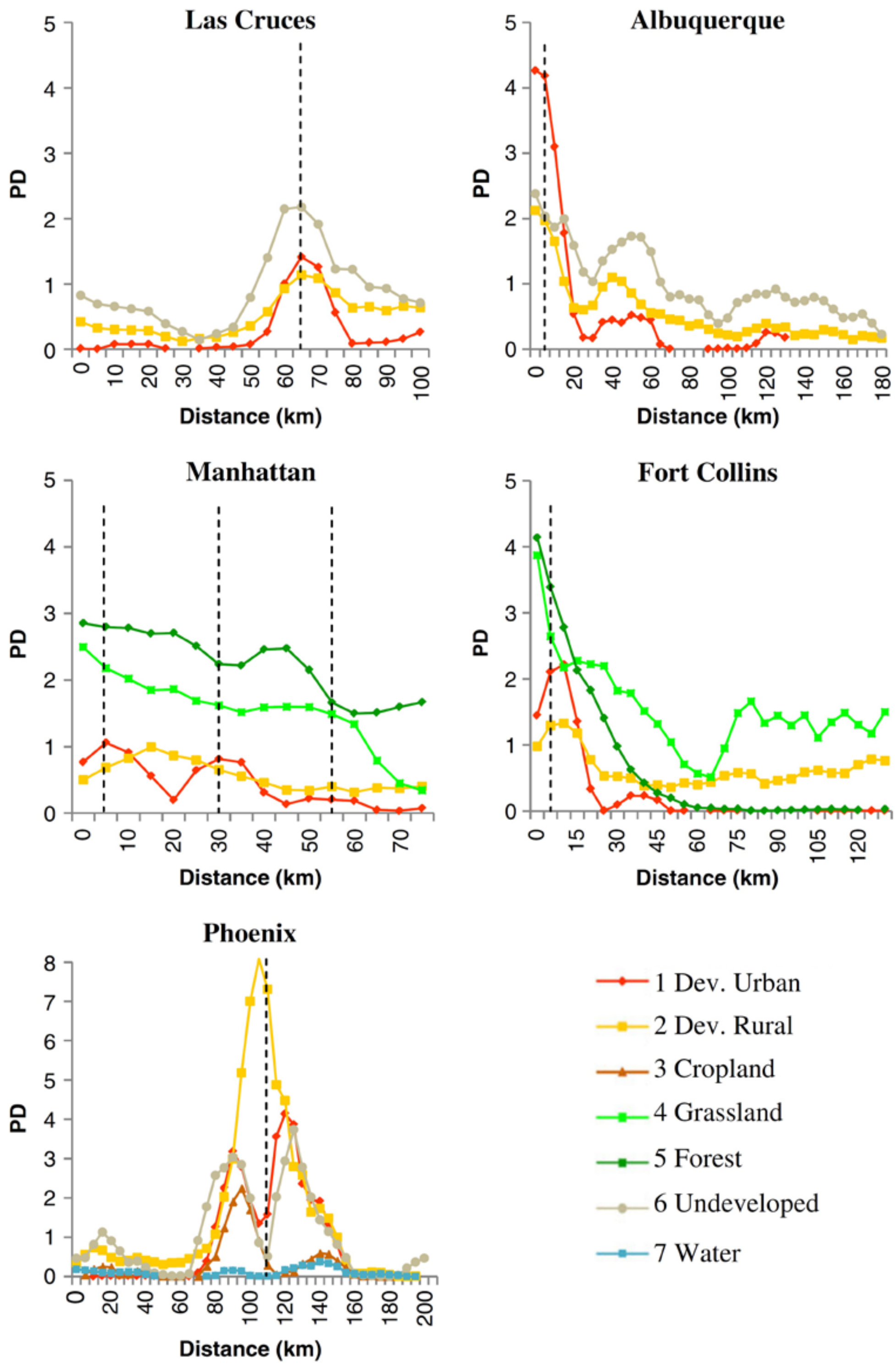


Fig. 4.3 Spatial distribution of PD (patches per hectare) at class-level along transect for the 5 sites in 2001. Dashed lines indicate the location of the center of the city or cities along the transect

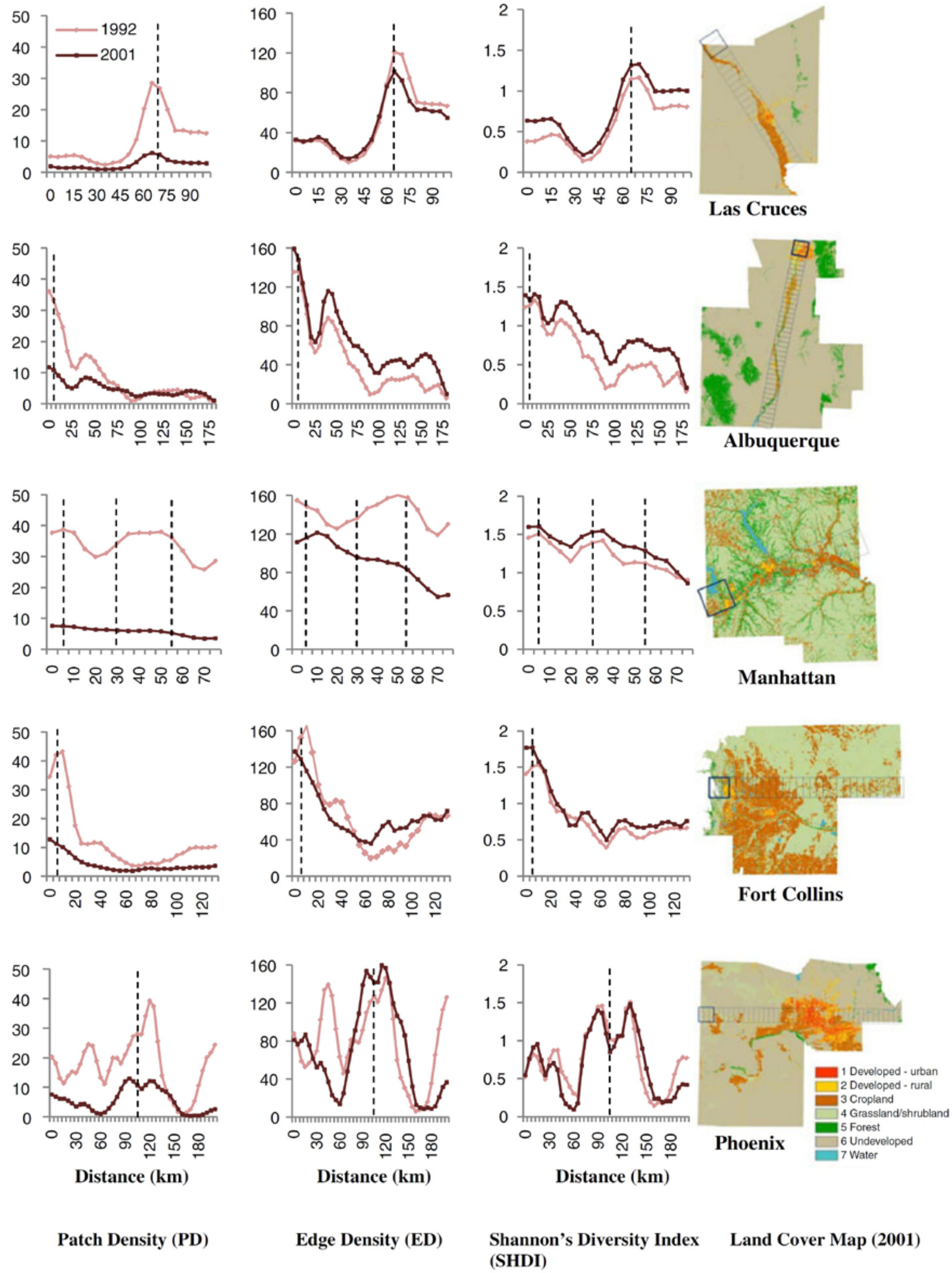


Fig. 4.4 PD (patches per hectare), ED (meters per hectare) and SHDI at landscape-level along transect for the 5 sites in 1992 and 2001. Dashed lines indicate the location of the center of the city or cities along the transect

4.3 Results

From 1992 to 2001, residential development increased land fragmentation on the fringes or the periphery of urban areas at all study sites. However, we observed three general fragmentation patterns corresponding to specific urban morphologies: (1) riparian-fragmentation along rivers; (2) polycentric-suburbanization and exurbanization in disaggregated cities; and (3) monocentric-rapid urban growth in a concentric ring pattern (Fig. 4.3 and 4.4). The riparian sites of Las Cruces and Albuquerque experience a peak level of fragmentation (specifically for patch density or PD) for most classes at the city center (Fig. 4.3 and 4.4). PD declines with increased distance from the city core, but remains at a relatively high level along the length of transect along the rivers. In addition, both Las Cruces and Albuquerque show increased fragmentation in agricultural areas with very low-density residential development.

Manhattan and Fort Collins show fragmentation in multiple areas reflecting their disaggregated, polycentric morphologies. In the Manhattan region, development occurred near the three cities of Manhattan, Wamego, and Junction City, indicated by a peak PD at 5 km, 30 km, and 55 km on the transect. In the Fort Collins region, high patch densities due to suburbanization and exurbanization have also taken place. Along the transect, PD peaks at 5 km and then increases again at 50 km related to suburbanization of Greeley and Fort Collins.

The monocentric pattern observed at the Phoenix site is distinct from the others, with expansion of development creating a mostly continuous high-density urban area, with highly fragmented low-density patches, and almost no undeveloped parcels. Phoenix has a much higher PD of all classes at the urban fringe and a lower PD within the urban center. This pattern of sprawl radiating outward from the urban center is consistent with a classic monocentric urban form model (Alonso, 1964; Mills, 1967; Muth, 1969).

Overall, PD decreased at all sites during the study period (Fig. 4.4), a finding similar to Schneider and Woodstock's (2008) characterization of development infill on undeveloped patches. In general, at all sites PD decreases as the transect moves away from the city core center in 1992, while in 2001 there is a more even distribution along the transect, indicating exurbanization trends and infill (Fig. 4.4). Infill is more prominent in Phoenix, while exurbanization and conversion from rural to urban and suburban land uses is more prominent at the remaining four sites, but both processes are evident at each site. Below we examine drivers that help to explain these observed patterns.

Drivers

4.3.1 Water provisioning

Surface water diversion, which provides water for agriculture via reservoirs, canals, and dams, altered the pattern of development at all five sites. The Bureau of Reclamation built its first major dam in Phoenix, the Roosevelt dam, in 1902, providing water for the growing agricultural interests in the valley (Luckingham, 1989). The city of Phoenix and state of Arizona continued to grow and agricultural production intensified, leading to a never-ending search for "new" water sources, such as Colorado River water transported in the Central Arizona Project canals (Glennon, 2009). In Albuquerque and Las Cruces, our riparian cities, current and historic water constraints (whether physical or institutional) tie development closely to the river. Native Americans, then Spanish, and finally Anglos settled along the Rio Grande building irrigation canals and ditches to support agrarian societies (Luckingham, 1982). With the completion of the Leasburg

Dam in 1908 near Las Cruces (Paddock, 1999) and the Isleta Dam in 1934 south of Albuquerque (USFWS, 2009), agriculture and settlement expanded throughout the Rio Grande valleys. Although groundwater pumping provides water for the cities of Albuquerque (Price, 2003) and Las Cruces (City of Las Cruces Utilities Department, 2008), land use development largely follows the river and irrigation canals even today, partially because of topography and institutional factors (discussed below).

More recently, large-scale irrigation expanded onto the plains in Kansas and Colorado with construction of large dams in the 1940s and 50s. In Kansas, prevention of catastrophic flooding was the primary impetus for building Tuttle Creek and Milford Reservoir dams, but both are used for irrigation and recreation. Groundwater sources largely serve the population in the Manhattan region, so the Flint Hills region, an upland area with limestone bedrock, and fairly inaccessible groundwater has remained mostly undeveloped. Around Fort Collins, the founders of Greeley, CO conceived a city built on communal irrigation cooperatives, and irrigation began in the 1880s in that community (Abbott et al., 1994). However, large-scale, wide-spread irrigation began later with the Colorado-Big Thompson project completed in 1959, which provides water for municipalities, agricultural, and power generation (USBR, 2009). The extensive projects increased opportunities for settlement throughout the plains sustaining growth in the Front Range cities, including Fort Collins, and creating attractive residential sites outside of urbanized areas in Kansas. In both regions, availability of irrigated water has contributed to polycentric fragmentation patterns.

Irrigation contributes to agricultural "water banks" saved for future development in Phoenix, Las Cruces, Albuquerque, and Las Cruces. In the past six decades in Phoenix, urban housing developments expanded on former agricultural lands with senior water rights (Redman & Kinzig, 2008). Assured Water Supply Rules (1994) associated with Arizona's Groundwater Management Act (1980) require developers to supply "100 years assured water" for all new residential developments outside of municipal water provision boundaries, which many achieve by purchasing farmland with senior water rights (Heim, 2001). Both Albuquerque and Las Cruces historically relied on groundwater for urban water use, but increased development has put the aquifers under severe pressure. Albuquerque sought, and continues to seek, additional water supply from the Colorado River Basin (Glennon, 2009), while Las Cruces and the downstream city of El Paso, Texas purchased over 2,200 acres of irrigated farmland to acquire the attached water rights. These rights allow the city to transfer water for municipal purposes, and the land may then be converted to development or allowed to lay fallow for future development (Skaggs & Smani, 2005). Cities along the Front Range in Colorado battle for water rights, too, by competing for farmland with senior water rights. Cities purchase land with senior rights and annex land with water in order to increase supply. Conversion of cropland to residential land use dewaters the plains. In contrast, agricultural conversion in Kansas is associated with exurbanization trends and lifestyle choice, which we address in the next section.

4.3.2 Urban population dynamics

Between 1990 and 2000, total population of the American West region surged by 19.7%, the fastest among all four regions in the country (Perry & Mackun, 2001). Western cities provided burgeoning economic opportunities for people in the region and for those seeking to retire in a place with better "quality of life" and amenities—

especially a warmer climate, year-round sunshine, and wilderness (Duncombe et al., 2003; Frey, 2003). Population and population density increased in all sites, except around Manhattan (Table 4.1).

Government employment opportunities, especially with the military, played an important role in the local economy of four of the sites: Phoenix, Albuquerque, Las Cruces and Manhattan. The clear skies and open spaces near Phoenix, Albuquerque, and Las Cruces drew military aviation bases and industries to the western deserts during World War II. These sites boomed in response to the influx of healthy defense contracts, which seeded high technology firms in Phoenix (Konig, 1982), nuclear in Albuquerque (Simmons, 1984), and weapons in Las Cruces (Welsh 1994). Establishment of large military bases created thousands of jobs, especially in Phoenix and Albuquerque with bases just outside the city. Phoenix's meteoric post-WWII growth (Luckingham, 1982) and Albuquerque's economy (Nash, 1994) are both linked closely to government contracts and jobs. In contrast Fort Riley, outside of Manhattan, began as a frontier outpost established to protect settlers traveling on the Oregon-California and Santa Fe Trails. After World War II, the 1st Infantry Division, nicknamed the "Big Red One," moved to Fort Riley and remained there until 1996 (Griekspoor, 1996). When the unit was relocated to Germany, Manhattan experienced a significant drop in population. The 1st infantry returned from Germany in 2006 and will likely boost the population for the 2010 census (Stairrett, 2006). Fort Riley served as an important outpost in settlement of the west, but never in the technological frontier of space, nuclear, and aviation. The fort has been an important contributor to the local economy, but never spurred growth in the same way as military investment in Phoenix, Albuquerque, and Las Cruces.

Booming job markets and aggressive economic growth in these southwestern cities also changed the regional migration pattern in the US (Johnson et al., 2005; Mueser & Graves, 1995). Metropolitan Phoenix experienced exponential population growth between 1992 and 2000, mainly from an influx of new migrants attracted by booming economic opportunities in the valley (Gober & Burns, 2002). Albuquerque grew rapidly, although population within city boundaries slowed and shifted to unincorporated Valencia County, partially due to the city's annexation policy (discussed below). Las Cruces grew by 25% due primarily to the influx of new migrants; home builders argue that the migrants, mostly retiree populations, sought refuge away from crowded cities like Phoenix and Las Vegas (Romo, 1997). At these desert sites, development of high-value recreation amenities like golf courses attract residents, especially retirees, while employment opportunities attract younger migrants (Table 4.3).

Much of the residential development in Fort Collins and Manhattan has occurred on the fringes on the small and medium sized cities scattered across the region. Both sites witnessed increased exurban development, although Manhattan's population decreased during the study period while Fort Collins' grew by 34%. In both cases, exurban development is driven by a desire for low-density housing, a piece of the "West", and opportunities to own hobby farms or ranchettes (Travis, 2007).

Table 4.3 The impact levels of the major drivers on land fragmentation

	Study sites				
	Phoenix	**Albuquerque**	**Las Cruces**	**Manhattan**	**Fort Collins**
Water	**High**	**High**	**High**	**High**	**High**
	Diversions from rivers	Cities along the Rio Grande, spread outward	Allocation of ground water and surface water	Cities along the Kansas river	Water storage in reservoirs
	Assured water supply plan	Albuquerque aquifer	Irrigated land, orchard	Dam and reservoir built after the 1953 flood	Water for irrigated land
	Water rights transfer from agriculture to development	Irrigation impact	Cities buying water rights	Flood plains’ reliance on irrigation	Water rights transfer from agriculture to development
Population	**High**	**High**	**High**	**Low**	**High**
	Exponential growth	Government contracts and jobs	Steady growth – Las Cruces	Decreased population	Steady exurbanization
	High density development	Exurbanization	New migrants	Steady exurbanization	Increasing retiree population
Topography	**Low**	**Medium**	**Medium**	**Medium**	**High**
	Vulnerable flood plains	Sandia mountains as a limiting factor	Mountains – limiting factor	Upland: less water, limestone bedrock, vulnerable plains	Upland: tourism based and lowland: irrigated land
	Mountains - limiting factor	Desert	Slope factor, dense valley	Suppression of fire	Leap-frog dev. in mountains
	Desert		Desert		
Transportation	**High**	**High**	**Medium**	**Medium**	**Medium**
	Late railroad and freeway development	Commercial hub dev. along interstates	Interstates	New developments along the road corridors	New commercial development along the interstates
	New freeways in 1990s	Connecting corridors	Access creating low density residential		

Institutional factors	**High** Indian lands: agri. or lease State trust land sales	**High** National labs, military Indian lands: agriculture	**High** Extensive public land holdings 54000 acres of land sold by BLM to developers	**Low** Vast majority of private lands Tallgrass National Prairie	**Low** National Forest, Grasslands Local attempts to regulate growth

4.3.3 Transportation

Communities in the Southwest have long recognized the importance of transportation networks; boosters enticed railroads with land grants and funds to cement their town's future as a commercial center. In the past, commercial centers grew near railroad depots, while today new strip malls, industrial complexes, and residential areas sprout near freeways.

Manhattan received the first railroad in 1866 (Miner, 2002), and the railroad reached Fort Collins eleven years later in 1877 (Abbott et al., 1994). The railroad tied small towns in Kansas and Colorado together increasing the ability of farmers to export products to both eastern and western markets, yet neither Manhattan nor Fort Collins emerged from the railroad age as a dominant commercial town. The railroad did, however, contribute to the disaggregated polycentric form by stringing small towns along the historic rail lines.

Between 1880 and 1887 railroads reached the three desert cities (Luckingham, 1982; Myrick, 1990). In Las Cruces the railroad replaced much of the traffic along the Santa Fe Trail enabling cattle to be picked up in Texas and shipped to urban markets on rails instead of drives to northern rail lines (Luckingham, 1982). Las Cruces was a city on the line, but was not a hub for the railroad, so the impact on commercial growth and land use was limited. Similar to Manhattan and Fort Collins development in Las Cruces has followed the railroad, which in turn traced the river and old freight roads. In Albuquerque, with the growth of the railroad, trade along east-to-west routes increased while the historically important trade along the freight roads with Mexico and towns to the south decreased in importance, although the volume increased with the extension of the railroad to El Paso (Luckingham, 1982). Today this southern railroad route is being revived with a new commuter rail system connecting towns along the Rio Grande to Albuquerque. Although the impacts of this change are not detected in our study period, it will surely continue the trajectory of exurban development. Phoenix was the last of our cities to welcome a railroad in 1887. City boosters quickly pursued completion of a second railroad connecting to the northern transcontinental Atchison, Topeka &Santa Fe, which reduced fares and increased access to the city (Luckingham, 1982). Like Albuquerque, access to multiple railroads fueled the growth of the agricultural sector and commercial center (Luckingham, 1982).

New roads in the form of freeways fueled development in the 20th century. Freeways in Manhattan, Las Cruces, and Fort Collins link the cities to the interstate system, although only in the past few decades have the interstates fueled growth along the corridors. Las Cruces connects to Albuquerque via I-25 and to El Paso, Phoenix, and Los Angeles on I-10. I-10 connects to I-25 from the west and merges in a mostly southern direction toward El Paso, reinforcing the north-south urban form along the river. Many of the state highways connecting the communities in Kansas were constructed along higher terraces or more elevated portions of the Kansas River valley, parallel to the railroad, while construction of I-70 south of Manhattan in the 1960s (Kansas Department of Transportation, 2009) shifted commerce and interstate travel south of the city. In the Fort Collins region, many cities (Fort Collins, Longmont and Loveland) fall along I-25 and the parallel Route 287 connects the communities. Completion of the interstate has led to intensified development in the exurban areas between these communities. In the three cases, the interstate highways contribute to the observed riparian pattern (Las Cruces) and polycentric pattern (Manhattan and Fort Collins), as well as the decreased grassland, rangeland, and farmland and increased fragmentation of rural lands during the study period.

