EXPLORING THE EFFECTS OF LOCAL DEVELOPMENT REGULATIONS ON ECOLOGICAL LANDSCAPE STRUCTURE

A Dissertation

by

JIN KI KIM

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2005

Major Subject: Urban and Regional Science

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Approved as to style and content by:

Christopher D. Ellis (Chair of Committee)	Byoung-Suk Kweon (Member)
Douglas F. Wunneburger (Member)	Robert N. Coulson (Member)
Forster Ndubisi (Head of Department)	

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ABSTRACT

Exploring the Effects of Local Development Regulations on Ecological Landscape Structure. (May 2005)

Jin Ki Kim,
B.S., Seoul National University, Korea;
M.L.A., Seoul National University, Korea;
M.A., Michigan State University
Chair of Advisory Committee: Dr. Christopher D. Ellis

An ecological approach to land-use planning is essential to maintain the long-term sustainability of ecosystem benefits, services, and resources. Concern about environmental quality and the long-term livability of urban areas is now a driving force in urban planning and design. The interrelated issues of growth management, smart growth, sustainable development, and new urbanism are topics in the most vibrant discussions at all levels of planning and landscape architecture. Within this context, this study starts from the interest in the ecological planning and management in urban areas, especially related to the issue of local development regulation and guidelines. Landscape regulations have come into existence recently in communities across the nation and these regulations vary from one region to another and from one community to another.

The aims of this study were to investigate the relationship between ecological landscape structure and local development regulations over time. Comparison analysis was conducted between two areas that had similar pre-development ecological conditions but were developed under vastly different regulatory environments. The Woodlands (regulated to protect ecological condition) and the North Houston area (which followed traditional subdivision regulations) were examined at three different developmental time periods: predevelopment, early development (after 10 years), and matured development (after 30 years). Aerial photos of each site from the three time periods were classified into forested and non-forested classes and the landscape structure was quantified with a number of landscape metrics related to fragmentation—an indicator of habitat degradation. Two factors, the ecological approach to landscape planning and the adoption of more restrictive landscape regulations and guidelines, are discussed on the premise that they exert influence in developing and maintaining the long-term sustainability of ecosystems.

In conclusion, this study provides the quantified landscape configuration and composition of the effects of development regulations on landscape structure. The ecologically planned community shows a less fragmented forest pattern and more restrictive development guidelines result in more ecologically structured environments. Understanding how elements of local development regulations affect ecological landscape patterns is important for landscape architects, planners, and administrators because it can lead to better strategies for planning and designing sustainable communities.

DEDICATION

I dedicate this dissertation to

Soon-Ae Oh

and the memory of

Hak-Jin Kim

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There are so many wonderful persons who helped with this dissertation. I would like to express my appreciation to my chair, Professor Christopher D. Ellis, for his thorough and patient guidance. He provided the guidance and continued support that was necessary to reach the successful completion of my graduate program.

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CHAPTER I

INTRODUCTION

1. Background of the Study

Concern about environmental quality and the long-term livability of urban areas is now a driving force in urban planning and design. The interrelated issues of growth management, smart growth, sustainable development, and new urbanism are topics in the most vibrant discussions at all levels of planning and landscape architecture (Talen and Knaap, 2003). Despite the controversial arguments over terminology and implementation strategy, limiting the land consumptive sprawl and supporting healthy communities for residents are the main issues. In addition, an ecological approach to land-use planning is essential to maintain the long-term sustainability of ecosystem benefits, services, and resources (Zipperer et al., 2000).

The consideration of ecological understanding in planning was developed by Ian McHarg (1969) in his *Design with Nature*, and continues to be examined in the works of many other researchers. Baschak and Brown (1995) applied the landscape ecological approaches to the development of urban river greenways. Hersperger (1994) provided a review of the key concepts and developments in the field of landscape ecology, and Flores et al. (1998) presented a framework for the incorporation of modern ecological thinking into regional planning or urban landscapes.

This dissertation follows the style and format of International Journal of Landscape and Urban Planning.

Landscape ecology outlines important principles of greenspace organization related to the theory of island biogeography (MacArthur and Wilson, 1967). In essence, large patch, high connectivity and proximity foster species diversity and ecosystem functions. Such spatial concepts have been widely adopted in urban landscape architecture and landscape planning projects (Goldstein et al., 1982/1983).

Recently landscape codes have come into existence in communities across the nation. Ordinances are adopted to regulate a realistic approach to the usage of vegetation in today's rural/urban sprawl. These ordinances vary from one region to another, from one community to another (Tereshkovich, 1990). As a result, landscape architects frequently have to change the way they approach design. More and more communities are requiring that landscape plans be drawn to code and meet various technical requirements that are being enacted by city councils across the land (Abbey, 1999).

In this study, these two approaches, the ecological approach to landscape planning and the adoption of more restrictive landscape regulations and guidelines, are discussed on the premise that they exert influence in developing and maintaining the long-term sustainability of ecosystem. The Woodlands and the North Houston area were selected as study areas. The comparisons of two sites over three time periods show how ecological local development regulations influence the landscape structure.

2. Problem Statement

Urban vegetation can be defined in two ways. First, it is defined as a static assemblage of plant material above, on, and below the ground surface within an urban area or its zone of influence. This definition includes species, age and size dimensions, conditions of health, amounts or densities of plant materials, and leaf area or tree crown density (Sanders, 1984). The other definition focuses on process and identifies those plant assemblages that are regularly subjected to urban influences (Sanders, 1984; McDonnell and Pickett, 1990). The process definition includes structural components and processes within urban areas as well as areas adjacent to or neighboring urban landscapes (McDonnell and Pickett, 1990).

Urban vegetation patterns have been explored in many different ways. Schmid's study (1975) on Chicago residential areas found that biomass, species composition, and arrangement of plants vary significantly between neighborhoods with different physical and social fabrics. Jim (1996) conducted urban forest studies in Hong Kong and found that tree frequency, density, and species composition varies significantly among urban districts with different development history, population density, land use pattern, and urban morphology.

Merging ecology and socio-economics methods have also been central to studies of urban to rural transects (McDonnell and Picket, 1990; Grove and Burch, 1997; Zipperer et al., 1997). Specifically, the urban vegetation cover has been studied in relation to the household income and household density (Iverson and Cook, 2000), patterns of social components and processes: socio-economic status, homeownership and ethnicity (Grove and Burch, 1997), natural environment and land use (Nowak et al., 1996), and human societies: wealth, education, status, property, and power (Logan and Molotch, 1987). In sum, a lot of existing studies focus on the relationship between urban vegetation pattern and socio-economic status.

These approaches may be well suited to meet their individual objectives. However, previous studies have focused on symptoms not causes. It may not be sufficient to assess the driving factors affecting ecological patterns or processes across urban landscape through these approaches alone. There may be more direct and reliable factors that affect the urban vegetation pattern as well as are critical to manage and maintain healthy environment.

The organization of government in the United States is based on the concept of jurisdiction. The importance of jurisdiction makes it impossible to separate geography from law, and this tight coupling is particularly evident in the ways that land-use decisions are made (Platt, 1996). Jurisdictions for land-use decisions form a nested, spatial hierarchy of local, state, and federal landowners (Caldwell and Shrader-Fechette, 1993). Because most of the authority for land-use decisions is vested at the lower levels of this hierarchy, the aggregate effect of land-use change results from many individual decisions that are diffuse in time and space (Dale et al., 2000). Talen and Knaap (2003) argue that local government regulation has led to a crisis of suburban fragmentation and decentralization and pushed development in one direction or another.

Even though local ordinances have been used as a means to affect the quality of the urban community in many previous researches as it has been reviewed, few studies have been conducted on the relationship between vegetation pattern and land use regulation. Abbey (1999) assembled knowledge about community landscape ordinances and discussed their impact on the design and planning professions that work with this type of legislation. Arendt (1999) offers three strategies for shaping growth around community's special natural and cultural features, demonstrating ways of establishing or modifying the municipal comprehensive plan, zoning ordinance, and subdivision ordinance to include a strong conservation focus.

However, recently more and more communities are requiring that landscape plans be drawn to code and meet various technical requirements that are being enacted by city councils across the land (Abbey, 1999). Therefore, the topic of the relationship between urban vegetation patterns from a landscape ecological perspective and local development regulations can be a critical issue in landscape architecture research.

3. Research Purposes

The general objective of this research is to examine the relationship between landscape structure and local development regulations from a landscape ecological perspective. In the United States, regulations for street trees, tree protection, landscaping, and associated features have been enacted mainly by municipal or local governments (Grey, 1996).