Like the railroad, Phoenix did not construct a major transcontinental freeway until relatively late when Interstate-10 was completed in 1990s. Automobile dependence combined with a lack of freeways led to traffic congestion and fueled expansion of the state highway system in the 1990s, looping around the city and pushing development outward, especially to the east, southeast, and north (Gober, 2005). Expansion of freeways began earlier in Albuquerque; Route 66 ran through downtown in the 1930s (Price, 2003), but completion of Interstates 25 and 40 in the 1960s pushed development, service stations, and commerce out to the West Mesa away from the city center (Price, 2003). Because of Indian communities and topography, discussed in the following sections, the extent of Albuquerque's eastern and western expansion has been somewhat limited compared to Phoenix.

4.3.4 Topography

The topography in each study area strongly influences the dynamics of how developed areas expand within the region, particularly differences between the uplands and lowlands. Mountains are important in Phoenix, Fort Collins, Albuquerque, and Las Cruces. The basin and range topography with isolated mountains in Phoenix has created opportunities for leap-frogging of residential development beyond the mountains (many of which are held by public entities). In the Fort Collins region, the slope and foothills of the Rockies' draw tourists and new exurban residents. As land prices increased during the 1990s western boom, exurbanites increasingly encroached on former rangeland and farmland (Travis, 2007). In Phoenix, the northern part of the valley generally is at higher elevations with cooler micro-climates, and has grown rapidly in the past few decades (Gober, 2005). This area is in contrast to the floodplains, such as South Phoenix, which has been “a stigmatized zone of racial exclusion and economic marginality” (Bolin et al., 2005). For well over a hundred years, the area south of the Salt River, which historically has been subject to large flood events, has been the domain of poor and immigrant communities while the northern part of Phoenix was reserved for Anglos. The Rio Grande, the bosque along it, and the numerous arroyos also hinder some forms of expansion in Las Cruces and Albuquerque. In addition to the river, in both New Mexican cities, mountains constrain development on their peaks, but draw rural residential development to the foothills. In Kansas, exurbanites are also drawn to lots perched on hilltops, although access to groundwater is restricted in the Flint Hills ecoregion, which has limited development. Thus, similar to Albuquerque and Las Cruces much of the residential development in Manhattan is located in portions of the landscape located between the river floodplain and uplands. Slopes leading to the rocky uplands offer areas without flooding risks and relatively smoother topography that is highly suitable for development.

4.3.5 Institutional factors

Policymakers and property ownership determines or influences whether land may be developed. In each of the study sites, public land, military bases, Bureau of Land Management (BLM) lands, state trust land, and Native American lands influence urban form. This is especially true in Las Cruces where public land, especially BLM and military lands, surround the city (Nash, 1994). Public land sales and land holding provide constraints and opportunities for development at Las Cruces, fueling exurban expansion and increased fragmentation as well as historically constraining residential development to the river valley. In Phoenix, the Tonto National Forest, four military bases, large city mountain parks, and state trust land surround the city. Growth on Forest Service or city park land is unlikely, but conversion of state trust land is relatively common (Gammage, 1999). Similar to Las Cruces, decisions of a land holding public agency, the State Land Department, affect the pattern of future urban growth in Phoenix and drive much of the exurban expansion during the study period, especially into the north and west valley.

In Albuquerque, Fort Collins, and Manhattan, federal landholding agencies have very different missions from those in Phoenix and Las Cruces, resulting in fewer land sales, such that public land primarily functions as a growth constraint or obstacle. In Albuquerque, the Kirtland Air Force Base, Sandia National Labs, and University of New Mexico hold extensive tracts of land, but most of this land will not likely be sold (Nash, 1994). At the Fort Collins site, federal ownership includes the Arapahoe-Roosevelt National Forest in the foothills and mountains, Rocky Mountain National Park, and Pawnee National Grasslands. In Manhattan, private lands dominate, with the exception of Fort Riley and the recent dedication of the Tallgrass National Prairie in the 1990s, a remnant of the Flint Hills, which will be preserved by a federal-private partnership (Miner, 2002).

Complex property rules, trust doctrines, and community or council decisions impact development in Indian communities throughout the west and play an important role at two of our sites: Albuquerque and Phoenix. Some of the lands belonging to Native American communities are leased to outsiders for commercial agriculture, or developed by the community for tourism, but most land remains agricultural with very low-density housing. Because of these policies, a bird's eye view over the cities show striking differences in land-use between the communities and neighboring cities. In Phoenix, urbanization "leapfrogged" from the suburbs of Mesa to Scottsdale, Fountain Hills, and Paradise Valley, leaving rural landscapes on Indian community land in between (Gober, 2005). Similarly, the city of Albuquerque is surrounded by tribal lands, with Laguna Pueblo lands to the west, Sandia Pueblo land to the northeast, and Isleta Pueblo land to the south (Simmons, 1982) again fueling leapfrogging.

Aside from public ownership, development depends on the suitability of potential sites, the desire of landowners to sell or retain their lands, and local land use policy: zoning, planning, economic development, and annexation. In Phoenix and Las Cruces, large public land sales often result in extensive developments on formerly state or federal lands while at Fort Collins and Manhattan land sales typically occur in the private market and are often smaller acreages than in the southwestern deserts, a process similar to that found throughout the Midwestern and Eastern US (Lang & LeFurgy, 2007).

In Manhattan, partly in response to losses incurred with the military base relocation in the 1990s, the city has focused on diversification strategies and promotion of Kansas State University as an incubator, especially in the area of biotechnology. Similarly, Albuquerque has suffered from an overreliance on government money throughout the 20th century. The city was known as "Little Washington" because of the dominance of federal agencies in the local economy (Nash, 1994). Beginning in the 1980s, Mayor Rusk and later administrations have attempted to diversify the local economy. Cities in the Fort Collins, Phoenix, and Las Cruces regions also pursued diversification strategies, but the rapid growth in the housing sector and service economies dominated these regions (Travis, 2007). In the aftermath of the housing bust in 2007, these and other western cities are now reeling from an overdependence on housing construction.

With regard to residential development, Albuquerque's anti-growth debate has primarily concerned annexation policy resulting in slowed annexation post-1960s (Logan, 1994). Similar to Albuquerque, Phoenix expanded rapidly due to annexation (Luckingham, 1982), although unlike Albuquerque large annexations continue. "Annexation wars" between neighboring jurisdictions, such as the battle for Ahwatukee by Tempe, Chandler, and Phoenix, were attempts to increase the property tax base and incorporate middle-class and wealthy regions. In the case of Ahwatukee, Phoenix won with an emergency midnight city council meeting (Heim, 2001). Similar annexation conflicts have erupted between Gilbert, Mesa, and Chandler in the southeast valley, illustrated by the debacle surrounding annexation of Williams Air Force Base (Lang & LeFurgy, 2007). Much of the conflict surrounding growth and annexation of undeveloped land in the Phoenix valley is associated with the growth imperative of the cities and emergence in the 1990s of numerous "boomburbs," cities with double digit growth, over 100,000 in population, and an increasingly voracious appetite for city expansion (Lang & LeFurgy, 2007).

In the 1990s in Colorado, Longmont and Greely emerged as "baby boomburbs" with double digit growth and populations above 50,000, prompting many debates about growth. This concern is not new to the region; Fort Collins' rapid residential growth along the Front Range in the 1970s led to the election of "no-growth" councilmen, something quite rare in American politics generally and western local politics in particular (Abbott et al., 1994). Loveland wrestled with growth adopting development impact fees in the 1980s to deal with the costs of residential expansion (Singell & Lillydahl, 1990). Even though the Fort Collins' communities attempted to deal with growth issues, rapid exurban development persisted throughout the past few decades with continuous population growth pressures (Travis, 2007). Las Cruces experienced significant sprawl during the 1990s (Fulton et al., 2001), but local attitudes about growth and sprawl has been largely skeptical (Van Splawn, 2001) until the 2007 mayoral race when it became a contentious topic of debate (Ramirez, 2007). Finally, because of Manhattan's mostly stagnant economy and population declines, the cities have largely allowed low density peri-urban and exurban residential development. Local policy responses to growth have been mixed across our sample partially reflecting communities' experiences with growth. Institutions in combination with water, population dynamics, transportation, and topography shape the growth opportunities, urbanization and exurbanization rates, and fragmentation patterns.

4.4 Discussion

The review of drivers demonstrates that *water* is a key variable in understanding land change in the US Southwest. At all five sites, damming major rivers for storage or prevention of flooding, coupled with prior appropriation laws, strongly affect land use decision-making[5]. Water provision has dominated historic settlement patterns, although the mechanisms vary. In Phoenix, the extensive canal network opened up much of the

[5] Kansas adopted this doctrine with the Water Appropriation Act in 1945, while all other states have applied the first in time rule since the 1800s.

valley to agricultural and urban development-groundwater pumping, particularly prior to 1994, and diversions from the Colorado River through the Central Arizona Project further opened up the valley contributing to the monocentric fragmentation pattern. At Las Cruces and Albuquerque historic settlement patterns along the Rio Grande persist, creating a riparian fragmentation pattern, as agricultural lands are developed, while reservoir construction and water provision has maintained a polycentric pattern in Fort Collins and Manhattan.

All five sites are affected by agricultural to urban conversion. With increased urban water demand and the institutional backdrop of prior appropriation, cities and developers frequently purchase agricultural lands for the associated senior water rights in Phoenix, Las Cruces, Albuquerque, and Fort Collins. Around Las Cruces and Fort Collins, cities strategically purchase or annex properties with water rights while in Phoenix, developers typically convert agricultural properties to residential or commercial to comply with Assured Water Supply Rules. Water provisioning contributes to the fragmentation patterns at all sites, but it is highly influential at Phoenix, Las Cruces, Albuquerque, and Fort Collins, and moderately influential at Manhattan.

Population dynamics and lifestyle changes fueled much of the historical land use patterns and trends during our study period. Federal aid (e.g., for water control and regulation, highways, military bases), low state and local income tax, growing labor and housing markets, amenity-driven migration, and an extraordinary pro-growth booster spirit fueled regional migration (Abbott, 1981; Glaeser & Tobio, 2007; Travis, 2007). The legacies of WWII-era high technology industries have continued to propel development in Albuquerque, Las Cruces, and Phoenix, while Manhattan suffered population losses as a result of military base relocations.

Even Manhattan, with its population loss, experienced exurbanization with shifting consumer preferences for low density housing. The entire southwestern region has championed growth largely dependent on amenities, mild winters, sunshine, and proximity of “wilderness” (Barcus, 2004). Regional migration and lifestyle choices drive exurban development, although the process is tempered by locally-specific characteristics. In the case of Manhattan, population decline coupled with exurbanization has generated what some have termed “rural sprawl” (Pendall, 2003). In Fort Collins, new low density housing has proliferated along the Front Range, a formidable barrier to expansion but also a very attractive amenity for home buyers. At Albuquerque and Las Cruces preference for low-density, semi-rural environments increased low density residential development, fragmenting agricultural areas, while in Phoenix agricultural conversion frequently connected disaggregated urban parcels allowing infill of existing urban areas.

Historic transportation location decisions also contributed to the observed patterns at all sites. Recent construction of freeways has shifted development into the exurban fringes. Towns in the Manhattan and Fort Collins regions grew along paths of railroads and freeways. Albuquerque and Phoenix grew into major metropolitan areas because of railroad connections. Because of Phoenix’s freeway loop expansion during the 1990s development has moved outward in a monocentric pattern. Polycentric, riparian, and monocentric patterns were reinforced by the location of transportation corridors.

Transportation may create opportunities for development, while in some places topographic barriers hinder urban growth. Topographic variation also influences microclimates and creates aesthetically pleasing and valuable viewsheds driving exurban development to the foothills and mountains. Topography of the five sites is extremely varied, but rivers dominate the landscape and land use decision-making at all sites.

Transportation corridors spur development and topography may either limit or attract development, but institutions constrain or direct development. Public land holdings and sales are especially important in Las Cruces and Phoenix, similar to many western cities (Lang & LeFurgy, 2007), while Indian communities have played an important role in the development of Phoenix and Albuquerque. Land use policy at the local level also affects fragmentation. Manhattan pursued a laissez-faire attitude about exurban development, perhaps due to its economic decline, while Fort Collins has attempted increases in impact fees and even “anti-growth” policies. Las Cruces experienced tremendous growth and sprawl during the study period that only recently led to local debate among politicians about urban growth. Phoenix and Albuquerque originally pursued annexation as a growth strategy, although Albuquerque abandoned its aggressive expansion in the 1960s while Phoenix continues today. Economic development diversification strategies were attempted by Manhattan and Albuquerque, although changes to the local economies have been rather limited. These community policies define and influence land use patterns, although the complex socio-ecological system and multiplicity of drivers limits the ability of a community to manage its growth rates and land use patterns.

We find evidence of three distinct fragmentation forms: riparian, polycentric, and monocentric, although some of the sites exhibit a more “ideal” form than others. The monocentric form of Phoenix is distinguished by expansion in all directions during the study period-the pattern observed is not a set of perfectly circular development rings particularly because of institutional and topographic constraints, but where growth has not been hindered by mountains and Indian communities the expansion has been tremendous. Prior work on Phoenix development has shown an early riparian form along the Salt River (see for example Jenerette & Wu, 2001), but with the rapid post-War II development the riparian form ballooned into a monocentric pattern. Las Cruces and Albuquerque still maintain riparian forms, particularly further along the transect away from the city centers, but the area closest to the city of Albuquerque has expanded in a somewhat monocentric pattern with the institutional constraints of the Indian communities impeding expansion in some directions. Overall, Albuquerque still exhibits a riparian form when compared to Phoenix. Both Manhattan and Fort Collins exhibit polycentric forms, although the influence of the Kansas River can be observed from pattern analyses, so we might suggest that Fort Collins has a more distinctly polycentric form than Manhattan. In Manhattan, like Albuquerque and Las Cruces, transportation location decisions paralleled the river, which reinforced the riparian form. Unlike, Las Cruces and Albuquerque Manhattan exhibits more extensive development away from the river, due to the water provisioning services via access to groundwater, except in the upland Flint Hills, and higher precipitation that historically enabled agricultural and residential development. Phoenix represents the most monocentric pattern, Las Cruces the strongest riparian, and Fort Collins the most distinctly polycentric in our study.

While we explore each of the drivers separately, we recognize that drivers are interrelated and work through the social-ecological system. In Las Cruces, the river defined a north-south development toward El Paso through the geophysical template and water provisioning ecosystem services, which was reinforced by the freight roads, railroads, and interstate highways human decisions. At Albuquerque, the pueblos and public land holdings, institutional factors in the human decision-making domain, help to maintain the riparian form even with the countervailing east-west pressure of Route 66 and I-40, complementary human decisions. In Manhattan, the railroad and freeways, locations based on human decisions, access to water, an ecosystem service, and topographic differences between the floodplains and Flint Hills maintain a disaggregated residential form with development concentrated on the land in the middle of the floodplain and limestone uplands. Fort Collins' rapid rural residential expansion in a polycentric form has been due to changes in lifestyle drawing residents to the west, an external driver, access to water on former agricultural lands, a combination of water provisioning ecosystem services and institutional human decisions, conversion of private ranches and farmland scattered throughout the plains, human decisions, and transportation corridors linking Greeley, Loveland, and Fort Collins, another type of human decision. Phoenix's monocentric pattern has been driven by aggressive annexation policy of all valley cities, an institution in the human decision-making domain, regional migration, an external driver, and expansion of the freeways, transportation location decision, agricultural land conversion, human decision and state trust land sales, institutions. Historically our five drivers shaped land use decision-making resulting in the patterns and trends we observe today through a complex and interconnected social-ecological system.

4.5 Conclusions

Throughout the post-WWII period the west changed rapidly with an influx of new residents and ever increasing demand for low-density, exurban housing. Even in the case of Manhattan, KS, a community with limited economic growth and devastating loss of a major military installment in the 1990s, rural lands have become increasingly fragmented. Yet, the patterns of fragmentation and rates of change are not uniform. In our study, we found three general fragmentation patterns: riparian, polycentric, and monocentric. Riparian growth trends occurred along the historically important Rio Grande Valley and were reinforced by transportation decisions and public land holdings. The polycentric patterns on the plains of Colorado and Kansas began with frontier towns connected by railroads and were later amplified by freeway construction and private agricultural land conversion. Finally, the monocentric pattern observed in Phoenix was due largely to the increased water available through diversion of the Salt, Gila, and Colorado rivers and the massive canal works throughout the valley. Public land sales, freeway development looping around the city, and conversion of agricultural land to residential tied to Assured Water Supply Rules help to explain the monocentric patterns of growth in Phoenix. Overall, we observed two general trends in fragmentation: expansion of the urbanized area and decreased fragmentation within the previously developed area. The first trend was prominent at all sites, while the second was strongest in Phoenix. These two general trends and three fragmentation patterns illustrate the recent western experience with growth and urbanization.

Cross-site projects studying land use patterns are challenging because of the legacies of land use decision-making and the particularities of each community and landscape, yet it is imperative to pursue comparative work to better understand general trends. Using a national land cover database, expert local opinion, and existing literature, we analyzed trends in land fragmentation and linked these results to relevant historical, contextual information. We identified five relevant drivers – water provisioning, population dynamics, transportation, topography, and institutions – that shape land use decision-making and fragmentation in the southwest. We developed an approach for integration of qualitative and historic analyses with land fragmentation metric and pattern analyses within a socio-ecological systems framework. The approach allows us to uncover the processes for observed fragmentation patterns driven by the integrated components of the socio-ecological system: the geophysical template, ecosystem services, human behavior, disturbance presses and pulses, and external factors. The socio-ecological framework and use of a common land use/cover classification system enabled cross-site comparison within a regional context. We contribute to a new cross-site approach to the urbanization and urban ecosystems literatures, which we hope will lead to more comparative work and spark new hypotheses about socio-ecological urbanization processes. Our work highlights the importance of understanding land use decision-making drivers in concert and throughout time, as historic decisions leave legacies on landscapes that continue to affect land form and function, a process often forgotten in a region and era of blinding change.

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Appendix

Table I: NLCD Recoding Scheme

NLCD 1992 land cover classes	1992 recode to 7 classes	NLCD 2001 land cover classes	2001 recode to 7 classes
11 - Open water	7 – Water	11 - Open water	7 - Water
12 - Perennial Ice/Snow	6 – Remnants/desert/undev.	12 - Perennial Ice/Snow	6 – Remnants/desert/undev.
21 - Low Intensity Residential	2 – Developed -- rural	21 - Developed, Open Space	2 – Developed – rural
22 - High Intensity Residential	1 – Developed – urban	22 - Developed, Low Intensity	2 – Developed – rural
23 - Commercial/Industrial/Transportation	1 – Developed – urban	23 - Developed, Medium Intensity	1 – Developed – urban
		24 - Developed, High Intensity	1 – Developed – urban
31 - Bare Rock/Sand/Clay	6 – Undeveloped/desert	31 - Barren Land	6 – Undeveloped/desert
32 - Quarries/Strip Mines/Gravel Pits	6 – Undeveloped/desert	32 - Unconsolidated Shore	6 – Undeveloped/desert
33 - Transitional	6 – Undeveloped/desert		
41 - Deciduous Forest	5 – Forest	41 - Deciduous Forest	5 – Forest
42 - Evergreen Forest	5 – Forest	42 - Evergreen Forest	5 – Forest
43 - Mixed Forest	5 – Forest	43 - Mixed Forest	5 – Forest
51 – Shrubland	4 – Grassland/shrubland	51 - Dwarf Scrub	4 – Grassland/shrubland
(in case of JRN, it is 6 – Undeveloped/desert)		52 - Scrub/Shrub	6 – Undeveloped/desert
61 - Orchards/Vineyards/Other	3 – Cropland		
71 - Grassland/Herbaceous	4 – Grassland/shrubland	71 - Grassland/Herbaceous	4 – Grassland/shrubland
		72 - Sedge Herbaceous	4 – Grassland/shrubland
		73 - Lichens	6 – Undeveloped/desert
		74 - Moss	6 – Undeveloped/desert
81 - Pasture/Hay	4 – Grassland/shrubland	81 - Pasture/Hay	4 – Grassland/shrubland
82 - Row Crops	3 – Cropland	82 - Cultivated Crops	3 – Cropland
83 - Small Grains	3 – Cropland		
84 - Fallow	3 – Cropland		
85 - Urban/Recreational Grasses	1 – Developed – urban		
91 - Woody Wetlands	5 – Forest	90 - Woody Wetlands	5 – Forest

92 - Emergent Herbaceous Wetlands	4 – Grassland/shrubland	91 - Palustrine Forested Wetland	5 – Forest
		92 - Palustrine Scrub/Shrub	1 - Undeveloped
		93 - Estuarine Forested Wetlands	5 – Forest
		94 - Estuarine Scrub/Shrub	4 – Grassland/shrubland
		95 – Emergent Herbaceous Wetlands	4 – Grassland/shrubland

Chapter 5

THE ROLE OF WATER PROVISIONING IN LAND SYSTEM CHANGE IN ARABLE URBAN AREAS – THE CASE OF PHOENIX WATER MANAGEMENT POLICIES

5.1 Introduction

Half of the world's population resides in urban areas. Rapid urbanization has changed land-use and land-cover (LULC) patterns around the world, with pervasive impacts on ecological systems that are the basis of survival for humans and others species (Defries et al., 2004). Land fragmentation, one components of land-use and land-cover change, is a global consequence of urbanization with that influences ecosystems and human quality of life. Fragmentation usually occurs where urban patches are mixed with non-urban areas, creating "patchy" or "leap-frog" landscape characteristics (Schneider & Woodcock, 2008). Land fragmentation alters ecosystem structure and the functioning of human settlements by breaking up habitat, ecosystems, or land-use types into smaller parcels (Forman, 1995), and is recognized worldwide as the primary force driving the loss of biological diversity.

Cities in the United States are experiencing growth characterized by various fragmentation patterns (e.g., "leap-frog" developments, edge cities, and ex-urban enclaves). Since the 1970's, the US has become a suburban nation, exhibiting spatially dispersed urban forms. Although decreased fragmentation can be found in urban-core areas due to high disturbance and the dominance of urban land-use, there is a significant increase of land fragmentation in mean fragmentation values along the urban-rural gradient in cities across the American landscape (Irwin & Bockstael, 2008; York et al., 2010).

Urban growth has been driven by the complex interactions among policies, socio-economic factors such as population growth, transportation technologies and investments, and biophysical factors such as topography and climate. In the United Sates, land-use policies have played an important role in shaping urban growth-patterns through comprehensive land-use plans, zoning ordinances, federal housing subsidies, tax structures, and home mortgage insurance (Mieszkowski & Mills, 1993; Munroe & York, 2005; Bolin & Darby, 2008; Bolin et al., 2010). For example, minimum lot-size restrictions, as found within the agricultural reserve zones, may actually lead to residential development on larger parcels than would be found without this requirement (Munroe & York, 2005). Most research has focused on the economic activities, technologies, and land institutions that drive land-use decisions; little attention has been paid to the role of water provisioning and water policies in driving land-system change and fragmentation.

In the arid cities typical of the southwest US, water provisioning has been an important factor in shaping the urban pattern. The provisioning of fresh water delivered through infrastructure is a fundamental pre-condition of growth (August & Gammage, 2006; Gober, 2005; York et al., 2010). Since the early nineteenth century, irrigation and groundwater withdrawals have permitted extensive and intensive agricultural development. Agricultural areas, which provide “banks” for water rights, actually facilitate land conversion to urban use (York et al., 2010; Keys et al., 2007). Due to the close relationship between water availability and urban growth, the institutions and policies of water management are particularly important. They are tightly coupled with land policies and play a pivotal role in deciding the formation of urban development. In Arizona, The Arizona Department of Water Resources (ADWR), which was established to implement the Groundwater Management Act (GMA, or the *Code*) in 1980 (Bolin et al., 2010), aims to ensure a long-term, sufficient, and secure water supply for the state (ADWR). GMA was the state's regulatory concession to the federal government to acquire federally subsidized water for the Phoenix metropolitan area (Reisner, 1993). However, how GMA policies influence developers when selecting land for development remains unknown. For example, the *100-year assured water supply* was enacted in 1994 under GMA, given the theoretical knowledge of its influence on the growth on the areas with senior water right and more water sources. No research has been carried out with practical evidence.

To understand the influence of water institutions on urban growth in the Phoenix metropolitan area of Arizona, I examined ground-water management and its policies. I sought answers to two questions. The first was, "What are the relationships among groundwater (which is represented by "wells") land cover, and land fragmentation?" I used archival and spatial correlation analysis with ArcGIS to answer this question. The second question evaluates the influence of the policy, asking, "Do these relationships change after the implementation of the *Assured Water Supply Rule*?" The methods I used to answer these questions, and my findings, are described later in this chapter.

5.2 Phoenix’s groundwater management

5.2.1 Background to the initiation of groundwater management

The Phoenix metropolitan region (hereafter, *Phoenix*) comprises of the city of Phoenix and other twenty-five municipalities. It is located in a broad, flat, alluvial basin at the confluence of the Salt and Gila Rivers in central Arizona. Since 1990, the region’s population has increased by 47% to 4.2 million people, and urban built-up areas have expanded from 3% of the total land in 1955 to almost 20% in 2001. As in other urban regions, the expansion of Phoenix has been supported by a series of social-economic factors. These include federal subsidies, the construction of highways, the popular use of motor vehicles, preference for a suburban lifestyle, and the availability of air-conditioning (Grimm & Redman, 2004). In addition to all these factors, water-supply projects and policies have spurred urban growth in this arid region (Bolin et al., 2010). As a desert city in the southwestern US, Phoenix depends largely on climate-sensitive watersheds. Throughout the city’s history, access to water has greatly influenced growth and land-use decision-making in Phoenix. Continuous access to water has played a pivotal role in rapid urban sprawl and increased land fragmentation at the urban fringes.

According to the description of historical land use change by Knowles-Yanez et al (1999), Anglo-American residents shifted north away from the Salt River in the mining boom period (1861-1862). By 1885, the demand for land in the north had outstripped the available supply of river water, so the Arizona Canal was constructed, making it possible to increase the amount of land under cultivation. The new water supply encouraged the formation of new towns in north Phoenix, including the cities of Scottsdale, Glendale, and Peoria. Meanwhile, the highland and consolidated canals facilitated the formation of towns in south Phoenix, such as Chandler and Queen Creek. Floods (1890-1891) and droughts (1897-1903) stimulated creation of the Salt River Project (SRP) in 1903. The Salt River Project provided hydroelectric power, water delivery, and protection from floods for a growing desert metropolis (Gammage, 1999). When new dams, reservoirs, and canals were built after World War II, agriculture expanded further. Consistently low land prices spurred the fast growth of manufacturing facilities during the boom years of 1941-1970. In the past six decades, urban housing developments have expanded very quickly on lands converted from agriculture, where water supply had been ensured through diversions from the Colorado, Salt, Verde, and Gila Rivers. Phoenix gradually transformed from a farming center to a residential center, then to an industrial center (Reisner, 1993; Redman & Kinzig, 2008). Like much of the southeastern United States (Goodman, 2007), Phoenix faces the risk of water scarcity. Although urban areas outbid agriculture for water needed (Gammage, 1999), farmers often established new farms in undeveloped areas, which maintained the level of total water demand (Redman & Kinzig, 2008). The fear of running out of water motivated construction of the Central Arizona Project (CAP) canal in the 1980s, after Arizona secured legal rights to a share of Colorado River water, and triggered action to maintain groundwater levels (Kupel, 2003). Action took the form of the *Groundwater Management Act of 1980* (Redman & Kinzig, 2008).

After its passage, the Groundwater Management Act reversed the expansion of farming. It decreased agricultural acreage and diverted water from agriculture to the urban sector (Reisner, 1993; Redman & Kinzig, 2008; Burns & Kenney, 2005). Until the housing-market bubble burst in 2007, urban growth in Phoenix had been so exponential and aggressive that developers sought alternative sources of water access by pumping groundwater through the Central Arizona Project. Not even the Assured Water Supply Rulehas impeded developers from converting more and more land to new urban uses; therefore, Phoenix continues to struggle with a dwindling water supply. As had been the case in Idaho and Montana, a lack of adequate water supply has led Arizona to deny permits for new coal-fired power plants since 2007 (Glennon, 2009). The current water-shortage challenge has also been caused in part by global climate change, which is evidenced by a long-term trend to a warmer and drier climate regime in the western US, accompanied by an overall decrease in surface water (Milly et al., 2005; Seager et al., 2007).

There are 100 water providers in Phoenix, but the three major providers are the Central Arizona Project (CAP), the Salt River Project (SRP), and underground water owners. The region's 2006 water budget planned to draw water from different sources as follows: 35.8% from groundwater, 51.7% from surface water (including 34.5% from the Colorado River and 12.30% from the Salt and Verde Rivers), and 12.3% from reclaimed water. Groundwater provides slightly more water than does the Colorado River. Phoenix is expected to face a severe surface-water shortage within the next 50 years as a result of the trends in climate change. Groundwater will be especially important water source for Phoenix in the future.

5.2.2 Groundwater management

With the state's regulatory concession to the federal government to acquire federally subsidized water in Phoenix (Reisner, 1993), the Arizona Groundwater Management Act of 1980 (GMA) (The Code) was implemented in 1980. The Arizona

Department of Water Resources (ADWR) was established to implement this policy. The GMA broadly defines the institutional rules under which entities and persons can use groundwater.[6] The law has three primary goals: to control severe overdraft, to provide a means to allocate the state's limited groundwater resources, and to augment Arizona's groundwater through water-supply development. The implementation of the GMA prohibited groundwater irrigation of new agricultural lands (Bolin et al., 2010). Under the GMA, Active Management Areas (AMAs) and Irrigated Non-Expansion Areas (INA) were defined in Arizona. The GMA created AMAs and zones where groundwater use is restricted in order to maintain aquifer levels. An AMA is a geographical area which has been designated pursuant to the Groundwater Code as requiring active management of groundwater or, in the case of the Santa Cruz Active Management Area, active management of any water, other than stored water, withdrawn from a well. The AMAs are defined by groundwater basins and not by the political boundaries of cities, towns, or counties. Groundwater withdrawals from within an AMA are strictly regulated.

Each AMA has its own goal and a management plan to reach this goal; the Phoenix AMA has a goal of achieving safe-yield groundwater use by 2025. The Phoenix AMA has an area of over 5,600 square miles, consisting of 287,000 acres of farmland. The Phoenix AMA uses over 2 maf annually, of which 0.9 maf is groundwater and 1.4 maf comes from other sources. The Phoenix AMA is subdivided into seven smaller sub-basins based on hydrologic conditions. Sub-basins include the West Salt River Valley,

[6] Groundwater means water under the surface of the earth, regardless of the geologic structure in which it is standing or moving. Groundwater does not include water flowing in underground streams with ascertainable beds and banks (A.R.S. § 45-101 (5)).

the East Salt River Valley, Carefree, Lake Pleasant, Fountain Hills, Hassayampa, and Rainbow Valley (ADWR, 2004).

More than nine thousand wells in the Phoenix area, both outside and within the AMA, are the main sources of groundwater. The majority of groundwater from wells is used for irrigation, domestic purposes, public supply, and stock watering. Irrigation refers to water supplied to farms for the watering of cultivated crops. Domestic usage refers to water used to supply household needs. Most domestic wells are in suburban or farming homes. Public supply refers to water that is pumped and distributed through a network that supplies several homes. Such supplies may be owned by a municipality or community, a water district, or a private water company. Stock refers to a well pumped to supply water to livestock. Wells are divided into two types: exempt and non-exempt. An exempt well has a maximum pump capacity of 35 gallons per minute. Typical uses include non-irrigation purposes, non-commercial irrigation of less than two acres of land, and watering stock. Most exempt wells are used for residences and are more than adequate for household use. In AMAs, new exempt wells used for non-residential purposes can withdraw a maximum of 10 acre-feet of water per year. A non-exempt well has a pump capacity exceeding 35 gallons per minute. This type of well is generally used for irrigation or industry. Non-exempt wells may be subject to special requirements. Generally, exempt wells are less regulated than non-exempt wells. For example, to drill wells outside AMAs and exempt wells inside AMAs, only a Notice of Intention to Drill form (NOI) must to be filed. However, to drill non-exempt wells inside AMAs, a drilling permit is required.

Safe yield is "a long-term balance between the annual amount of groundwater withdrawn in the AMA and the annual amount of natural and artificial recharge" (Bolin et al., 2010). To attain the elusive goal of safe yield under the GMA, any new subdivision in an AMA must demonstrate an *assured water supply (AWS),* a rule which was implemented in 1994. This means that the subdivision must have physical and legal access to a sufficient quantity of water to last 100 years, as well as the infrastructure to deliver it. Failure to prove access to an AWS will prevent a subdivision from being approved for construction (Heim, 2001).

5.3 Data and Research Method

To better understand how water policies have influenced urban growth patterns in Phoenix, I wanted to identify the relationships among groundwater availability, land cover, and land fragmentation. I also wanted to discover whether those relationships changed after implementation of the ASW rules.

I hypothesized that during the implementation of the AWS, more conversion of land cover to developed use would have occurred in areas closest to ground/well water sources, and that Land fragmentation would have tended to occur in areas with higher well-density during the 1992-2001 time period. I also hypothesized that land fragmentation would be more closely related to groundwater availability outside the Phoenix AMA than within it.

Because it includes most of the Phoenix metropolitan area's cities, I selected all of Maricopa County for as the area for analysis of the impact of AWS. Maricopa County also includes most of the Phoenix AMA area. Spatial patterns of land fragmentation and land cover in Maricopa County were generated based on the National Land Cover

Datasets (NLCD) for 1992 and 2001. I conducted a series of tests of a moving window sized from 90 m to 2370 m, and found that a 690 m side length was optimal for interpreting the fragmentation pattern, using a raster map of continuous fragmentation value. Contagion metrics were selected as the fragmentation index. Contagion measures both patch type interspersion (the intermixing of units of different patch types) and patch dispersion (the spatial distribution of a patch type) at the landscape level. Higher values of contagion indicate large, contiguous patches; lower values indicate small and dispersed patches (McGarigal et al., 2002). To determine developers' site preferences relative to groundwater provisioning, I used wells point data obtained from the ADWR 2003 dataset. There are 8,579 wells in Maricopa County, of which 5,279 are currently in use and were selected for the study. There are 4,398 wells within the Phoenix AMA, and 776 wells are located outside any of the AMAs. The wells are used for three major purposes: irrigation (46%), domestic (28%), and public supply (14%). Wells have been measured from 1912 to 2004, and 56% of the wells were measured during the 1990s and 2000s.

I examined the change in land cover around each well between 1992 and 2001. Then I applied a buffer area around each well at a distance of 1-6 km. By comparing land conversion rates at different distances to wells, I was able to determine the extent to which wells have influenced the rate of land conversion (Fig. 5.1).

Next, I evaluated the spatial relationship between density of wells and land fragmentation, and compared relationships within and outside of the Phoenix AMA, as well as changes in the relationship from 1992 and 2001. A 10 km × 10 km grid was used to calculate the total number of wells in each grid cell. I then calculated the mean value of land fragmentation represented as the Contagion index, and correlated the two datasets to examine the relationship between the distribution and density of the 5279 wells and the Contagion values. Finally, I compared the differences in fragmentation among twelve selected municipal jurisdictions, distinguished by cities. The twelve cities were selected geographically and evenly distributed.

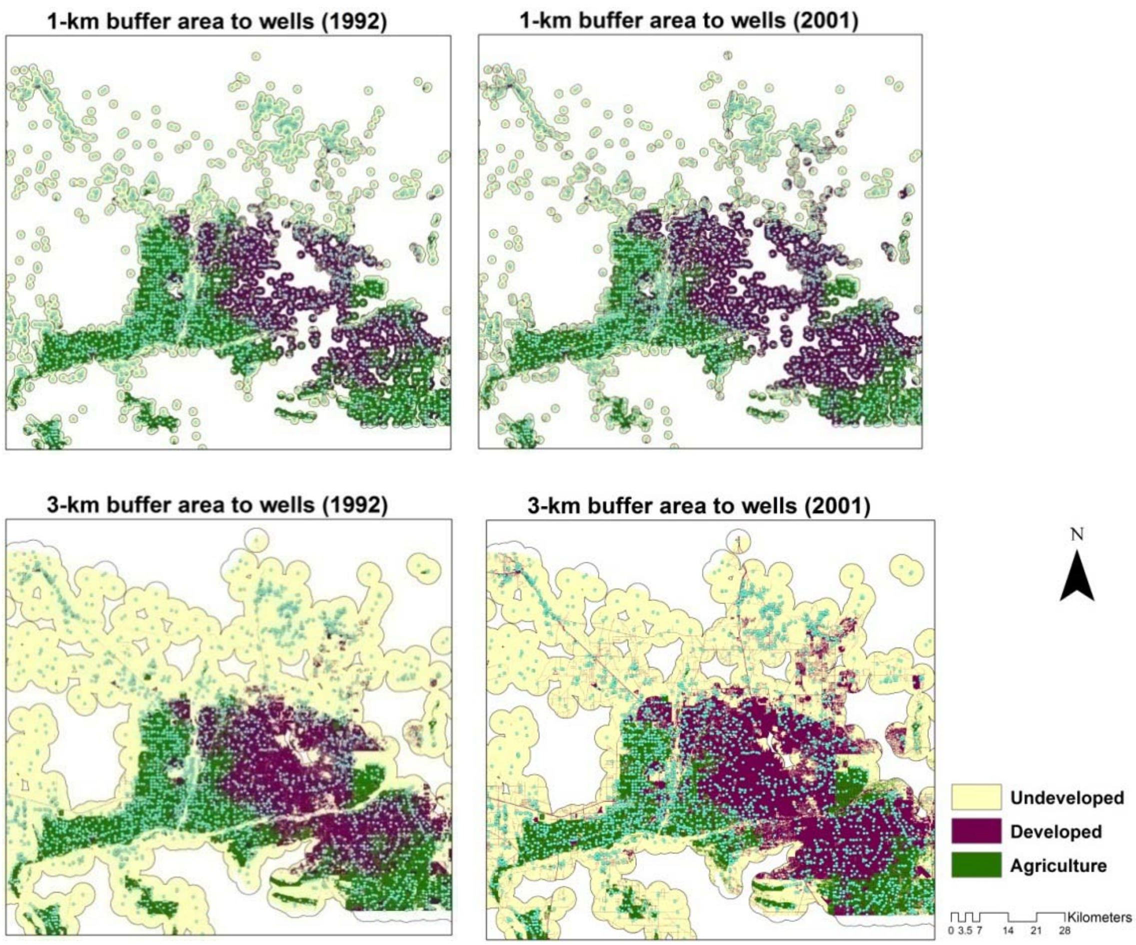


Fig. 5.1 Distribution of wells and land cover within 1 km and 3 km buffer zones.

5.4 Results

I compared the change in land-cover type at each well location. Results indicated that land cover at 21.37% of the well points underwent conversion from either agriculture or undeveloped to developed use. The number of wells located in the developed area increased by 98%, while the number of wells in undeveloped and agricultural areas decreased by 24.04% and 45%, respectively (Table 5.1).

Table 5.1 Land-cover change at the location of wells from 1992-2001

Land cover	Total number of wells in 1992	Total number of wells in 2001	% change
Undeveloped	2358	2027	-14.04
Developed	1150	2278	98.09
Agriculture	1771	974	-45.00
Total wells	5279	5279	
Land cover	Number of wells for domestic use in 1992	Number of wells for domestic use in 2001	% change
Undeveloped	1046	862	-17.59
Developed	155	423	172.90
Agriculture	270	186	-31.11
Total wells	1471	1471	
Land cover	Number of wells for irrigation use in 1992	Number of wells for irrigation use in 2001	% change
Undeveloped	659	639	-3.03
Developed	530	1147	116.42
Agriculture	1249	652	-47.80
Total wells	2438	2438	

By testing the area at different buffering distances to wells, I was able to evaluate the extent to which the wells influenced land-cover change. Fig. 5.2 shows that the land closer to a well has a stronger tendency to change to developed land than does land further from a well. In the 6 km buffer zone around each well, 3.44% of land was converted from undeveloped and agricultural land to developed land (1.46% from agricultural to developed, and 1.98% from undeveloped to developed land). With the shrike of the buffer radii, the areas examined get closer to the well locations, and the closer they get, the more land conversion occurs. In the buffer zone of 1 km around the well, conversion to developed land increased to 9.19% of the buffer area. More agriculture land (5.88%) than undeveloped land (3.31%) contributed to the rapid increase of developed land. These results imply that once the 100-year water-assurance policy was implemented, developers became more likely to select sites with accessible wells than those without, and preferred areas that were originally meant for agriculture use.

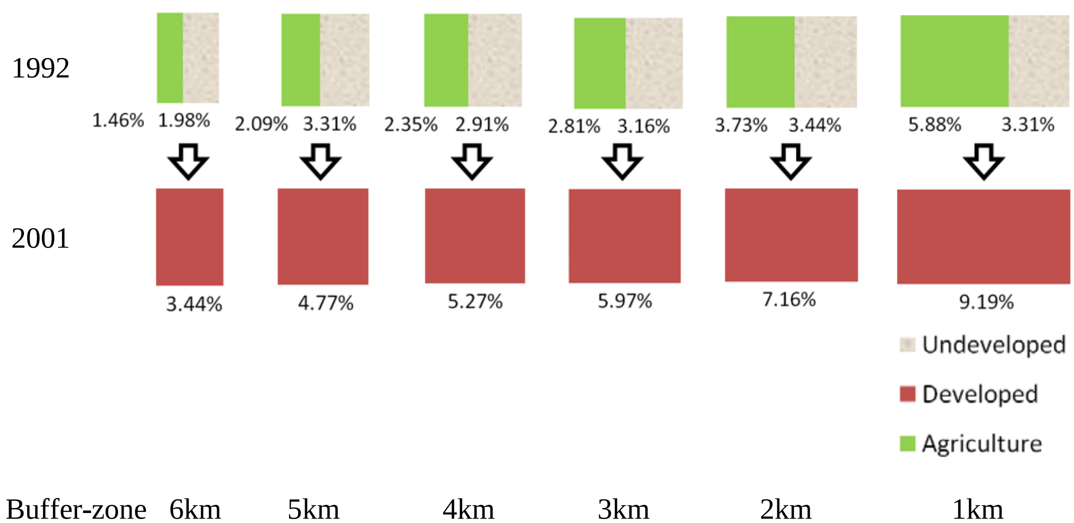


Fig. 5.2 Land cover change within area at different buffering distance to wells from 1992 to 2001

I then compared the distance to wells (groundwater) and degree of land fragmentation before and after implementation of the AWS, as well as within and outside the Active Management Area (AMA). Results (Fig 5.3) indicate that fragmentation tended to occur in the area surrounding wells after policy implementation. Furthermore, a higher correlation (R^2 = 0.6) between land fragmentation and well density was found outside the AMA than within it. Outside the AMA, water-supply assurance is not required and groundwater withdrawals are not strictly regulated. Steeper regression slopes were found in 2001 than in 1992, both within and outside the AMA, indicating that land fragmentation increased especially in the areas with a high density of wells.