In this context, this study started with some basic questions: Are there any relationships between local land development regulations and ecological landscape structure? If there are relationships, how these development regulations affect the ecological landscape structure and how planning methods affect the fragmentation of urban vegetation. In addition, if the landscape structure differences exist, how the differences would change over time?

Based on these questions, the main research objectives are as follows;

1) To investigate the relationship between local development regulations and ecological landscape structure.
2) To examine the differences in land cover change over time in experimental and control groups
3) To reach some conclusions about local development regulation guidelines and how they support ecologically healthy environments

4. Organization of the Dissertation

This dissertation consists of five chapters. Chapter I introduces the background of the study and study purposes. Chapter II reviews the literature related to the topic of this study. Literatures in Chapter II include principal concepts of landscape ecology, landscape ecological planning, models and theories of landscape ecology, quantification of landscape pattern, fragmentation and landscape metrics, and urban sprawl and local development regulations. Chapter III contains research methods and data. Specifically, this chapter states the study flow, hypotheses, biophysical characteristics of study areas, applied land development regulations to each sites, and study design which covers data collection, classification, variables, and sampling method. Chapter IV presents the results of analysis including descriptive analysis, landscape changes described by selected landscape metrics, relationship between landscape structure and development regulation, and the main effect and interaction effect of variables. Finally, a discussion and summary of study results are presented in Chapter V.

CHAPTER II

THEORIES AND CONCEPTS

1. Introduction

This chapter reviews literature related to the study topic; landscape ecology, fragmentation, and local development regulations. This chapter consists of four subchapters. The first subchapter includes landscape ecology theory and landscape ecological planning. This subchapter also refers why landscape ecology theory is important to landscape architecture and urban planning and landscape ecological planning framework. Next subchapter states patch-corridor-matrix (PM) model which is one of the leading models in landscape ecology discipline. The third subchapter discusses the fragmentation and selected landscape metrics. Specifically, this subchapter presents habitat fragmentation, quantification of landscape pattern, landscape metrics, and single fragmentation measurement. In final subchapter, urban sprawl and local development regulations are discussed. Especially, land development regulations that can directly affect physical community settings, such as subdivision regulations, design guidelines, covenants, and landscape ordinances, are discussed.

2. Landscape Ecology and Landscape Ecological Planning

2.1. Landscape Ecology

On the broad level, landscape ecology involves the study of landscape patterns, the interactions among patches within a landscape mosaic, and how these patterns and interactions change over time. It promotes the development of models and theories of spatial relationships, the collection of new types of data on spatial pattern and dynamics, and the examination of spatial scales rarely addressed in ecology (Pickett and Cadenasso, 1995). In addition, landscape ecology involves the application of these principles in the formulation and solving of real-world problems (McGarigal and Marks, 1995). Collectively, this set of definitions emphasizes two important aspects of landscape ecology that distinguish it from other subdisciplines within ecology.

First, landscape ecology explicitly addresses the importance of spatial configuration for ecological processes. Landscape ecology is not only concerned with how much there is of a particular component, but also with how it is arranged. The underlying premise of landscape ecology is that the explicit composition and spatial form of a landscape mosaic affect ecological systems in ways that would be different if the mosaic composition or arrangement were different (Wiens, 1995). Most ecological understanding previously had implicitly assumed an ability to average or extrapolate over spatially homogeneous areas. Ecological studies often attempted to achieve a predictive knowledge about a particular type of system without consideration of its size or position in a broader mosaic. Considered in this way, with its emphasis on spatial heterogeneity, landscape ecology is applied across a wide range of scales.

Second, landscape ecology often focuses on spatial extents that are much larger than those traditionally studied in ecology. In this sense, landscape ecology addresses many kinds of ecological dynamics across large areas. However, it is important to note that, although these areas are typically larger than those used in most community level studies, the spatial scales are not absolutes. Landscape ecology does not define specific spatial scales that may be universally applied; rather, the emphasis is to identify scales that best characterize relationships between spatial heterogeneity and the processes of interest. These two aspects, explicit treatment of spatial heterogeneity and a focus on broad spatial scales, are not mutually exclusive and encompass much of the breadth of landscape ecology.