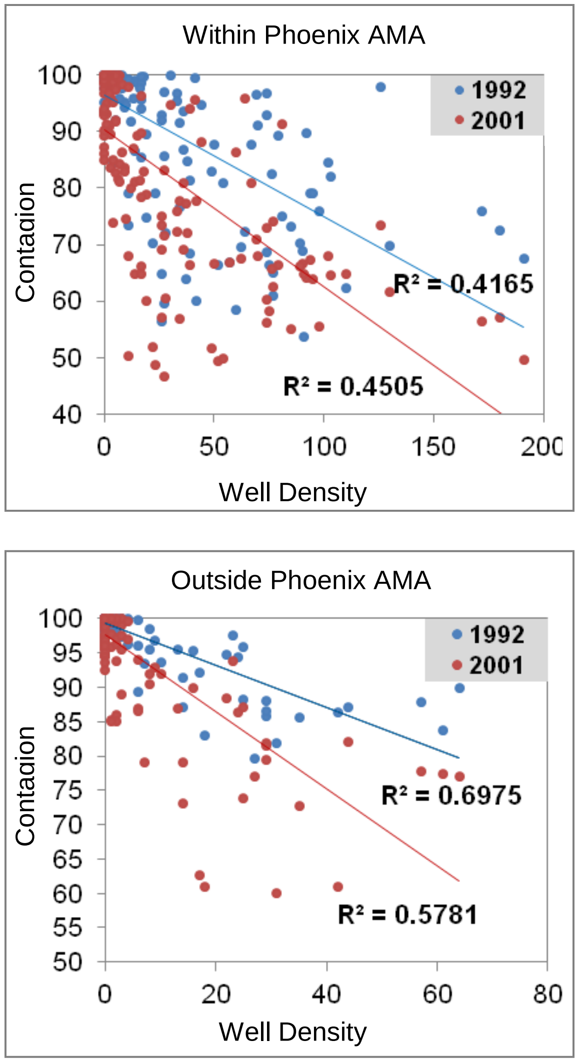


Fig. 5.3 Correlation between land fragmentation and well density within and outside the AMA

5.5 Conclusions

I conducted a spatial statistical analysis to evaluate the relationship between institutions and land-system change. I explored how variability in water sources and water rights has affected urbanization patterns and land-fragmentation levels through space and time.

Findings suggest that compared to land far from the presence of wells, land near wells has experienced fast conversion from agriculture and undeveloped to developed land use from 1992 to 2001. This change may reflect the fact that because of AWS, developers are most likely to buy farmland with senior water rights. The use of well water (e.g., for agriculture, for domestic use) has affected land–conversion characteristics. This is especially apparent in the fact that where well water was used for domestic purposes, developed land area increased by 172.9%. Results of this study show a stronger correlation between well counts and land fragmentation outside AMAs, where AWS is not applied. Since the implementation of AWS, new development has tended to occur outside AMAs. All wells outside of AMAs are non-exempt wells, and are not limited by maximum withdrawal regulations of 35 gallons/minute. Therefore, in areas outside AMAs, where there is a lack of infrastructure, non-exempt well water can be a major water source. Our finding that the slope of linear regression was greater in 2001 than in 1992 is consistent with our hypothesis, and indicates that fragmentation increased faster in the areas with more wells. Our findings provide empirical evidence that water policy affects land conversion and fragmentation, which in turn affect urban ecosystem functions and services.

Appendix

There are total of 2388 well owners; below are the owners who own more than 10 wells.

Well owner	**Number of wells**
SRP	254
RID	105
CITY OF PHOENIX	103
PALOMA RANCH	96
ARIZONA STATE LAND DEPT	77
RWCD	67
BIC	54
GOODYEAR FARMS	54
GRIC	50
CITY OF SCOTTSDALE	46
MWD	42
ARIZONA-AMERICAN WATER CO	41
CITY OF MESA	33
CITY OF CHANDLER	31
GILLESPIE LAND & IRRIGATION CO	27
PHOENIX AGRO	24
SALT RIVER INDIAN TRIBE	22
CITY OF GLENDALE	20
CITY OF PEORIA	20
GILA RIVER RANCHES	18
NW MUTUAL LIFE INS CO	18
PAINTED ROCK RANCH	17
SUN CITY WATER CO	17
SUNCOR DEVELOPMENT	17
ARIZONA GAME AND FISH DEPT	16
BLM	16
LUKE AFB	16
APS	15
CITIZENS WATER RESOURCES WATER CO	14
ARROWHEAD RANCHES	13
ADAMAN MUTUAL WATER CO	12
BOSWELL COTTON CO	12
MCMWCD 1	12
PHOENIX PARKS AND RECREATION	12
TURNER & TURNER, LTD	12
BOGLE FARMS	11
CAVE CREEK WATER CO	11
CITY OF TEMPE	11
B F YOUNGKER	10

CHAPTER 6

MULTI-SCALE ANALYSIS OF INFLUENCES OF LAND COMPOSITION AND FRAGMENTATION ON BIRD BIODIVERSITY

6.1 Introduction

Habitat fragmentation has been studied extensively in ecology, and has often been described as having a negative effect on biodiversity by isolating blocks of natural habitat (Clark, 2011; Cook & Faeth, 2006; Bolger et al., 2000; Gibb & Hochuli, 2002). Fragmentation can be caused either by nature or by human activity. How land fragmentation is defined depends on the characteristics of the study area. If research focuses on the interaction between urban and natural land, fragmentation is most likely to occur in suburban areas where developed and undeveloped land mixes together intensively. If the focus is on the fragmentation of urban land form, land fragmentation can be represented by a mixture of different land-use classes such as low-, mid-, and high-density residential areas. Fragmentation can also be measured by land functions, such as school, commercial, residential, or industrial areas. Fragmentation may also be defined according to land ownership. Therefore, land fragmentation in urban areas is conceptually different from natural-habitat fragmentation. It can be fragmentation of peri-urban agriculture, fragmentation of urban land use or land cover, or fragmentation of ownership.

Therefore, a single map may not show “fragmentation” for all research questions. In the case land use, for example, a single place such as a neighborhood can be considered highly fragmented or unfragmented, based on what types of lands are considered to be the “same” type. For example, in Figure 6.1, the area in map A is a low-density residential area, while the area in map B is located in the urban core of Phoenix. Based on the criterion of land ownership, area B could be highly fragmented. Based on the criterion of land uses such as education, industry, or residential development, B could also be more fragmented than area A. However, if the research focuses on the contrast of developed land, desert, and cultivated land, A might be more fragmented than B.

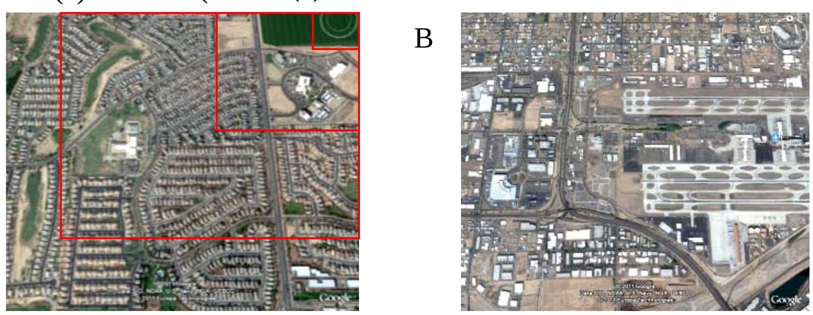


Fig. 6.1 Examples of different land forms and land fragmentation

After decades of suburbanization in the US, the most fragmented areas are generally considered to be the product of low-density urban sprawl along the urban fringe. The term “fragmentation” was originally used in ecology to describe a process occurring in natural habitats. When applied to urban areas, fragmentation describes the “isolation” and “segmentation” of urban habitat. Therefore, the term fragmentation is most often used to describe urban-fringe and low-density areas where the residential areas are relatively isolated, and have more management problems and more resource and energy-consumption problems than urban core areas. To understand the fragmentation pattern in an urban area, we must first understand how land is classified. Land classes play an essential role in identifying fragmentation, because fragmentation is based on patches, and patches are defined by different land classes. Land fragmentation is a form of land use and land cover (LULC). It can refer to low-density expansion into natural areas, which manifest as mixed land-cover of development, undeveloped areas, and cultivated land, but it can also refer to mixed land-use in an area, manifested as a diversity of urban land-use types. While low-density urban sprawl is regarded as unsustainable by most urban planners, mixed land-use is considered a sustainable urban form. Because of the different meanings of the term "fragmentation," studies of the Phoenix metropolitan area have concluded that fragmentation happens mostly on the urban fringe (e.g., Schneider & Woodcock, 2008), and the opposite—that fragmentation highest in urban center (e.g., Buyantuyev et al., 2010).

Land fragmentation in urban area has seldom been studied, especially in terms of how it relates to biodiversity and urban-ecosystem dynamics. Land fragmentation and biodiversity in natural, non-urban areas, however, has been widely researched. Research has identified land *cover* variables for biodiversity in urban areas (Nilon & Warren, 2009; Shochat et al., 2004; Shochat et al., 2010), as well as the relationships between socio-economic factors and biodiversity (Kinzig & Warren, 2005; Hope, 2003). However, little research has been done on fragmentation and biodiversity. Fahrig (2003) points out that habitat loss nearly always affects species in a negative way, but fragmentation does not affect all species equally. To help fill the gap in our understanding of how urban land fragmentation impacts urban ecosystems, this study linked fragmentation to biodiversity in the Phoenix metropolitan area, using birds as an indicator of biodiversity. The first phases of my study focused on human intervention, so in the urban-gradient analysis (described in Chapter 3) I grouped land use into only three classes: developed, undeveloped, and cultivated. Different bird species prefer different land-use types, so for the part of my study described in this chapter, I defined fragmentation as urban-habitat fragmentation, and identified seven land types with different "urban habitats." Land fragmentation was assessed and correlated to each bird group. The focus on seven land classes of urban land-type and their relationships with bird biodiversity was also chosen in order to make sure that this research would be relevant to policy and planning decision-making in the region.

Geographic scale is an important factor in determining the level of land fragmentation, because fragmentation metrics are calculated within a specific area. For example, land fragmentation in Figure 6.1 might gradually increase as the study area widening from scale (a) to scale (c). For the purpose of ecological analysis, scales should be selected based on the appropriate scale of habitat for the species. Appropriate scale of habitat depends on a species traits and behavior, such as dispersal, food acquisition, and predator avoidance (Fuhlendorf et al., 2002; Levin, 1992; Wiens et al., 1993). There is no single standard for habitat scale in bird biodiversity research. I explored the effects of urbanization, land composition, and land fragmentation on bird biodiversity using multiple scales from 90 m to 2490 m side length square buffers. Selection of the scales was based on Hostetler and Knowles-Yanez's (2003) study, in which circular buffer areas with a radius of 100 m - 2500 m were applied.

6.2 Research Method

The study area for this research matches that of the Central Arizona-Phoenix Long-Term Ecological Research Project (CAP LTER) in the Phoenix metropolitan area. Bird biodiversity data from the 52 sites surveyed in 2001 by the CAP LTER project were acquired from the project's database. The bird species survey is conducted during all four seasons each year, and three surveys are conducted at each site during each of the four seasons. In the 2001 surveys, a total of 128 bird species are identified, with 86 species found in spring, 70 in summer, 77 in fall, and 88 in winter. Because bird behavior varies according to the season, I selected data from only one season for my biodiversity analysis, spring. In the spring of 2001, 2464 birds of 86 species were observed at 51 sites (one riparian site, PN-2A, was not monitored). I filtered the bird data by using the maximum bird count among three surveys. To improve robustness of the analysis, I excluded birds that were counted more than 40 m away from the survey location, as well as birds that only “flew through” the site.

Twenty-three of the survey sites were on land classified as urban, twenty-one sites were desert, and seven sites were cultivated. Site classification was based on the proportion of land cover in the buffer area of each site (based on the predominant land class that covered the highest percentage of land); I also recorded the CAP LTER land-use code as a reference. Land cover was classified as developed, undeveloped, or cultivated based on the National Land Cover Dataset (NLCD) 2001 data. Because scale of the buffer area might have an influence on the identification of the type of sites, I tested land proportion within the buffer zone from 690 m to 1890 m. The percentage of landscape within multiple buffer zones did not change much, and did not affect site classification. Figure 6.2 shows the proportion of land cover at each site location, using 690 m buffer zones around the sites as an example. Each type of site also includes one to six riparian sites. CAP LTER listed 11 riparian sites, while in this research, Y-19 was also listed as riparian site based on NLCD land-cover data; thus, there are 12 riparian sites. Land cover identified by CAP LTER and site type identified by this research for each site is shown in Support Information Table I. Among the 39 non-riparian survey sites, 18 were urban, 15 were desert, and 6 were cultivated (Fig. 6.3). Land cover was grouped into seven classes based on the NLCD 2001 data: (1) open space, (2) low intensity, (3) medium intensity, (4) high intensity, (5) desert, (6) water, and (7) cultivated. A suite of land-fragmentation metrics were selected and calculated to reflect the fragmentation level using land patch, edge, shape, and connection. Although land fragmentation was computed based on seven land classes, I also looked at the edges between developed, undeveloped, and cultivated land by using Contrast Weighed Edge Density (CWED). Fig. 6.4 shows the differences of “Contrast Weighed Edge” based on selected land types and “Edge” based on all land types. “Developed land” is the sum of classes (1) through (4). “Undeveloped land” is the sum of class (5) and (6). The weight between “Developed” and “Undeveloped” was set as “1,” and the weight between “Cultivated” and the other two types was set as “0.5”. Biodiversity indices were abundance, richness, and evenness.

Five scales of buffering area were selected based on the scales used in Hostetler and Knowles-Yanez (2003). I tested the relationships among land composition, fragmentation, and bird biodiversity at five scales of buffering area, from 90 m to 2490 m, using side-length square areas. Pearson correlation and multiple regressions were conducted to build models of bird biodiversity based on land composition and fragmentation at these scales.

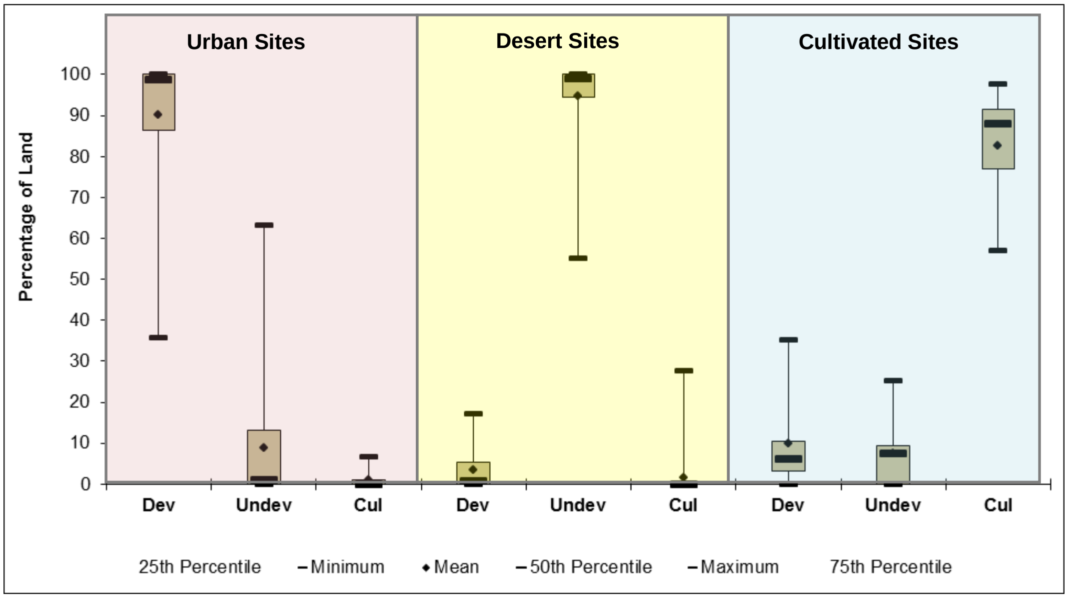


Fig. 6.2 Proportion of land cover in each site using 690 m buffer zones around bird monitoring sites

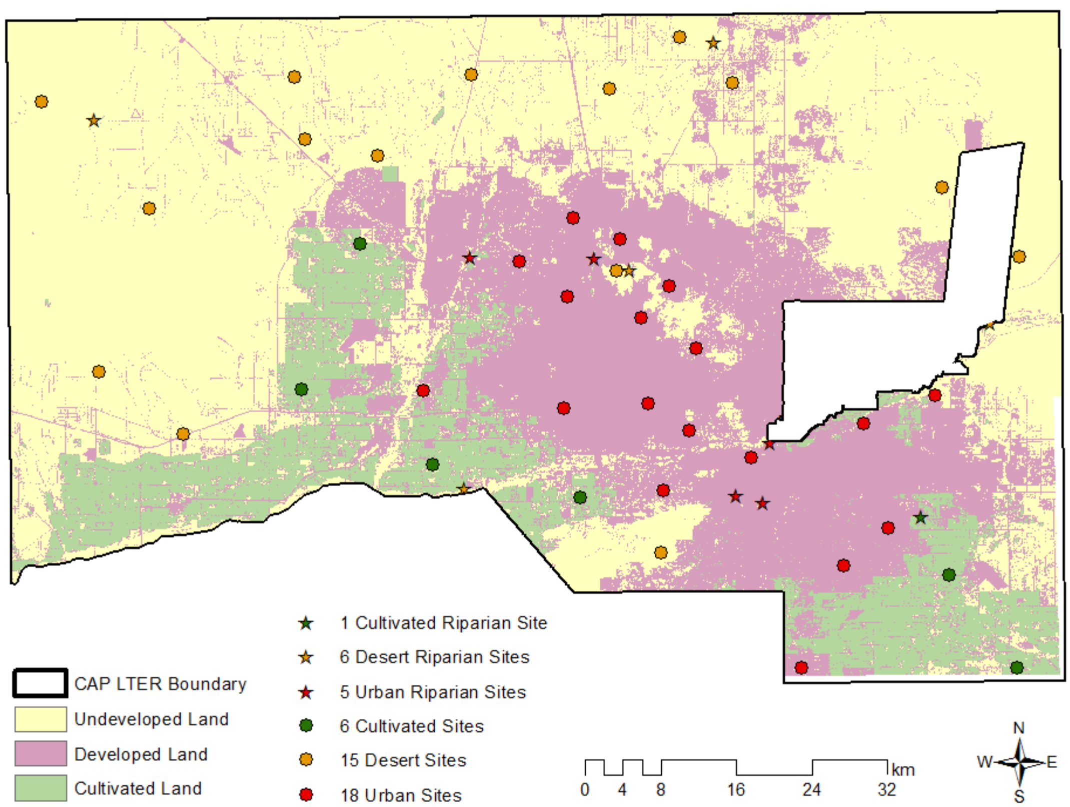


Fig. 6.3 Map of CAP LTER study area and the distribution of 51 bird-survey sites

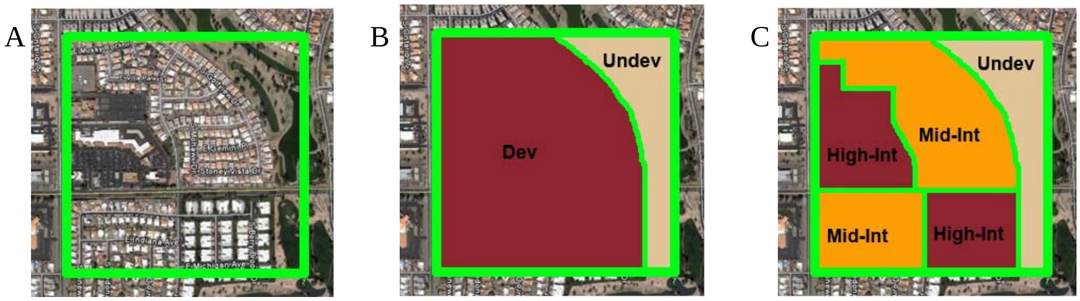


Fig. 6.4 A. 690 m buffer zone of site Z-23, with B. Contrast Weighed Edge, and C. Edge

NLCD 2001 has 16 land classes. Because the purpose of this study was to examine effects of urbanization and land composition on bird biodiversity, I did not consider desert-habitat fragmentation caused by natural factors such as shrub land or grassland. I used three land classes, developed, undeveloped, and cultivated, for the analysis. In this land-classification scheme, shrub land, barren land, grassland, and forest were all part of the category of undeveloped land. When taking a closer look at how different land type influences each species of bird, I further divided land classes to seven categories that included developed land at various levels of intensity. The "open space" category included areas "with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most comm. only include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes" (citation missing). Low Intensity includes areas "with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units." Medium Intensity includes areas "with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units." High Intensity includes "highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover." Water includes open water, woody wetlands, and herbaceous wetlands, which means all areas of open water, or the soil or substrate is periodically saturated or covered with water. Undeveloped land includes a majority of shrub/scrub, barren land (Rock/Sand/Clay), with a small proportion of forest, grassland/herbaceous, and pasture/hay. Cultivated Crops includes areas where land used for the production of annual crops accounts for greater than 20 percent of total vegetation (Homer et al., 2004).

6.3 Results

6.3.1 Urbanization and land fragmentation

Urbanization level can be measured by the proportion of developed land. Urbanization disturbs natural habitat and causes habitat loss and habitat fragmentation. As such disturbance increases, more developed areas are connected and land heterogeneity is reduced. Fig. 6.5 shows the non-linear relationship between percentage of developed land and land fragmentation in my analyis of 39 non-riparian sites at scales of 90 m to 2490 m. Along the desert-urban gradient fragmentation first rises, then falls as urban areas become contiguous. Fig. 6.5 also compares the difference in land-fragmentation levels using Edge Density (ED) and CWED. In Fig. 6.5A, edge density was measured by contrast edges among three major land classes, developed, undeveloped, and cultivated land. CWED increased with the increase of percentage of developed land.

As the proportion of developed land increases and more developed land patches are connected to form a bigger patch, CWED starts to decrease. When the developed area reaches 100%, CWED drops to zero as no contrast edges occur. This finding supports Lambin's (1999) hypothesis that with the increase of landscape disturbance, spatial heterogeneity will rise and then fall. But, as I discussed above, conclusions about fragmentation levels depends on how land is classification and how fragmentation (or heterogeneity) is defined. Fig. 6.5 B shows that when I measured edge density among all seven land classes (and thus in 100% of the developed portion of the study area), edge density remained high because of mixed developed land with various intensities. The comparison of the two figures reflects the effect of land classification on fragmentation evaluation. Fig. 6.5A indicates that the most highly fragmented areas are located at urban-rural fringes, while Fig. 6.5B indicates the most highly fragmented areas are in the fully developed urban cores. This disparity is consistent with what other researchers have found (Schneider & Woodcock, 2008; Buyantuyev et al., 2010).

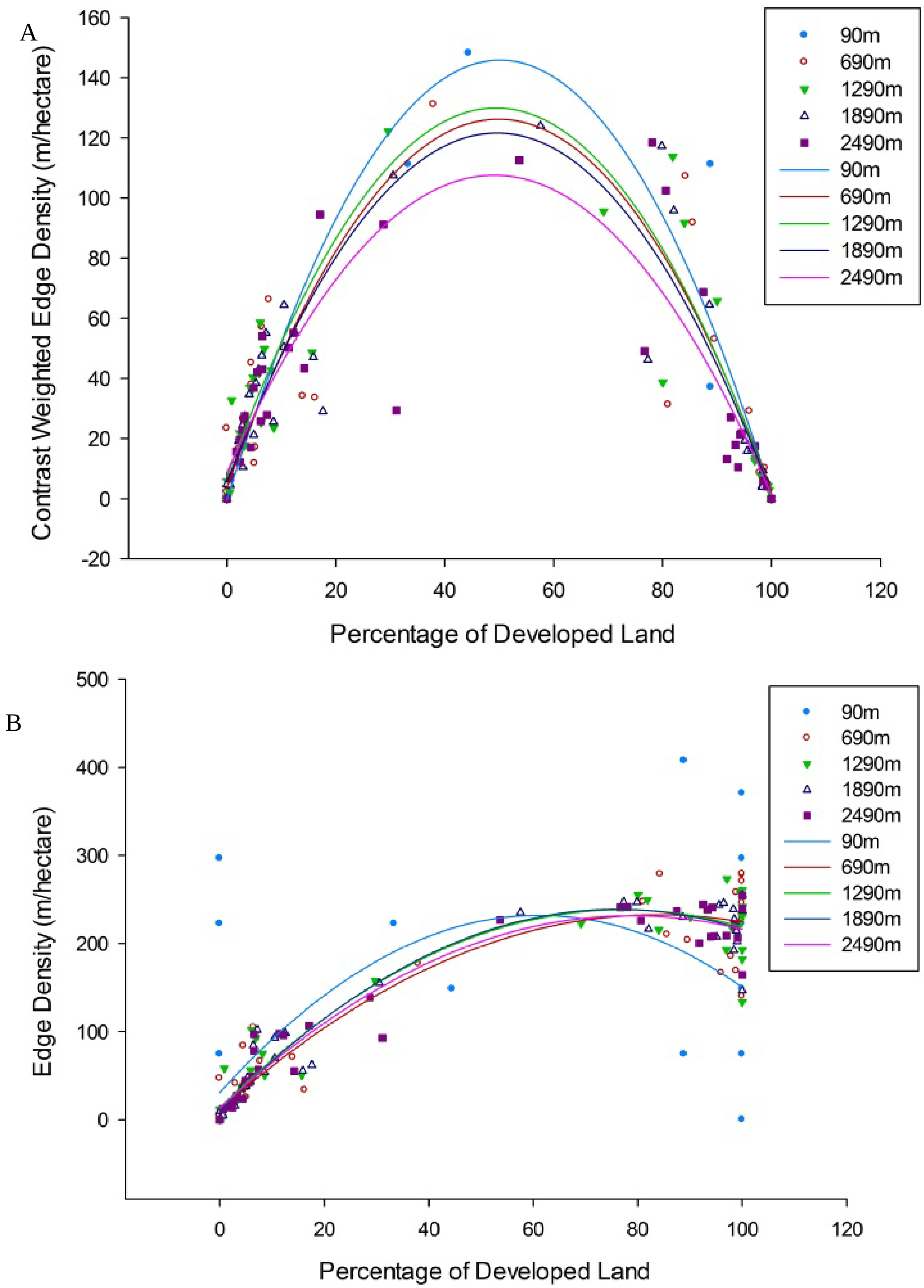
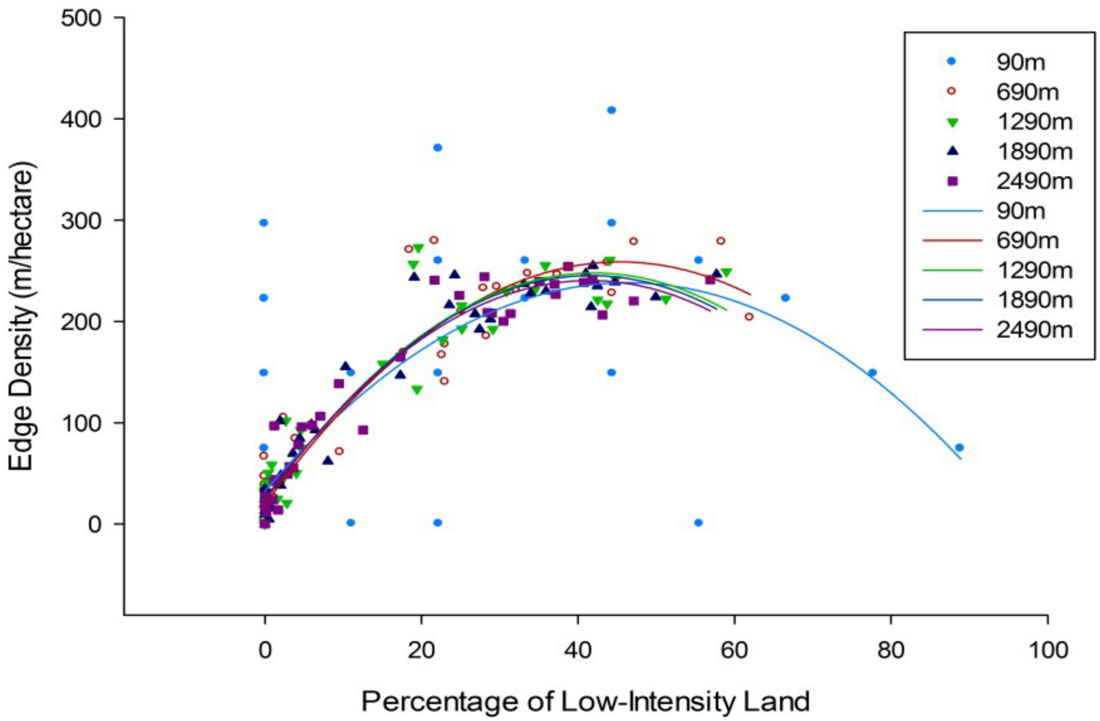


Fig. 6.5 Proportion of developed land and fragmentation level using A. ED, and B. CWED

6.3.2 Land composition and fragmentation

To determine which land class contributes the most to land fragmentation, I correlated each land class with land fragmentation. Results indicated that land fragmentation is strongly correlated with low-intensity land and desert. Fig. 6.6 uses edge density (ED) as an example of fragmentation to show the relationship. Land fragmentation keeps increasing with the increase of low-intensity land, until the proportion of this type of land exceeds about 50%. Thereafter, fragmentation starts to drop as low-intensity areas become connected. Five scales of buffer areas were tested. As the scale increased, the correlation became more apparent; i.e., scales of 1290 m and 1890 m revealed the correlation better than smaller scales. This finding supports Irwin and Bockstael's (2007) finding that the sprawl of low-density residential areas creates an urban form of land fragmentation. However, in my study, percentage of low-intensity land was strongly correlated with land-fragmentation metrics, as represented by ED. My results indicate that as ED increases, the landscape tends to be more heterogeneous, but it not clear whether heterogeneity is caused by the mix of low-intensity land use and undeveloped desert, or by the mix of developed land with different intensity levels. This uncertainty is relevant, because when linking land fragmentation with bird biodiversity, it is important to understand whether highly fragmented land refers to fragmentation of desert habitat or to urban habitat with mixed levels of intensity. Because of this uncertainty, I further tested the relationship between the percentage of low-intensity land and CWED. I found no obvious correlation, so I inferred that the increased land fragmentation with low-intensity land is mainly represented by a mix-land use of developed land. I also found a strong negative correlation between fragmentation and desert land. When the percentage of desert equals zero, fragmentation can be based on the configuration of other land types. When the percentage of desert land cover reaches 100%, fragmentation drops to zero, which indicates an undisturbed desert habitat.



90m	$y = -0.096x^2 + 8.8824x + 32.718$	$R^2 = 0.4454$
690m	$y = -0.1163x^2 + 10.548x + 19.582$	$R^2 = 0.9063$
1290m	$y = -0.1272x^2 + 10.691x + 23.283$	$R^2 = 0.9171$
1890m	$y = -0.1281x^2 + 10.667x + 23.208$	$R^2 = 0.9426$
2490m	$y = -0.1255x^2 + 10.401x + 24.928$	$R^2 = 0.9469$

Fig. 6.6 Relationship between low-intensity land and fragmentation

6.3.3 Urbanization and bird diversity

In the preceding sections of this chapter, I have discussed the relationships I found among urbanization, land composition, and fragmentation, as well as what urban forms are most responsible for fragmentation. This information could be useful to decision-makers when fragmentation is a policy concern. The remainder of this chapter explores the relationship among urbanization, land composition, fragmentation, and birds. This section discusses bird distribution in urban environments on three types of sites: urban, desert, and agricultural.

I calculated the average number of birds per site using the sum of the number of birds at each site dived by the total number of sites of a particular type. Species richness is the average number of species per site type, calculated by dividing the sum of species numbers in each site by the total number of sites of that type. Species richness excludes the overlapping species – same species in more than one site of a particular type. Total species numbers are the "accumulated" sum of species numbers observed at a particular type of site, that is, the species that repeatedly appear in different sites were only counted once. For example, if sites X and Y had two and four bird species respectively, and one of those species was observed at both sites, then the species richness was calculated to be three species per site, and the total species number was five. The Simpson diversity, Shannon diversity, and species evenness indices were computed for each site using PAST software (Hammer et al., 2001).

Figures 6.7A and B show how bird abundance and diversity were influenced by land-use type and land fragmentation at the 1890 m buffer scale. Fig. 6.7A shows that the higher the land fragmentation, represented by the lower contagion values, the lower the bird biodiversity, represented by bird evenness at the sites. But the average number of birds per site is positively associated with land-fragmentation level. Figure 6.7B shows that although there was plenty of scatter, low-intensity land cover was positively related to bird numbers and negatively related to bird biodiversity.

A

B

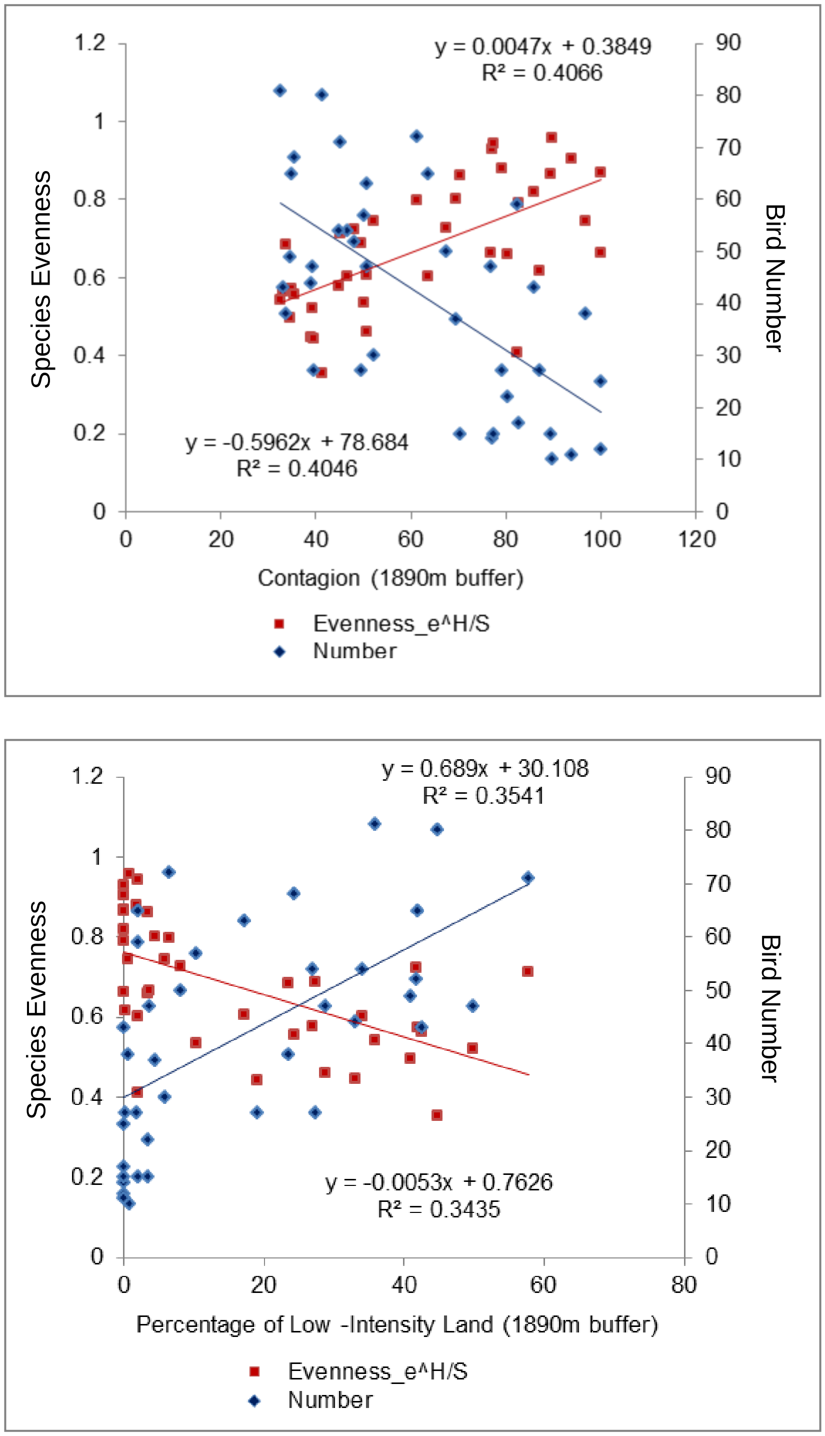


Fig. 6.7 Low-intensity land, fragmentation, and bird abundance and evenness

I compared bird distribution at the three types of survey sites (see Fig. 6.8). The numbers in the parentheses in Fig. 6.8 are the number of sites. Focusing on the three types of sites revealed a striking contrast between abundance and species richness. Agricultural sites had the highest bird abundance, but the total number of species and the average species per site was the lowest among the three site types. Agricultural land is a favored habitat for certain kinds of birds. Desert sites have the lowest bird abundance but the highest number of total species and the highest average number of species per site. Fig. 6.8C compares the biodiversity indices among the three sites. Results of this comparison further verified that desert is associated with the highest bird biodiversity. Urbanization somehow increases the bird abundance, but only for partial species, as indicated by the lower biodiversity at urban sites. Figures 6.8B and 6.8D show how bird distribution at riparian sites compared to that at non-riparian sites. If we exclude riparian sites from the larger category of desert sites, species richness and average species numbers per desert site dropped lower than those of urban sites (Fig. 6.8B), but desert biodiversity remained the highest among the three categories of non-riparian sites (Fig. 6.8D). Desert sites not only had a higher average-biodiversity value than urban sites, but also a lower standard deviation (STDEV). Fig. 6.8D shows that average Simpson diversity at desert sites was 0.84, with a STDEV value of 0.025, while at urban sites, average Simpson diversity was 0.75, with an STDEV of 0.069. This indicates that the biodiversity levels at urban sites had a larger range than at desert sites. Desert riparian sites play a critical role in increasing the number of species at desert sites. Agriculture riparian sites had the largest number of birds, but the lowest number of species and diversity. Therefore, it can be inferred that agricultural sites, especially riparian sites, provide preferred habitat to a limited number of bird species, but an abundance of individual birds of those species. Desert was found to be a preferred habitat for native birds, and desert riparian cover provided an attractive shelter for most birds. These findings are consistent with the statement in Nancy et al. (2008) that "urbanization and suburbanization usually reduce both species richness and evenness for most biotic communities, despite increases in abundance and biomass of birds." Shochat et al. (2010) made similar findings.

I found that of a total of 86 species counted at all sites, 68 were found in riparian sites. Among these 68, 29 were observed only at riparian sites, and 39 species were found at both riparian and non-riparian sites. Only 18 bird species were never observed at riparian sites. Among these 18 species, 5 were observed to inhabit only desert sites. The remaining 13 species were all observed at agricultural or urban sites; 6 species appeared only at agriculture sites, 2 appeared only at urban sites 3 appeared at both desert and urban sites, 1 at both desert and agricultural sites, and 1 at both urban and agricultural sites. Among the 86 species, only 3 are exotic species: the European Starling is identified as an urban bird, and the European Starling and Rock Dove are identified as adaptable birds. The other 83 species are all native birds. This finding suggests that in an arid landscape, urbanization improves bird habitat in some ways, perhaps owing to extra food and water sources that encourage native birds to shift to urban areas. Although arid urban areas may have an abundance of birds, the species present at urban sites can be quite different from those at desert sites. Therefore, it is necessary to understand how each species is affected by urbanization. To do that, I counted the relative density of each bird species in three site types and grouped birds into three categories based on their distribution among the site categories.

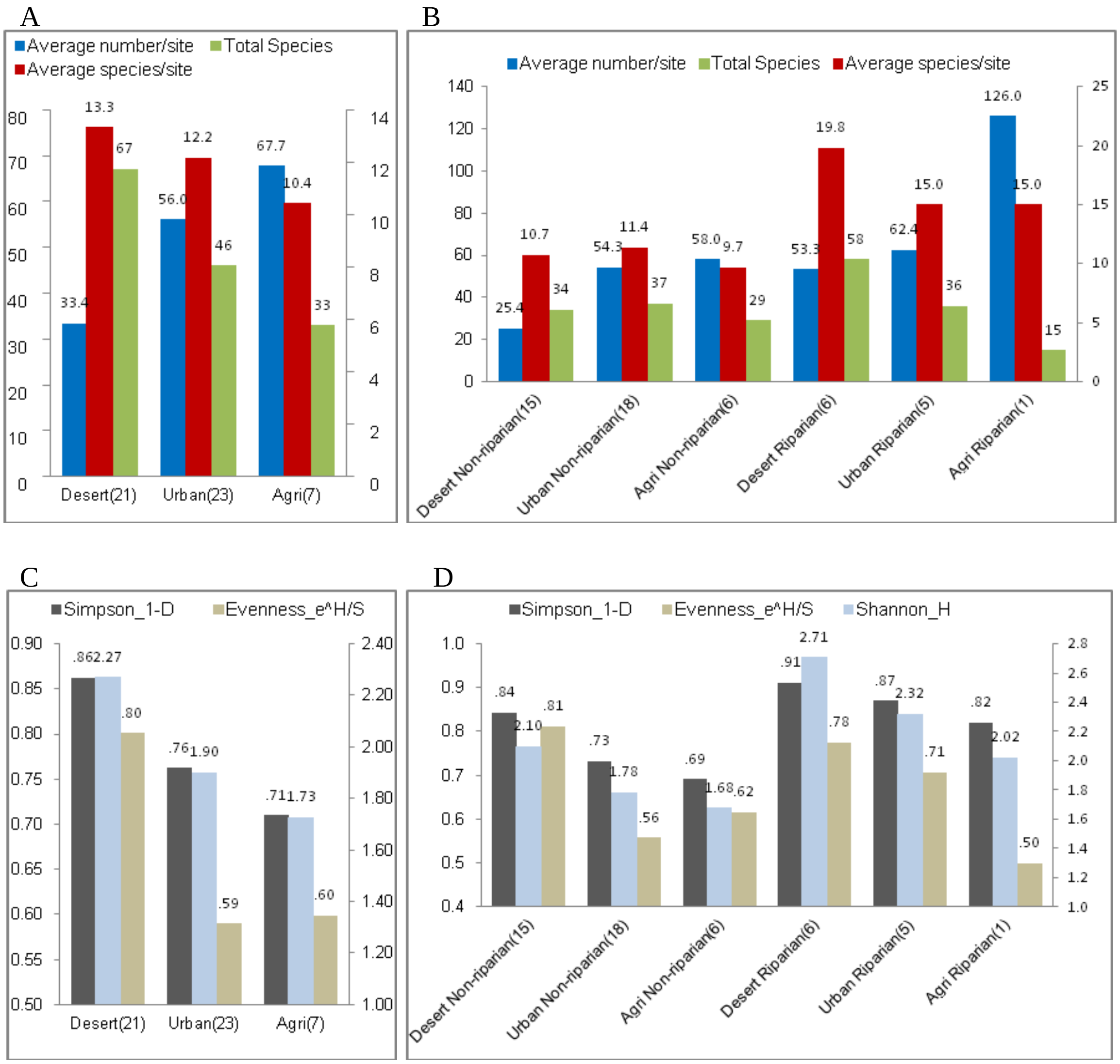


Fig. 6.8 Site location and bird biodiversity

(Numbers in parentheses are the number of sites)

6.3.4 Three group of birds based on density

The study results described above indicate that urbanization increases bird abundance but decreases biodiversity. Zooming in further to the level of individual bird distribution, I found that each species' behavior and response to urbanization was different. Some species avoid urban areas, while some are able to adapt to urban areas. I analyzed the distribution of each bird species to find out how each species is affected by urbanization, and how to create bird-friendly urban conditions.