Landscape ecology focuses on three characteristics of the landscape: structure, function, and change (Forman and Godron, 1986). Landscape structure is the spatial relationships among the distinctive ecosystems or elements present. More specifically, it focuses on the distribution of energy, materials, and species in relation to sizes, shapes, numbers, kinds, and configurations of the ecosystems. Landscape function is the interactions among the spatial elements, that is, the flows of energy, materials, and species among the component ecosystems. Fig. 2.1 summarizes a common theme of landscape ecology and important components of each theme (Hobbs, 1997).

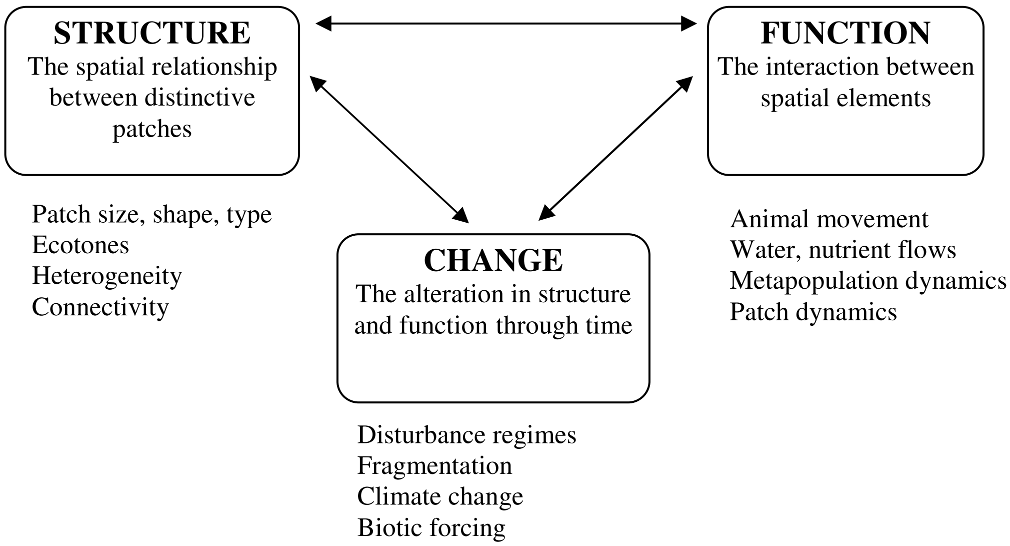


Fig. 2.1. A common theme of landscape ecology and important components of each theme (Hobbs, 1997)

The role of humans, obviously a dominant influence on landscape patterns world wide, is sometimes considered an important component of a definition of landscape ecology. Landscape ecology is sometimes considered to be an interdisciplinary science dealing with the interrelation between human society and its living space-its open and built up landscapes (Naveh and Lieberman, 1994). Landscape ecology draws its disciplines from a variety of fields, many of which emphasize social sciences, including geography, landscape architecture, regional planning, economics, forestry, and wildlife ecology. The scientific contributions of landscape ecology are essential for land management and land use planning.

In sum, landscape ecology emphasizes broad spatial scales and the ecological effects of the spatial patterning of ecosystems. Specifically, it considers 1) the development and dynamics of spatial heterogeneity, 2) the interactions and exchanges across heterogenous landscapes, 3) the influences of spatial heterogeneity on biotic and abiotic processes, and 4) the management of spatial heterogeneity.

2.2. Why Landscape Ecology is Important to Landscape and Urban Planning?

Forman (1995a) discussed the four reasons why landscape ecology is important to researchers, planners, designers, and managers in several fields. The most obvious reason for the rapid expansion of landscape and regional ecology is the subject. It is at the human scale, where nature and people are seen to interact daily, and where land planning, design, conservation, management, and policy must take place. Society craves ecological understanding at this scale. Since planning is normative containing choices for future land uses, planning is anthropocentric (in terms of being human-responsible, rather than being human-centered). On a moral basis of environmental ethics, landscape planners and designers may reconcile the inherent worth of nature with needs and demands of society, and legitimize interventions in the landscape. For both human-centered (anthropocentrism) and nature-centered (biocentrism) points of view, norms for planning and design are perceived by people. The integration of landscape ecology and landscape planning should be viewed from the notion of people’s responsibility for nature, rather than from the emerging ecological insights.

A second reason is its analytic focus. It provides understanding and predictive ability useful for more wood products, species, game, clean water, housing, recreation, or other often-conflicting societal objectives. Advocacy focuses on the intelligent use of landscape and regional ecology in all land-use issues.