Because birds were counted by different birders, to enhance accuracy I excluded from this part of the study the species that were observed at only one site. Given the extraordinary effect of riparian habitat on bird biodiversity (Fig. 6.8), I also filtered the data and limited the sites to the 39 non-riparian sites in order to avoid bias when analyzing the influences of urban land-fragmentation on birds. The 39 sites were comprised of 18 urban, 15 desert, and 6 agricultural sites. I then selected 39 bird species for further analysis. Among the 39 species, there is one species that only appears in urban sites, one species that only appears in cultivated sites, and six that only appear in desert sites. Two are in both cultivated and desert. Nine are in both urban and cultivated and eight in both urban and desert sites. The rest twelve are found in all three sites. Fig. 6.9 displays the distribution of species on the three site types. Each species was categorized as an urban exploiter, a suburban adapter, or an urban avoider based on Blair (1996). Because the total numbers of sites for each type were unequal, I compared relative density of each bird species among the three site types. Relative density was calculated as the average number of individuals of a species found at each type site. Birds were classified based on relative density, followed by manually justification. The three groups were defined as follows:

- Urban bird: the density of the species at urban sites far exceeds (by more than two times) the density at desert and agricultural sites.

-Desert bird: the density of the species at desert sites far exceeds (by more than two times) the density at urban and agricultural sites.

-Adaptable bird: the species shows no obvious preference for urban or desert areas.

Greater Roadrunner, Brewers Sparrow, and Loggerhead Shrike were adjusted from “suburban adaptable” to “urban avoiders,” though all are common around agricultural fields. Rock Dove was adjusted from “suburban adaptable” to “urban exploiter” because, though the species is abundant in agricultural fields, it also appears abundantly in impervious-surfaced landscapes. Brown-headed Cowbird and Northern Mockingbird was adjusted from “urban exploiters” to “suburban adaptable.”

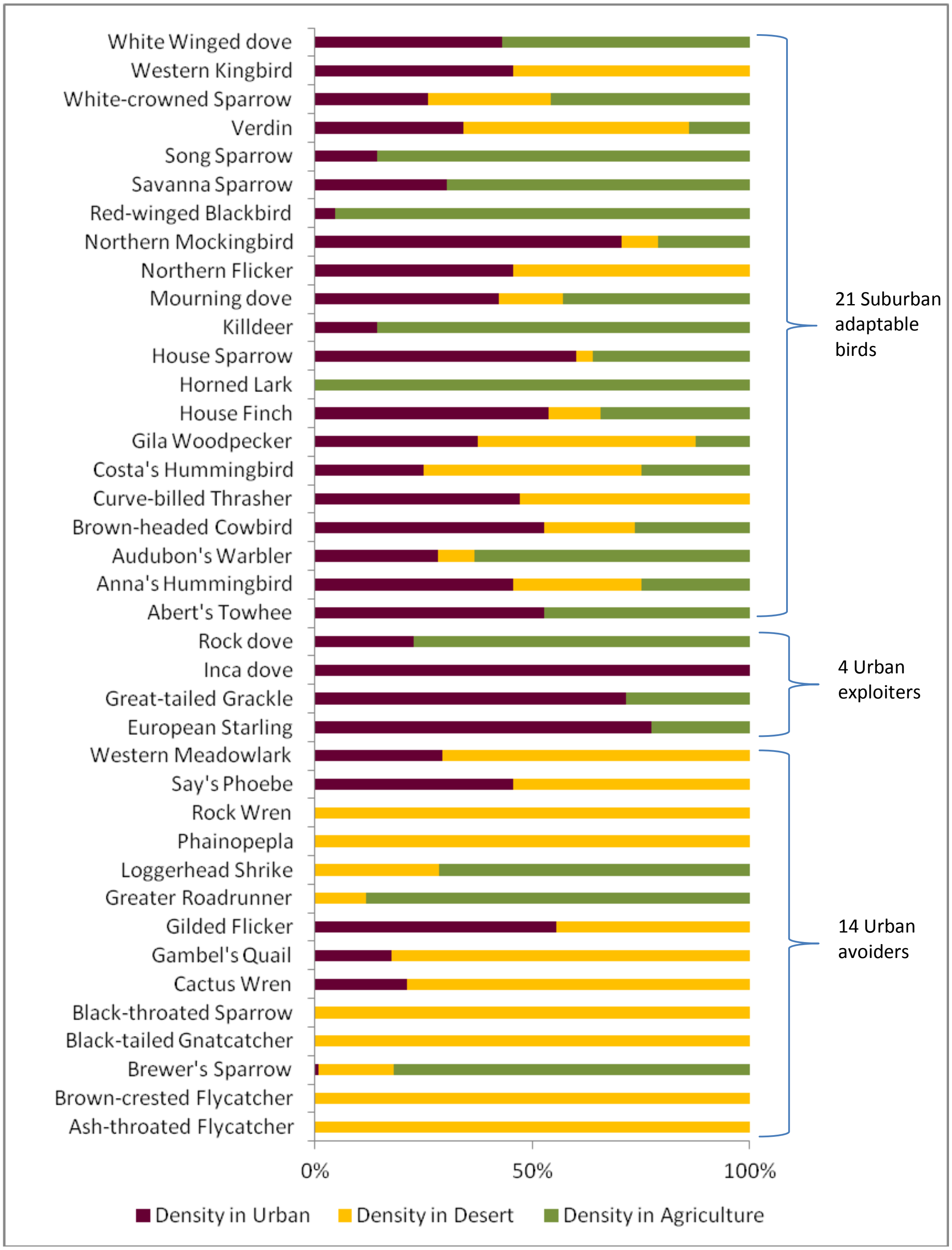


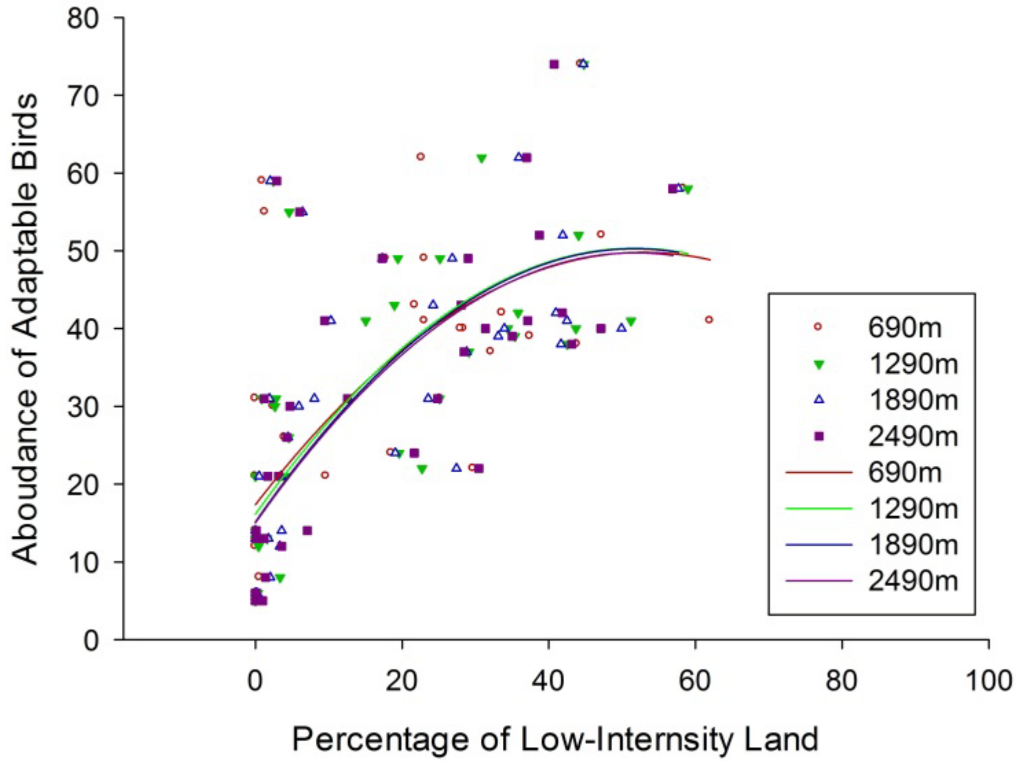
Fig. 6.9 Three bird categories based on distribution

6.3.5 Effects of land composition and fragmentation on each group of birds

In this section, I discuss each group of birds and their relationships with land composition and fragmentation. I looked at these relationships at four scales, 690 m, 1290 m, 1890 m, and 2490 m, (because analyses conducted earlier in the study indicated that 90 m is too small to identify land configuration in the habitat).

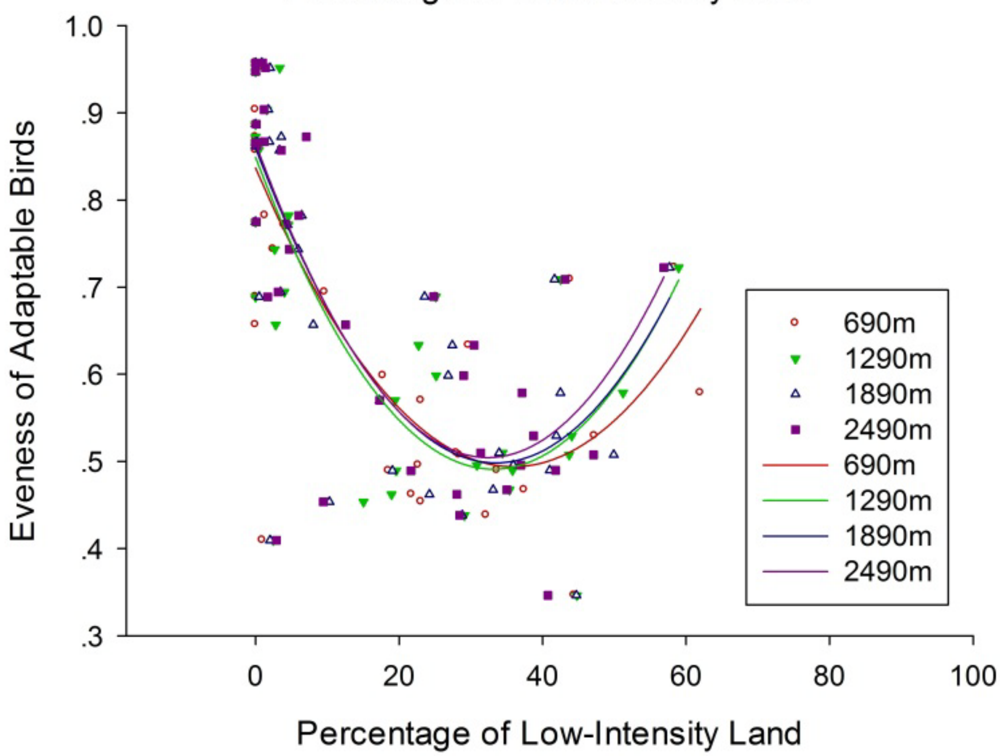
Suburban-adaptable birds are the largest group of birds (Fig. 6.9). This group contributes most to biodiversity in urban areas. Therefore, it is important to explore these species' preferences for land composition and configuration in an urban habitat. Fig. 6.10 displays the relationships among low-intensity and fragmented land and abundance and biodiversity of adaptable birds. Figures 6.10A and C show that abundance was positively correlated with percentage of low-intensity area and land-fragmentation level (i.e., contagion index). Figures 6.10B and D show that diversity (i.e., evenness index) was negatively correlated with percentage of low-intensity area and land fragmentation.

A



Aboudance of Adaptable Birds
Percentage of Low-Internsity Land
690m
1290m
1890m
2490m
690m
1290m
1890m
2490m

B



Eveness of Adaptable Birds
Percentage of Low-Intensity Land
690m
1290m
1890m
2490m
690m
1290m
1890m
2490m

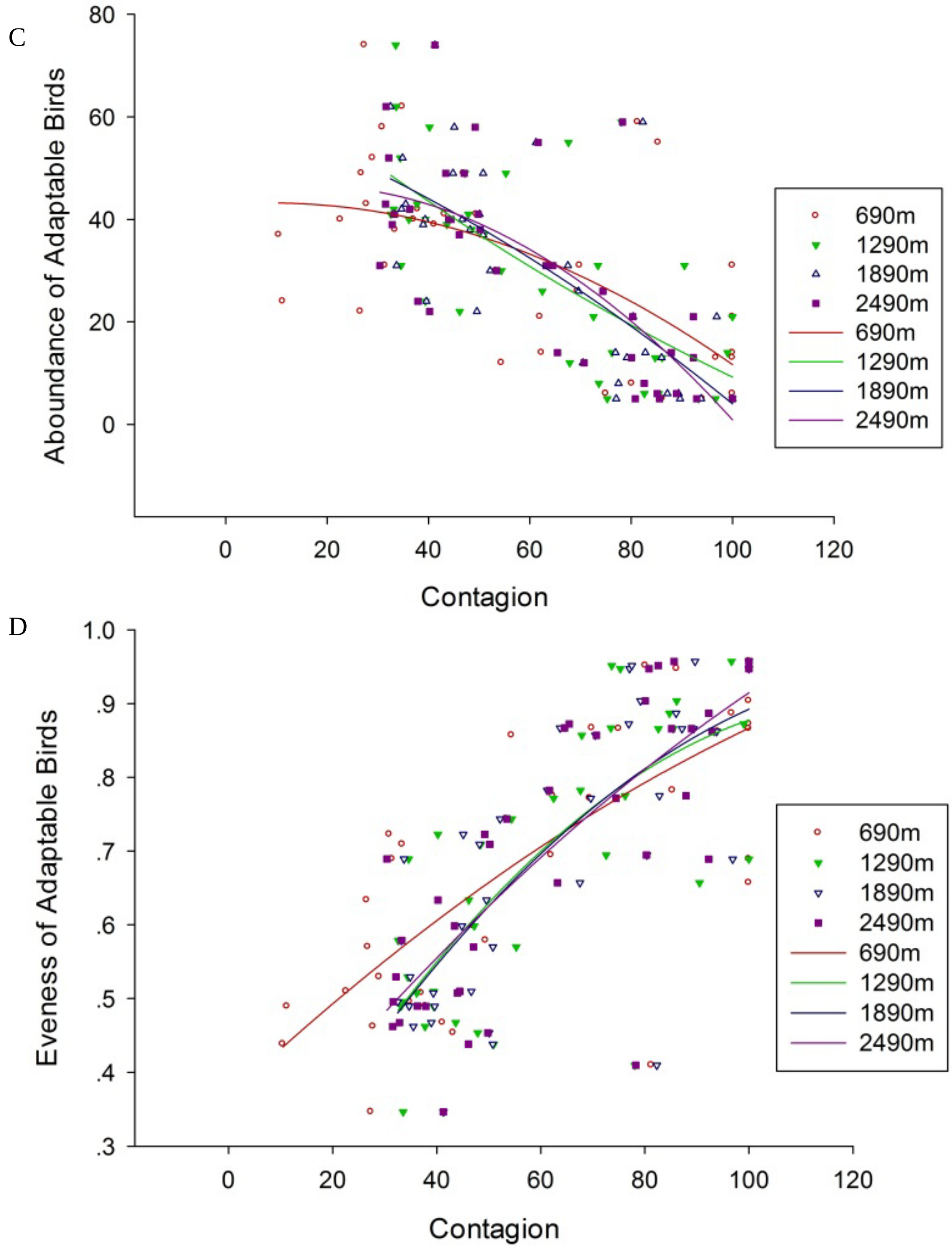


Fig. 6.10 Relationships among low-intensity and fragmented land and abundance and biodiversity of adaptable birds

Table 6.1 shows the correlations among percentage of land cover, bird abundance, species richness, and diversity (Simpson diversity index, Shannon diversity index, and

Shannon evenness index). Correlations between land composition and birds, and correlations between land fragmentation and birds were examined. Findings indicated that low-intensity and highly fragmented urban sites correlate with high biodiversity of urban-exploiter bird species. Urban avoiders showed strong sensitivity to fragmentation (Table 6.2). The species that are most sensitive to fragmentation include Black-throated Sparrow, Black-tailed Gnatcatcher, and Ash-throated Flycatcher. Black-throated Sparrow is a common species, and despite its relative abundance, all 51 Black-throated Sparrows observed were found at 11 desert sites, and none were recorded at urban or agricultural sites. Similarly, 28 Black-tailed Gnatcatchers were observed at 14 desert sites, and 12 Ash-throated Flycatchers were observed at 9 desert sites.

Table 6.1 Pearson correlation between land composition, abundance and biodiversity of three group of birds, based on 1890 m buffer zones

	PerOpen	PerLow	PerMid	PerHigh	PerDesert	PerCulti	PerWater
Num Avoiders	-0.330	-0.555 **	-0.555 **	-0.321	0.485 **	0.292	-0.210
Spe Avoiders	-0.371 *	-0.624 **	-0.632 **	-0.405 *	0.773 **	-0.162	-0.156
Sim Avoiders	-0.566 **	-0.688 **	-0.649 **	-0.478 *	0.897 **	-0.329	-0.256
Sha Avoiders	-0.541 **	-0.685 **	-0.637 **	-0.458 *	0.869 **	-0.301	-0.232
Eve Avoiders	0.366	0.377	0.412 *	0.310	-0.334	-0.242	0.214
Num Exploiters	0.181	0.343	0.471 *	0.178	-0.500 *	-0.160	-0.224
Spe Exploiters	0.213	0.382	0.605 **	0.442 *	-0.673 **	-0.184	-0.207
Sim Exploiters	0.106	0.039	0.420	0.429 *	-0.425 *	-0.273	-0.241
Sha Exploiters	0.095	0.066	0.462*	0.445*	-0.423	-0.317	-0.251
Eve Exploiters	-0.212	-0.303	-0.122	0.071	0.052	0.287	0.129
Num Adaptable	0.280	0.715 **	0.515 **	0.143	-0.788 **	0.187	0.108
Spe Adaptable	0.223	0.469 **	0.238	-0.001	-0.402 *	0.040	-0.015
Sim Adaptable	0.121	-0.229	-0.465 **	-0.448 **	0.366 *	0.007	0.029
Sha Adaptable	0.169	-0.012	-0.277	-0.313	0.101	0.075	0.013
Eve Adaptable	-0.170	-0.671**	-0.700 **	-0.426 **	0.757 **	-0.008	-0.065

**Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Table 6.2 Pearson correlation between land fragmentation, abundance and biodiversity of three groups of birds, based on 1890 m buffer zones

	PD	ED	LPI	CONTAG	COHESION
Num Avoiders	-0.528 **	-0.548 **	0.514 **	0.519 **	0.439 *
Spe Avoiders	-0.699 **	-0.721 **	0.671 **	0.710 **	0.602 **
Sim Avoiders	-0.775 **	-0.785 **	0.710 **	0.764 **	0.674 **
Sha Avoiders	-0.755 **	-0.771 **	0.709 **	0.749 **	0.662 **
Eve Avoiders	0.359	0.374	-0.361	-0.413 *	-0.356
Num Exploiters	0.497 *	0.471 *	-0.239	-0.481 *	-0.116
Spe Exploiters	0.591 **	0.597 **	-0.357	-0.585 **	-0.292
Sim Exploiters	0.269	0.277	0.045	-0.240	-0.042
Sha Exploiters	0.290	0.300	0.038	-0.257	-0.026
Eve Exploiters	-0.305	-0.289	-0.015	0.288	-0.090
Num Adaptable	0.727 **	0.735 **	-0.685 **	-0.743 **	-0.595 **
Spe Adaptable	0.476 **	0.482 **	-0.492 **	-0.541**	-0.415 **
Sim Adaptable	-0.271	-0.285	0.205	0.190	0.220
Sha Adaptable	-0.037	-0.040	-0.027	-0.061	0.009
Eve Adaptable	-0.758 **	-0.768 **	0.691 **	0.745 **	0.632 **

PD = Patch Density, ED = Edge Density, LPI = Landscape Shape Index, CONTG = Contagion, and CPHESION = Cohesion Index.
**Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

The correlations shown in the two tables above indicate that land fragmentation caused by urbanization increases bird abundance, but reduces overall bird biodiversity. To examine to what extent land fragmentation affects specific bird groups, I divided land fragmentation values into high, middle, and low levels, and checked the characteristics of each bird group at each fragmentation level. Fig. 6.11 uses Patch Density (PD) to compare distribution of the three bird groups. PD values at the 39 sites were grouped into three ranges based on even intervals indicating three land-fragmentation levels. The abundance, species richness, and species Shannon diversity of each group of bird in each level of fragmentation is illustrated in Fig. 6.11. As shown in Figures 6.11A and B, the abundance (Num) and species richness (SR) of suburban-adaptable birds and urban exploiters was highest at the highly fragmented sites. Urban avoiders were most abundant at sites with middle fragmentation level (A), and urban avoiders were most abundant at sites with low fragmentation levels. Figure 6.11C shows that the Shannon diversity (SH) of urban avoiders is where land fragmentation is low, and the biodiversity of urban exploiters is highest on land that is highly fragmented. Biodiversity of suburban exploiters is highest on land with mid-level fragmentation. The same findings were found using CONTAG and other land-fragmentation metrics. Therefore, I concluded that urban-avoider birds are sensitive to land fragmentation, while adaptable birds and urban exploiters prefer fragmented land. As shown in Fig. 6.11C, the SH diversity index of adaptable birds is similar on land at all three fragmentation levels: 1.3 at low fragmentation, 1.6 at mid-level fragmentation, and 1.4 on highly fragmented land.