A third reason is holistic; the mosaic emerges as much more than the sum of its parts. The central prerequisite for wise landscape planning is understanding of natural and social processes and their influences on the landscape, the relevant parameters and to which extent these parameters influence the landscape. Landscape planners deal with questions as, for example, which landscape structure or spatial configuration of ecosystems will concurrently optimize soil conservation, biodiversity, wildlife populations, scenic quality, outdoor-recreation opportunities and other interests?

The fourth reason is the assays or areas of ecological interest. The full meaning of ecology as interactions among organisms and the environment is included, rather than only current interests within ecology. Landscape ecology contributes to an understanding of heterogeneous landscapes and the changes associated with natural processes and human interventions. Landscape ecology provides the planner with a set of theories, knowledge and experiences of landscape study, especially related to the spatial structure of landscapes, their origin, and the processes which alter the spatial structure. It also provides a conceptual framework within which planners can explore how the structure of land evolves with relevant natural processes. Thus, four categories of ecological assays are recognized throughout, specifically production, biodiversity, soil, and water characteristics. Ecological integrity refers to near-natural levels present in all four categories.

2.3. Landscape Ecological Planning

The landscape ecological planning is centrally based on key biotope-ecological corridor model. The overall objective of the landscape ecological planning is to maintain an area's native biodiversity, both structural and of species. This means that the present objective emphasizing species should be complemented by objectives for preservation and active maintenance of natural habitats.

Planning has been defined as the use of scientific, technical, and other organized knowledge to provide options for decision makings as well as a process for considering and reaching consensus on a range of choices. Environmental planning is the initiation and operation of activities to manage the acquisition, transformation, distribution, and disposal of resources in a manner capable of sustaining human activities, with a minimum distribution of physical, ecological, and social process (Steiner, 2000).

Ecological approaches of landscape planning are developed as useful planning frameworks, including guidelines for the way data should be collected, analyzed and presented, for participation of interest groups and for implementation and monitoring plans (McHarg, 1969; Fabos, 1979; Vink, 1983; Steiner, 1991). These approaches require a focus on interactions between landscape components and processes, and on the context in which the plan area is placed. This approach is more or less based on ecological theories.

To enhance the ecological integrity of the landscape and achieve sustainable land use, landscape planning should consider natural and social processes and their spatial relationships in a comprehensive way. This approach offers the challenge to design landscapes which are beautiful, ecologically healthy, as well as productive of goods and services required by society. In addition, it should include a framework to assess and protect landscapes for their intrinsic values.

Planning the landscape involves decisions about alternative futures focusing on the wise and sustained use of the landscape to accommodate human needs. Landscape planning provides an opportunity to influence spatial practices and to create new landscape structures. It attempts to allocate land use activities while minimizing the disturbance effects of these activities on other land uses and the environment. In this context, landscape planning is a process of managing transformations of the landscape to bring land use in harmony with natural processes, based on knowledge or the reciprocal relationships between people and the land (Cook and Van Lier, 1994).

2.4. Landscape Ecological Planning Framework

Forman (1995a) recommended to start with a coarse-grained landscape with only large patches or areas of the major land uses present and to scatter small patches (and corridors) of natural vegetation over the agricultural and built areas to provide bits of heterogeneous nature over developed areas, to protect dispersed rare species and small habitats, and to provide stepping stones for species movement. It was also recommended to add major corridors connecting the large natural vegetation patches to facilitate movement of patch-interior species, and to add small patches of agriculture near the boundaries between natural vegetation and built areas. Built patches must be isolated with distance from large natural vegetation. An ecological framework was developed on the basis of ecological principles and P-M model.

2.4.1. A Holistic and Interdisciplinary Approach

An important presupposition of landscape planning and landscape ecology is that, people, plants, animals and the abiotic substrate, all become understood as interdependent parts of a larger system. Holistic axiom that "the whole is more than the sum of its parts" was first stated by Smuts in 1926. It has been considered that the holistic approach provides a better appreciation and it has become a basic philosophical concept in landscape ecology. In essence, the holistic approach in landscape ecology and landscape planning views the landscape not just as an aesthetic asset (as by most landscape architects) or as part of the physical environmental (as by most geographers), but as the total spatial and visual entity of human living space, integrating the geosphere with the biosphere and the man-made artifacts (Naveh and Lieberman, 1994).