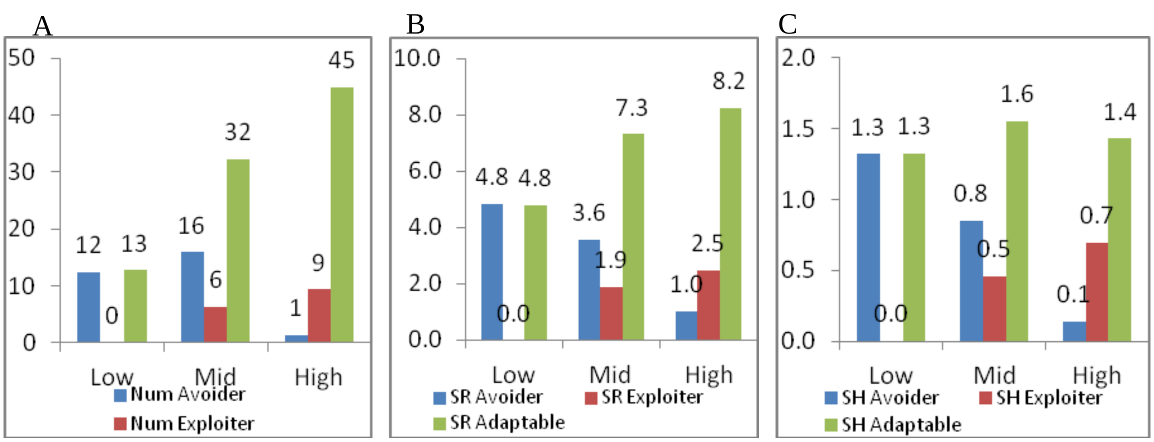


Fig. 6.11 Level of patch density and distribution of each bird group

6.4 Conclusion

Urbanization and fragmentation in the greater Phoenix region have a non-linear relationship with one another. As percentage of developed area increases, fragmentation first rises and then falls. Low-intensity development is a key driver of land fragmentation. The overall bird species richness and diversity, which is illustrated by Simpson, Shannon, and evenness indices, is highest in the desert. Agricultural land has the highest bird abundance but the lowest species richness and diversity. Riparian sites contribute to the bird diversity for all three types of sites. Taking riparian sites out, the total number of species and average number of species per site is highest in urban non-riparian areas, but the diversity is still highest in desert non-riparian locations. These findings indicate that landscape fragmentation in urban areas has a negative impact on biodiversity. Similar findings have been demonstrated by ecologists

Landscape fragmentation benefits certain groups of birds. Urban exploiters, urban adaptors, and urban avoiders have different preferences for land types and different sensitivities to land fragmentation. Urban adapters make up the largest group of birds. While their abundance is positively correlated with percentage of low-intensity area and land fragmentation level i.e., contagion index), their diversity (i.e., evenness index) is negatively correlated with percentage of low-intensity area and land fragmentation. The abundance and species richness of urban avoiders are negatively correlated with all four types of developed area and with land-fragmentation level. Urbanization results in loss of and damage to their habitat, and reduces their populations.

Cities with a higher percentage of low-density land and high fragmentation have a higher abundance of suburban-adaptable and urban–exploiter birds. This finding suggests that mixed land-use at high, low, or medium intensity, and agricultural land are preferred by those species over homogeneous urban patterns and desert land. The land class "low-intensity" is itself a mixed land-type combining 50-80% vegetation and 20-49%

impervious surfaces. Mixed-land sites permit interactions of human beings and birds, and serve as co-habitats for human beings and birds. Low-intensity mixed land-uses may provide more vegetation cover, less people, less noise and transportation than fully developed urban core areas; they may also provide more food and water sources and vegetation than remote desert. The “luxury effect” on plant diversity in the neighborhoods of the Phoenix metropolitan area (Faeth et al., 2011) might also contribute to desirable bird habitat. Through multi-scale spatial analysis, this study compares the geographic scope effect and found that larger scales around 1890 m and 2490 m have a more effective illustration on the relationship between land configuration and birds. This research reveals that urbanization and urban land-fragmentation help urban-exploiter and suburban-adaptable birds, but at the expense of urban-avoider birds. In terms of overall bird abundance and biodiversity, urban areas have higher bird numbers and slightly lower biodiversity. A key question is what biodiversity means in a social and economic context, and what the priorities are when urban planners and policy makers consider urban development. To developers and local residents, the overall bird number and biodiversity, which is related to quality of life, ecosystem services, and land or property values (Farmer et al., 2011), might be priorities. To ecologists, wildlife managers, and conservation biologists, the protection of imperiled species might be more relevant. Most birds on the Birds of Conservation Concern list are urban avoiders such as the Loggerhead Shrike, Gilded Flicker, and Brewer's Sparrow, and several species are suburban-adaptable birds such as the Gila Woodpecker and Costa's Hummingbird (U.S. Fish and Wildlife Service, 2008).

This study used birds as in indicator to investigate the influences of land fragmentation and urbanization on urban biodiversity. A proportion of birds can adapt to urban conditions, probably because their ability to fly makes them less sensitive to land fragmentation. Other animals, such as reptiles, arthropods, and mammals, cannot easily cross areas of human disturbance, such as canals and freeways, and are likely to be more vulnerable to land fragmentation than birds. To understand the relationship of land fragmentation to ecological-friendly, sustainable urban form, researchers need to use more species as indicators of biodiversity and abundance in studies of interactions among ecological and social indictors in complex urban ecosystems. Conservation managers should consider species diversity and abundance in their efforts to balance ecological, social, and economic values. The results of this study provide information that may be helpful in linking planning for and policies on urban form with protection of bird biodiversity.

Appendix: Supplementary Information

A. Coordinate System

Projected Coordinate System:NAD_1983_StatePlane_Arizona_Central_FIPS_0202
Projection: Transverse_Mercator
False_Easting: 213360.00000000
False_Northing: 0.00000000
Central_Meridian: -111.91666667
Scale_Factor: 0.99990000
Latitude_Of_Origin: 31.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_North_American_1983
Datum: D_North_American_1983
Prime Meridian: Greenwich
Angular Unit: Degree

B. The scheme of three types of sites

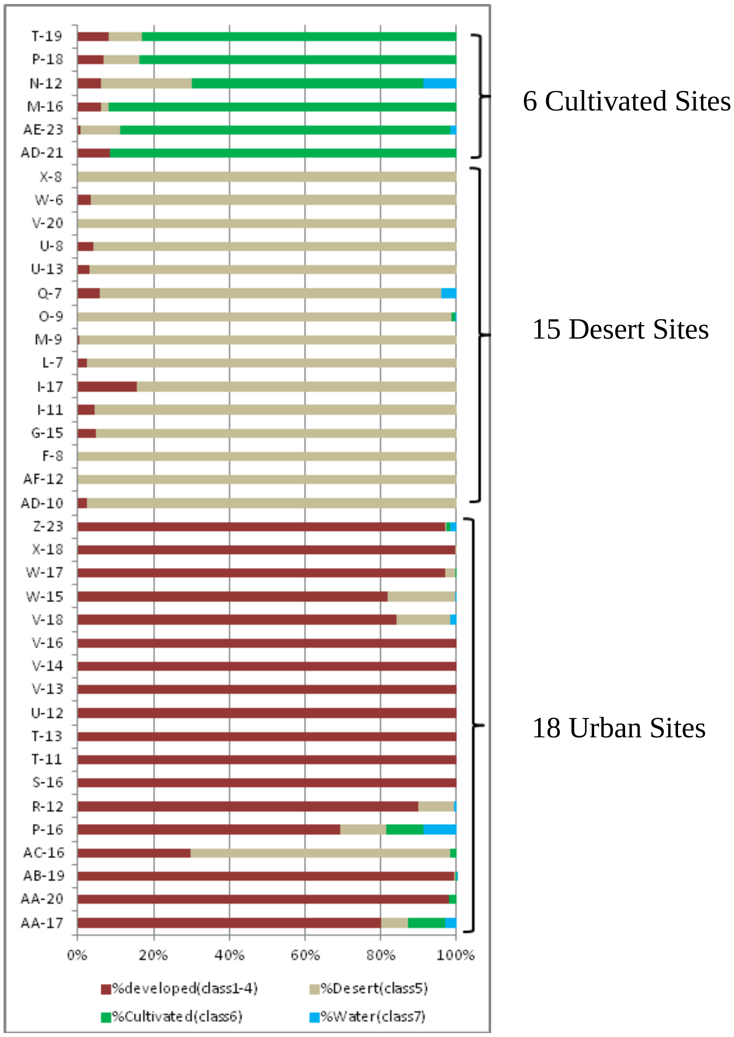
The ongoing project (begun in October 2000) documents the abundance and distribution of four habitats (51 sites): Urban (18) Desert (15) Riparian (11) and agricultural (7). The 40 non-riparian sites are a subset of the 200 CAP- LTER points.
Site classification is based on the CAP LTER land-use code, NLCD2001 land classification, and the view available from Google Earth.
1) In the CAP LTER land code only 6 of 51 sites are coded as agricultural sites.
2) Z-23 vacant is manually revised to urban (low-intensity) area.
3) AC-16 industrial is located in desert; thus, the percentage of undeveloped area and the percentage of developed area are similar, so I classified it as an urban site.
4) Y-19 is classified as riparian in this study because of its proximity to water.
Site types for this study are: Urban (18), Desert (15), Agricultural (6), and Riparian (12).

Table I: Comparison of Site Identification in this Study and in CAP LULC

No.	Site ID	CAP LULC	Site identification in this study
1	AA-17	Medium Density Residential	Urban
2	AA-20	Small Lot Residential	Urban
3	AB-19	Small Lot Residential	Urban
4	AC-16	Industrial	Urban
5	AD-10	Recreational Open Space	Desert
6	AD-21	Agriculture	Agriculture
7	AE-23	Agriculture	Agriculture
8	AF-12	Rural	Desert
9	EE-15A	Riparian	Riparian in Urban
10	EE-6A	Riparian	Riparian in Urban
11	EE-7C	Riparian	Riparian in Urban

12	EN-4B	Riparian	Riparian in Desert
13	EN-7B	Riparian	Riparian in Desert
14	F-8	Vacant	Desert
15	G-15	Vacant	Desert
16	I-11	Vacant	Desert
17	I-17	Vacant	Desert
18	L-7	Vacant	Desert
19	M-16	Agriculture	Agriculture
20	M-9	Vacant	Desert
21	N-12	Agriculture	Agriculture
22	O-9	Vacant	Desert
23	P-16	Small Lot Residential	Urban
24	P-18	Agriculture	Agriculture
25	PE-10B	Riparian	Riparian in Desert
26	PE-11A	Riparian	Riparian in Agriculture
27	PE-13A	Riparian	Riparian in Desert
28	PE-1D	Riparian	Riparian in Urban
29	PN-1B	Riparian	Riparian in Desert
30	PN-7A	Riparian	Riparian in Desert
31	Q-7	Vacant	Desert
32	R-12	Small Lot Residential	Urban
33	S-16	High Density Residential	Urban
34	T-11	Small Lot Residential	Urban
35	T-13	Small Lot Residential	Urban
36	T-19	Agriculture	Agriculture
37	U-12	Small Lot Residential	Urban
38	U-13	Dedicated or Non-developable Open Space	Desert
39	U-8	Vacant	Desert
40	V-13	Educational	Urban
41	V-14	Community Retail Center	Urban
42	V-16	Small Lot Residential	Urban
43	V-18	Vacant	Urban
44	V-20	Recreational Open Space	Desert
45	W-15	Large Lot Residential	Urban
46	W-17	Neighborhood Retail Center	Urban
47	W-6	Vacant	Desert
48	X-18	Educational	Urban
49	X-8	Vacant	Desert
50	Y-19	Small Lot Residential	Riparian in Urban
51	Z-23	Vacant	Urban

C. Three Site Types: Percentage of Land Cover at 1290 m Side-length Buffer Area



D. Contrast Edges Settings for Each Land Class

FTABLE	Open	Low-Int	Mid-Int	High-Int	Undeveloped	Agriculture	Water
Open	0	0	0	0	1	0.5	0.5
Low-Int	0	0	0	0	1	0.5	0.5
Mid-Int	0	0	0	0	1	0.5	0.5
High-Int	0	0	0	0	1	0.5	0.5
Undeveloped	1	1	1	1	0	0.5	0.5
Agriculture	0.5	0.5	0.5	0.5	0.5	0	0.5
Water	0.5	0.5	0.5	0.5	0.5	0.5	0

E. Bird Name and Code

No.	**Species name**	Total(128 species in 2001)	Spring(86 species)	Summer(70 species)	Fall(77 species)	Winter(88 species)

1	Abert's Towhee	ABTO	ABTO	ABTO	ABTO	ABTO
2	American Coot	AMCO	AMCO	AMCO	AMCO	AMCO
3	American Kestrel	AMKE	AMKE			AMKE
4	American Robin	AMRO			AMRO	
5	Anna's Hummingbird	ANHU	ANHU	ANHU	ANHU	ANHU
6	Ash-throated Flycatcher	ATFL	ATFL	ATFL	ATFL	ATFL
7	Audubon's Warbler	AUWA	AUWA		AUWA	AUWA
8	Brown-crested Flycatcher	BCFL	BCFL	BCFL		
9	Black-chinned Hummingbird	BCHU	BCHU	BCHU	BCHU	
10	Black-crowned Night-Heron	BCNH	BCNH		BCNH	BCNH
11	Belted Kingfisher	BEKI			BEKI	BEKI
12	Bendire's Thrasher	BETH	BETH	BETH		
13	Bell's Vireo	BEVI	BEVI	BEVI		
14	Bewick's Wren	BEWR	BEWR		BEWR	
15	Blue-gray Gnatcatcher	BGGN	BGGN	BGGN	BGGN	BGGN
16	Brown-headed Cowbird	BHCO	BHCO	BHCO	BHCO	
17	Black Phoebe	BLPH	BLPH	BLPH	BLPH	BLPH
18	Black-necked Stilt	BNST	BNST	BNST		BNST
19	Brewer's Blackbird	BRBL	BRBL		BRBL	BRCR
20	Brown Creeper	BRCR			BRSP	BRSP
21	Bronzed Cowbird	BROC		BROC		
22	Brewer's Sparrow	BRSP	BRSP	BTGN		
23	Black-tailed Gnatcatcher	BTGN	BTGN	BTSP	BTGN	BTGN
24	Black-throated Sparrow	BTSP	BTSP		BTSP	BTSP
25	Bullock's Oriole	BUOR	BUOR	BUOR		
26	Bushtit	BUSH	BUSH			
27	Cactus Wren	CACW	CACW	CACW	CACW	CACW
28	Cassin's Kingbird	CAKI		CAKI	CANT	
29	Canyon Towhee	CANT		CANT		
30	Canyon Wren	CANW		CANW		CANW
31	Common Black Hawk	CBHA				CBHA
32	Curve-billed Thrasher	CBTH	CBTH	CBTH	CBTH	CBTH
33	Chestnut-collared Longspur	CCLO				CCLO
34	Cedar Waxwing	CEDW			CEDW	
35	Chipping Sparrow	CHSP	CHSP			
36	Cinnamon Teal	CITE				CITE
37	Cliff Swallow	CLSW	CLSW			
38	Cooper's Hawk	COHA			COHA	COHA
39	Costa's Hummingbird	COHU	COHU	COHU	COHU	COHU
40	Common Moorhen	COMO	COMO	COMO	COMO	COMO
41	Common Raven	CORA	CORA	CORA	CORA	
42	Common Yellowthroat	COYE	COYE	COYE		COYE

43	Double-crested Cormorant	DCCO	DCCO			DCCO
44	European Starling	EUST	EUST	EUST	EUST	EUST
45	Gambel's Quail	GAQU	GAQU	GAQU	GAQU	GAQU
46	Great blue Heron	GBHE	GBHE	GBHE	GBHE	GBHE
47	Gray-headed Junco	GHJU				GHJU
48	Gilded Flicker	GIFL	GIFL	GIFL	GIFL	GIFL
49	Gila Woodpecker	GIWO	GIWO	GIWO	GIWO	GIWO
50	Great Egret	GREG	GREG	GREG	GREG	GREG
51	Green Heron	GRHE	GRHE	GRHE	GRHE	
52	Greater Roadrunner	GRRO	GRRO	GRRO		
53	Greater Yellowlegs	GRYE			GRYE	GRYE
54	Great-tailed Grackle	GTGR	GTGR	GTGR	GTGR	GTGR
55	Green-tailed Towhee	GTTO	GTTO		GTTO	
56	Harris' Hawk	HAHA		HAHA	HAHA	
57	House Finch	HOFI	HOFI	HOFI	HOFI	HOFI
58	Horned Lark	HOLA	HOLA		HOLA	HOLA
59	Hooded Oriole	HOOR	HOOR	HOOR		
60	House Sparrow	HOSP	HOSP	HOSP	HOSP	HOSP
61	Inca Dove	INDO	INDO	INDO	INDO	INDO
62	Killdeer	KILL	KILL	KILL	KILL	KILL
63	Lark Sparrow	LASP	LASP		LASP	LASP
64	Long-billed Curlew	LBCU	LBCU			
65	Little Blue Heron	LBHE				LBHE
66	Ladder-backed Woodpecker	LBWO	LBWO	LBWO		LBWO
67	Lesser Goldfinch	LEGO	LEGO	LEGO	LEGO	LEGO
68	Lesser Nighthawk	LENI	LENI	LENI		
69	Least Sandpiper	LESA	LESA			LESA
70	Lincoln's Sparrow	LISP				LISP
71	Loggerhead Shrike	LOSH	LOSH	LOSH	LOSH	LOSH
72	Lucy's Warbler	LUWA	LUWA	LUWA		
73	Mallard	MALL	MALL	MALL	MALL	MALL
74	Marsh Wren	MAWR	MAWR		MAWR	MAWR
75	Mountain Bluebird	MOBL				MOBL
76	Mourning Dove	MODO	MODO	MODO	MODO	MODO
77	Northern Cardinal	NOCA	NOCA	NOCA	NOCA	NOCA
78	Northern Flicker	NOFL	NOFL	NOFL	NOFL	NOFL
79	Northern Harrier	NOHA			NOHA	NOHA
80	Northern Mockingbird	NOMO	NOMO	NOMO	NOMO	NOMO
81	Northern Pintail	NOPI				NOPI
82	Northern Rough-winged Swallow	NRWS	NRWS		NRWS	NRWS
83	Northern Shoveler	NSHO				NSHO
84	Orange-crowned Warbler	OCWA			OCWA	OCWA
85	Oregon Junco	ORJU				ORJU