2.4.2. Recognition of Human Influences in the Landscape

As an interface of natural and social processes, the landscape reflects the history of the dialogue between people and the land. Both the continuity and the variability of land use are present in the landscape. Most landscapes have been more or less influenced by human practices. The resulting landscape mosaic is a mixture of natural and human-managed patches that vary in size, shape and arrangement. Landscape planning addresses those issues that concern the interactions between people and the land. Naveh and Lieberman (1994) state that one of the central features in the theory of landscape ecology is the recognition of the dynamic role of man in the landscape and the quest for the systematic and unbiased study of its ecological implication.

2.4.3. Ecological Networks

The network approach in landscape ecology distinguishes nodes, associated with hospitable habitat patches, and links, associated with corridors between these habitat patches. Habitat networks may be essential for the survival of populations of native species which are poorly adapted to human-dominated landscapes.

Networks provide opportunities for an efficient migratory route, as well as to alter the flow of nutrients, water and energy across the landscape (Forman and Godron, 1986). This can be viewed as a basic principle for landscape planning for nature, at any scale and any context. An optional spatial structure of an ecological network must be developed utilizing three scales: site, local, and region. Planning, design and management should also be applied at all three scales.

At the site level, a managed ecosystem is a collection of response to the physical environment, availability of species, and management over time (Baines, 1987). At the local level, the fundamental structural elements include the background matrix of the city. Landscape planning should minimize the isolation of natural landscape remnants and maximize the linkage to provide for flow of energy, mineral nutrients, and species. At the regional level, a typical management objective would be to ensure that indigenous plant species be used, and that diverse plant communities with spatial heterogeneity be created in the city.

Overall, the success of the ecological framework approach depends on planning, design, and management being coordinated and integrated. This can only be achieved through the establishment of teams with appropriated expertise and a framework to facilitate implementation.

3. Patch- Corridor-Matrix Model

Forman (1995a) described that a land mosaic is composed of only three types of spatial elements. Every point in a landscape is either within a patch, a corridor, or a background matrix, and this holds in any land mosaic, included forested, dry, cultivated, and suburban. In this model, patches, corridors, and the matrix are the basic spatial elements of any pattern of land. The patch-corridor-matrix (P-M) model provides an insightful way to see ecological system. In P-M model, patch refers to a contiguous area sharing a narrow range of values for an identified set of descriptive parameters; a more or less homogeneous region while matrix is the area of distinct habitat surrounding identified patches. Mosaic refers to the entire landscape, divided into any number of patches of discrete size and shape. In a study on the ecological effects of landscape changes, the P-M model provides a handle for analysis and comparison, plus the potential for detecting general patterns and principles. The patch-corridor-matrix approach pinpoints general patterns and principles that cut across the incredible diversity of species, habitats, landscapes, and regions. This model is also a useful template to analyze landscape and to detect changes because cartographic models generalize spatial relationships using the location and configuration of landscape elements (Trani and Giles, 1999).

3.1. Landscape Mosaics

Landscape mosaics are described by the landscape components of patches, corridors, and the surrounding matrix (Forman and Godron, 1984; Turner, 1987). Patches, corridors, and matrix directly influence the spatial patterning and flows in a landscape. Spatial scale also greatly affects landscape structure, heterogeneity, and connectivity.

Landscape structure is determined by the flow of materials, animals, energy, and water through the landscape elements of patches, corridors, and matrix. Factors, such as patch size and shape, corridor characteristics, and connectivity, work together to determine the pattern and process of the landscape. The correlation between pattern and process results in interdependency between landscape structure and function. Landscape patterns influence process, which in turn affect the patterns. The arrangement of spatial elements, especially barriers, conduits, and highly-heterogeneous areas, determine the resistance to flow or movement of species, energy, material, and disturbance over a landscape (Forman, 1995b). Landscape resistance is described as the effect of spatial pattern impeding the rate of flow of objects, such as species and materials (Forman, 1995a).

In general concept, an optimum landscape has large patches of natural vegetation, supplemented with small patches scattered throughout the matrix. Alternatively, most of the small-patch functions can be provided by small corridors in the matrix (Forman, 1995b). The importance of understanding and studying landscapes is illustrated when looking at an ecological phenomenon such as recolonization. Recolonization is enhanced by spatial patterns such as corridors, networks, stepping stones, and small patches (Forman, 1995a).