86	Osprey	OSPR			OSPR	
87	Pied-billed Grebe	PBGR	PBGR	PBGR	PBGR	PBGR
88	Peach-faced Lovebird	PFLB		PFLB		PFLB
89	Phainopepla	PHAI	PHAI	PHAI	PHAI	PHAI
90	Ruby-crowned Kinglet	RCKI			RCKI	RCKI
91	Rufous-crowned Sparrow	RCSP	RCSP			
92	Ring-necked Duck	RNDU				RNDU
93	Red-naped Sapsucker	RNSA				RNSA
94	Rock Dove	RODO	RODO	RODO	RODO	RODO
95	Rock Wren	ROWR	ROWR	ROWR	ROWR	ROWR
96	Red-shafted Flicker	RSFL	RSFL	RSFL		RSFL
97	Red-tailed Hawk	RTHA	RTHA		RTHA	RTHA
98	Red-winged Blackbird	RWBL	RWBL	RWBL	RWBL	RWBL
99	Say's Phoebe	SAPH	SAPH	SAPH	SAPH	SAPH
100	Savanna Sparrow	SASP(SAVS)	SASP		SASP	SASP
101	Snowy Egret	SNEG	SNEG	SNEG	SNEG	SNEG
102	Song Sparrow	SOSP	SOSP	SOSP	SOSP	SOSP
103	Solitary Vireo	SOVI		SOVI		SOVI
104	Spotted Towhee	SPTO			SPTO	SPTO
105	Summer Tanager	SUTA		SUTA		
106	Turkey Vulture	TUVU	TUVU			
107	Unidentified Dark-eyed Junco	UDEJ			UDEJ	UDEJ
108	Unidentified Flycatcher	UNFL			UNFL	
109	Unidentified Hawk	UNHA		UNHA	UNHA	
110	Unidentified Hummingbird	UNHU			UNHU	
111	Unidentified Sparrow	UNSP			UNSP	UNSP
112	Unidentified Thrasher	UNTH			UNTH	
113	Unidentified Towhee	UNTO				UNTO
114	Unidentified Vireo	UNVI	UNVI			
115	Unidentified Warbler	UNWA	UNWA			
116	Unidentified Woodpecker	UNWO				UNWO
117	Vermilion Flycatcher	VEFL		VEFL		VEFL
118	Verdin	VERD	VERD	VERD	VERD	VERD
119	White-breasted Nuthatch	WBNU				WBNU
120	White-crowned Sparrow	WCSP	WCSP		WCSP	WCSP
121	Western Flycatcher	WEFL		WEFL		
122	Western Kingbird	WEKI	WEKI	WEKI		
123	Western Meadowlark	WEME	WEME		WEME	WEME
124	Western Wood-Pewee	WEWP	WEWP	WEWP		
125	Wilson's Phalarope	WIPH	WIPH			
126	Wilson's Warbler	WIWA	WIWA			WIWA
127	White Winged Dove	WWDO	WWDO	WWDO	WWDO	
128	Yellow Warbler	YWAR	YWAR	YWAR	YWAR	YWAR

F. Species and Number of Birds Observed During the Spring of 2001 at Each Survey Site

Species Code (86 species in Spring, 2011)	Site ID	Total Species	Total Number	Site Type
1	AA-17	10	49	Urban
2	AA-20	8	47	Urban
3	AB-19	13	52	Urban
4	AC-16	14	57	Urban
5	AD-10	17	46	Desert
6	AD-21	6	22	Agriculture
7	AE-23	13	73	Agriculture
8	AF-12	12	25	Desert
9	EE-15A	20	100	Riparian in Urban
10	EE-6A	15	69	Riparian in Urban
11	EE-7C	15	37	Riparian in Urban
12	EN-4B	21	56	Riparian in Desert
13	EN-7B	13	32	Riparian in Desert
14	F-8	5	12	Desert
15	G-15	9	27	Desert
16	I-11	8	14	Desert
17	I-17	10	15	Desert
18	L-7	8	15	Desert
19	M-16	5	59	Agriculture
20	M-9	7	11	Desert
21	N-12	9	32	Agriculture
22	O-9	7	11	Desert
23	P-16	7	43	Urban
24	P-18	10	90	Agriculture
25	PE-10B	21	75	Riparian in Desert
26	PE-11A	15	126	Riparian in Agriculture
27	PE-13A	22	59	Riparian in Desert
28	PE-1D	13	32	Riparian in Urban
29	PN-1B	21	60	Riparian in Desert
30	PN-7A	21	38	Riparian in Desert
31	Q-7	11	19	Desert
32	R-12	18	85	Urban
33	S-16	9	44	Urban
34	T-11	10	47	Urban
35	T-13	12	63	Urban
36	T-19	15	72	Agriculture
37	U-12	16	80	Urban

38	U-13	16	50	Desert
39	U-8	8	17	Desert
40	V-13	5	27	Urban
41	V-14	13	55	Urban
42	V-16	14	69	Urban
43	V-18	11	38	Urban
44	V-20	15	44	Desert
45	W-15	16	72	Urban
46	W-17	8	27	Urban
47	W-6	14	28	Desert
48	X-18	13	68	Urban
49	X-8	14	47	Desert
50	Y-19	12	74	Riparian in Urban
51	Z-23	8	54	Urban
	Total	633	2464	

Chapter 7

CONCLUSION

Cities have become habitat for more than half of the world's population. In the More Economically Developed Countries (MEDC), such as North America and Europe, 80% or more of the population lives in urban areas. Much of the urban growth in North America, and increasingly in other wealthy regions of the world, is characterized by suburbanization, or low-density, fragmented expansion on the urban fringe. In the Less Economically Developed Countries (LEDC), the speed of urbanization continues to grow. In the next twenty years, there will be nearly two billion new urban residents, primarily in LEDC countries (UNFPA, 2007). Besides the conspicuous phenomenon of expansion on the fringe, urbanization is also associated with high energy and resource consumption, and therefore with increases in greenhouse gas emissions. Cities now consume 65 percent of the world's energy and generate 70 percent of greenhouse gas emissions (Solecki et al., 2013). Building sustainable cities has therefore been recognized as a critical component in the next phase of the Sustainable Development Goals of the United Nations. In the words of the Executive Director of the United Nations Environment Program, "The battle for sustainable development, for delivering a more environmentally stable, just and healthier world, is going to be largely won and lost in our cities" (UNEP, 2005). Part of the challenge is recognizing that cities are ecosystems nested within larger ecosystems, and that sustainable solutions for cities and the globe need to incorporate a socio-ecological understanding of urban dynamics.

Studying urban sustainability requires a complex system analysis. This dissertation applies a Socio-Ecological System (SES) Framework with an empirical case study that contributes to urban sustainability research. Land-use and land-cover change (LULC) was selected as the bridge for linking social and ecological systems. LULC is one of the most important phenomena of urbanization. Although at a global level urban areas only occupied 3% of the Earth's landmass, at local scales the rapid LULC change that results from rapid urbanization has significant impacts on ecosystems, including both habitat loss and habitat fragmentation. This dissertation research focuses on land fragmentation because of its significant implications for biodiversity and ecosystem services and functions.

7.1 Summary of findings

In this dissertation, I applied the SES framework to address the following questions: (i) what is the status of LULC and land fragmentation in the Phoenix metropolitan region; and (ii) what drives land fragmentation and how does it affect urban ecosystems, especially in an arid environment? Below is a summary of key findings. They can be grouped in four areas: methodological advances in fragmentation analysis; land-fragmentation status in Phoenix and other cities in the southwestern US; socio-ecological drivers of land fragmentation and the role of policy and governance in the process; and the impacts of land fragmentation on bird biodiversity in an arid urban setting.

7.1.1 Advances in land-fragmentation analysis methods

Chapter 2 of this dissertation focused on methodologies for land-fragmentation analysis. By synthesizing the existing, widely applied analysis methods, the discussion highlighted how sensitive the evaluation of land fragmentation is to the scales of analysis used. It also noted the lack of a method for identifying an effective moving window (MW) scale. In response, I proposed a method to identify an effective MW size for the Phoenix metropolitan area. To test the robustness of the proposed method, I demonstrated its use in six cities in the Phoenix metropolitan area that have substantial variation in land composition and configuration. Results indicated that the effective MW size at city level ranges from 450 m × 450 m to 1 km × 1km, while at the Phoenix regional level the most effective sizes were 690 m × 690 m for the year 2001 and 930 m × 930 m for the year 1992. The regional effective size of 690-930 m can be taken as a reference for other metropolitan regions. These findings have recently been applied by a research program, DAUME, [7] which is funded by the French National Research Agency (ANR) and studies Mediterranean urban systems supported by. DAUME researchers applied the effective moving-window method to the Mediterranean region and found the effective moving window for land fragmentation analysis to be around 700 m. That window size is similar to the size we measured in Phoenix metropolitan areas.

Chapter 2 also discussed the methods of measuring fragmentation gradients, compared two approaches, and concentric ring- and transect-based approaches. I argue that the selection of the method needs to consider urban form as a critical factor (e.g., monocentric, polycentric, or leapfrog forms). Because this research developed an innovative fragmentation-measurement model using effective scales and methods, it contributes to methodology in geography and landscape ecology. The study demonstrates a way to increase the accuracy of fragmentation assessment in rapidly urbanizing regions, and provides a method that can be replicated elsewhere.

[7] http://www1.montpellier.inra.fr/daume/

7.1.2 Phoenix land use and socio-ecological implications

Chapter 3 evaluated the land-fragmentation patterns in greater Phoenix. The rapid urbanization of the Phoenix Metropolitan Area exemplifies the dominant urban growth patterns of the Southwestern part of the U.S during the past six decades. Working with colleagues, I quantified and characterized spatiotemporal patterns of land fragmentation observed in Phoenix, using a combination of multi-temporal land-cover data, gradient analysis, and landscape metrics. A second objective of the research was to assess the applicability and accuracy of the National Land-cover Database (NLCD), a widely used land-cover dataset, to detect and measure urban growth and land-fragmentation patterns in the relatively treeless desert biome of the Southwestern US. In contrast to studies done in the temperate Eastern US., where NLCD has proved inaccurate for the detection of exurban development, our study demonstrated that NLCD is a reliable data source for measuring land use in the Southwest, even in low-density environments. Results revealed land fragmentation along rural-to-urban gradients, using four transects crossing the region in different directions. Results showed that Phoenix's growth has been characterized by high fragmentation on the urban fringes, and with the trend of suburbanization, fragmentation grows outward.

Chapter 4 discussed my study of land fragmentation in the five cities and metropolitan areas associated with the Central Arizona-Phoenix (Phoenix, Arizona), Sevilleta (Albuquerque, New Mexico), Jornada (Las Cruces, New Mexico), Short Grass Steppe (Fort Collins, Colorado), and Konza Prairie (Manhattan, Kansas) Long Term Ecological Research (LTER) sites. The study found uneven patterns of fragmentation and rates of change among the five cities. The three general fragmentation patterns identified were riparian, polycentric, and monocentric land fragmentation. Cross-site projects studying land-use patterns are challenging due to the particularities of each community and landscape, but are necessary to better understand general trends of land fragmentation and the legacies of decision-making.

7.1.3 Socio-ecological drivers of land fragmentation

By combining qualitative analyses of social-ecological drivers with fragmentation analyses, the study described in Chapter 3 may contribute to improved understanding of cities, urban geography, and urbanization. The study identified five major socio-ecological drivers critical to understanding the urbanization processes and fragmentation patterns: population dynamics, water provisioning, technology and transportation, institutional factors, and topography. It provided key insights for the human modification framework widely used in the science of land change. Chapter 4 described my analysis of fragmentation drivers and identified five themes: water provisioning, urban population dynamics, transportation, topography, and institutions. Chapter 5 focused on the institutional factors, exploring the role of land and water institutions on land fragmentation. Results of the study described in Chapter 5 indicated that fragmentation is highly correlated to well density (number of wells/100 km^2), especially outside of Phoenix Active Management Areas (AMA), where groundwater withdrawals from wells are not strictly regulated. Results indicated that areas with more groundwater accessibility tend to experience land conversion from desert and agricultural to urban use, and with higher land fragmentation level, than do areas with less groundwater accessibility. The Phoenix AMAs were further subdivided into seven sub-basins based on hydrologic conditions. Topographic and physical differences were found to help explain differences in fragmentation patterns among the seven sub-basins.

7.1.4 Fragmentation and urban biodiversity implications

Chapter 6 described the consequences of land fragmentation on bird biodiversity. The results of the study described in Chapter 6 indicate that urban avoiders (such as the phainopepla and cactus wren species) have a stronger negative relationship to fragmentation in urban lands than in native lands, while the presence of urban adaptors (such as the great-tailed grackle) and exploiters (such as the rock dove and house sparrow) is positively correlated with urban land fragmentation. Among native birds, urban avoiders are more sensitive to land fragmentation than urban adaptors. The analysis indicated that agricultural land can be a semi-natural habitat for adaptive birds, and that the highest bird abundance occurs in agricultural areas rather than in urban or desert areas. Despite high bird abundance on agricultural land, overall species diversity is highest in desert areas. Agricultural land has lower bird biodiversity than either desert or urban land. In natural habitats, fragmentation of forest, grassland, and wetland results in very small, isolated patches, which can negatively affect biodiversity. However, in an urban setting, land fragmentation showed a different influence on different species; therefore, it should not be regarded simply as an unsustainable urban pattern. In highly fragmented and mixed land-use area with human disturbance, abundance and diversity of adaptive birds are higher than in less fragmented areas, such as homogenously developed urban areas or desert areas. My findings suggest that these fragmented urban lands, typically low-intensity residential areas, might become a useful urban habitat for suburban-adaptive and urban-exploiter birds. By considering these findings, urban planners and policy makers can build bird-friendly urban areas that enhance bird numbers and diversity while providing the aesthetic benefits of wildlife-viewing and the ecosystem services and functions associated with birds and their habitats.

My study focused on land use as a lens for studying socio-ecological dynamics in a city. It is important to note, however, that other elements like water supply, energy use, and transportation can also serve as lenses through which to view the links between social and ecological systems, using the SES framework.

7.1.5 Future Directions

Future investigation could focus on other components of an SES framework. One example is an in-depth institutional analysis of land and water institutions. In Chapter 5, I began to investigate some of the institutional factors that might explain the relationships between water rights and land use in Phoenix. A next step would be to compare fragmentation in the biggest 35 water-provider service-boundaries, and to examine more closely how water provisioning and management affects land-use and fragmentation patterns. Another suggestion for future research is to monitor biodiversity change under land fragmentation over an extended period of time. With the release of NLCD 2006, it would be worthwhile to expand the study to 2006, monitoring biodiversity change from 2001 to 2006 and investigating whether the relationship between land fragmentation and biodiversity has changed during those five years, and how. Other impacts related to fragmentation such as energy, resource consumption, and micro climate could be evaluated under the SES framework. Finally, the SES framework and the research methods used in this study could be applied to non-desert cities; a comparative study on what land fragmentation means to urban sustainability in an arid city and a non-arid city would be an interesting and worthwhile undertaking.

7.2 Contributions

The results of this dissertation study provide a documented dataset that can be used to bridge the relationship between human activities and biotic processes in an urban setting, and contribute to sustainable urban development. Below I provide brief summaries of the study's contribution to our understanding of socio-ecological dynamics, to land-use and land-cover change science, and to the field of urban sustainability.

7.2.1 Application of SES for an empirical interdisciplinary case study

A principal contribution of this dissertation is an in-depth empirical analysis of land-cover and land-use change within a socio-ecological systems (SES) framework developed by the Central Arizona Phoenix LTER. The SES framework was applied to answer questions about drivers and consequences of land fragmentation under rapid urbanization. It combined social-spatial-ecological methods such as archival analysis, remote sensing, spatial statistical analysis, and ecological analysis. Spatial analysis is particularly useful for linking institutional data, ecological data, and land data, because they can all be represented and analyzed in spatial terms.

This dissertation study showed that land fragmentation can be both positive and negative, depending on the form of land fragmentation and the species that are of concern. When studying fragmentation issues in an urban area, researchers are interested in *urban* habitat rather than *natural* habitat. It is important to understand what causes the fragmentation of a given urban habitat. For example, low-intensity development has been demonstrated to be highly correlated to fragmentation. In an urban habitat, low-intensity land can be fragmented by high-intensity land to form areas of mixed land use, or it can produce areas of fragmented desert by sprawling into remote, undeveloped areas. Because fragmentation has different effects on different groups of species, its assessment as positive or negative assessment also depends on what species are of concern. Therefore, there is no simple answer as to the question of whether land fragmentation affects biodiversity negatively or positively in an urban setting.

By using an SES framework, this research provides a working example of a multi-method interdisciplinary analysis. Spatial analysis was a major method used in the study. In urban sustainability studies, many research questions need to be answered through analyzing urban structure. Spatial analysis has proven to be a robust method for linking human and environmental dynamics by exploring pattern, pattern change, and pattern to process, and it is the primary tool used in urban social geography (Knox, 2000[1982]) and urban environmental studies. Social and ecological characteristics can be discerned through patterns, e.g. land, biodiversity, demographic, pollution, housing, density, amenity, and heat island. When social patterns are correlated with ecological patterns through geographic regressions, it helps to uncover the process behind patterns. To uncover drivers and consequences of land fragmentation in a complex SES, I used not only spatial-temporal analysis and spatial correlations, but also a combination of various types of methods, including historical analysis, archival analysis, qualitative analysis, and institutional analysis—all within the larger SES framework.

7.2.2 Theoretical contribution to land fragmentation in an urban setting

This research contributes to land fragmentation and LULC theory and practice in a number of ways. It applies land fragmentation approaches to urban habitats, and fills several research gaps. For example, the importance of scales in analysis of land use and land cover has been known for long time, but methods for selecting scales have remained inadequate. Chapter 2 proposes a research method for determining a moving-window scale that makes land-fragmentation analysis more efficient and accurate. Land policy and regulations are critical in urban planning, but water policy has never been linked to land fragmentation. Chapter 5 helps to fill this gap by thoroughly analyzing potential social and ecological drivers, giving special attention to the role of coupled institutions. And, although fragmentation research has been done on biodiversity, mostly on natural habitats such as forests, little research has considered fragmentation in an urban ecosystem. Chapter 6 adds to our knowledge about how land fragmentation is related to biodiversity in urban areas.

Based on my findings, I classify urban landscape fragmentation into two types, "negative land fragmentation" and "positive land fragmentation." Negative land fragmentation occurs when urban land sprawls into natural land and generates segmented and isolated natural habitats and human settlement. It does not necessarily imply a low-density urban form, because high-density form can also sprawl. Negative land fragmentation has a number of downsides, including increased energy costs associated with longer travel times, inefficient delivery of services such as roads and water, and biodiversity loss. On the other hand, positive landscape fragmentation, such as diverse and mixed land-use, has often been promoted as fundamental for urban sustainability (Newman & Jennings, 2008). Positive land fragmentation increases animal abundance and biodiversity of certain kinds of species (i.e., of urban adapters and exploiters, not overall species; the biodiversity of overall species is still highest in undeveloped areas, as discussed in Chapter 6). Positive landscape fragmentation that includes green space increases livability, mitigates micro-climate, and reduces the urban heat island effect. Fragmentation that mixes residential with open space provides aesthetic value, increases property values, and can decrease heating and cooling costs. Positive landscape fragmentation also improves the health and well-being of local residents by creating recreational space for physical activity, providing shade, buffering wind and noise, and decreasing stress (Giles-Corti et al., 2005). Positive landscape fragmentation that takes the form of dense, mixed land-use can help consumers to conserve energy and water resources.

I discovered that in the Phoenix Metropolitan Region, land fragmentation is most highly correlated with mixed land-use, and is positively correlated with bird abundance and the biodiversity of urban adapters and exploiters. I also discovered that low-density areas are highly associated with land fragmentation. While very high much density may cause overcrowded and unpleasant urban settings, along with environmental problems such as noise, pollution, urban heat islands, and reduction of urban biodiversity, very low density may cause reduction of rural productivity (World Bank, 2012), inefficiency of energy and infrastructure services, and increased traffic congestion. Another negative effect of very low density is overconsumption of natural resources such as land and water. Sustainable urban form depends on suitable-density and mixed-density designs, and these must be created based on each city's individual context. One conclusion of this study is that land fragmentation that causes segmentation or isolation of a natural or urban habitat has negative consequences for urban ecosystems, but also violates the ideals of sustainable urban development. In contrast, land fragmentation with mixed land-use at suitable density can increase the efficiency of energy and resource consumption, enhance abundance and diversity of animals and plants, and create a more sustainable urban environment. How to create urban habitats for animals and plants within livable settlements for human beings remains a question that those who make policies and regulations must answer. While using the SES framework can facilitate understanding of urban areas as ecosystems, managing social-ecological systems sustainably, making trade-offs, and balancing priorities in the domains of society, economy, and environment are key tasks for urban planners and policy makers.

7.2.3 Policy implications for urban sustainability

Learning how to govern socio-ecological systems sustainably is one of the biggest challenges of sustainability. The socio-ecological framework employed in my research is not only a means of explaining the patterns and processes of land fragmentation, but can also be used to identify appropriate interventions. Land managers can use my findings to enhance their understanding of the complexity of land fragmentation, and how that complexity creates far-reaching consequences for people and the environment when a site is developed. This research can thus help planners assess the range of trade-offs associated with land management decisions. For example, if biodiversity is a priority, findings from my research can help to identify how fragmentation correlates with biodiversity and, more specifically, where and under what social and ecological conditions those correlations are strongest.

Urban sustainability depends in part on careful land management, and this dissertation examined fragmentation as one component that affects urban ecosystem structure and function. Further, it focused on bird biodiversity as one aspect of urban ecosystems that is influenced by land fragmentation. Fragmentation analyses should also consider broader impacts on agricultural productivity, energy consumption, transportation, service, environmental amenity, quality of life, economic development, and management problems. By using land fragmentation as a window, with the Phoenix metropolitan area as a case study, this research explored interactions of social and ecological dynamics, a key knowledge domain and approach for sustainability.

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APPENDIX A

STATEMENT OF PERMISSION

I declare that I have obtained explicit permission from the first authors and co-authors for including three peer-reviewed scientific journal manuscripts as chapters in this dissertation. They are:

Milan Shrestha (Chapters 2, 3 and 4);

Abigail M. York (Chapters 2, 3 and 4);

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