3.2. Patches

In landscape ecology, patches are spatial units at the landscape scale. From an ecological perspective, patches represent a nonlinear surface area differing in appearance from its surrounding. The land, interacting with climate factors, along with the other factors such as the establishment of flora and fauna, soil development, natural disturbances, and human influences, work together to determine patch size, shape, location, orientation, and dynamics of patches. The size, shape, and nature of the edge are particularly important patch characteristics (Forman and Godron, 1984). Patch size can affect species habitat, resource availability, competition, and recolonization. Spatial scale is especially important when dealing with patches because an area large enough to be a patch to one species may be a barrier or insignificant to another species.

Patch shape and orientation also play an important ecological role. An ecologically optimum patch shape usually has a large core with some curvilinear boundaries and narrow lobes (Forman, 1995a). This shape may allow both interior species and edge species to flourish. Patch shape also determine the edge length. Most common configurations in landscapes are 1) a matrix or large landscape patch surrounding or adjacent to many patches, 2) a corridor bisecting the landscape, and 3) the unit formed by a network of interacting corridors (Cantwell and Forman, 1993).

Forman (1981) distinguished four types of patches at the landscape level: disturbance patches, remnant patches, introduced patches, and environmental resource patches. Three of the landscape patch types are disturbance-caused. In essence, spot disturbance patches originate from disturbance or alteration in a small area, whereas conversely, remnant patches originate from disturbance of a large area surrounding an undisturbed small area. Introduced patches originate by people planting trees or grain, erecting buildings, etc. Environmental resource patches (or vegetation) originate from the patchy distribution of relatively permanent environmental resources such as a rock or soil type through space. Regenerated patches originate from region on a previously disturbed site. The causative mechanisms of these five patch types differ sharply, but the resulting species dynamics of the patches are just as diverse.

3.3. Corridor

Corridors are elongated patches that connect other patches together. Three major types of corridors are line, strip, and stream. Many different kinds of corridors can be found in landscape. They can vary from wide to narrow, high to low connectivity, and meandering to straight (Forman, 1995a). These variables influence the role that corridors play in landscape patterns and processes. Corridors frequently form interconnected networks across the landscape, such as road systems and hedgerow networks (Cantwell and Forman, 1993). Corridor characteristics, such as width, connectivity, curvilinearity, narrows, breaks, and nodes, control the important conduit and barrier functions of a corridor (Forman and Godron, 1984). These factors determine whether a landscape element is a barrier or a conduit to a particular species. Linear elements or corridors are often major movement conduits and sources of pollution and energy consumption. Corridors can act as barriers as many animals tend to avoid crossing even narrow roads (Cantwell and Forman, 1993).

Connectivity usually involves corridors and networks and describes how patches are connected in the landscape. Networks are described as channels of movement through space (Cantwell and Forman, 1993). A spatial connection means either that the patches are sufficiently close that movement can occur among them, or that there is some corridor along which the organisms can move (Fahrig and Merriam, 1985). Connectivity also determines the function of the landscape (Forman and Godron, 1984), illustrating again how much landscape processes are dependent on patterns.

3.4. Matrix

Patches and corridors are imbedded in the matrix, which is usually the most extensive and connected landscape element present. However, the matrix may play a dominant role in the functioning of the landscape without being the most extensive landscape element. Determining what is the matrix in a landscape depends on either connectivity, dominance, or function. Each landscape should be evaluated individually.

As corridor type of a landscape, the matrix is usually extensive in area, highly connected, and exerts a major influence on the successive dynamics of the landscape. The matrix encloses and affects patches as well as corridors. The three main attributes are area, connectivity, and control over dynamics. Total area is the first and easiest criterion. If the two most extensive element types are similar in total area, connectivity should be used to differentiate them. Matrix connectivity is the inverse of the proportion of linkages that must be added to have a fully connected system.

3.5. Implication of P-M Model in Landscape Analysis

The main benefit of the use of P-M model in landscape analysis study is that it provides a tool to translate the landscapes into understandable, tangible, and manipulatable digital information by using simple cartographic concepts in GIS, such as patch corresponding to polygon, corridor corresponding to line or polygon, size corresponding to area, and so on.

Turner (1989) stated that landscape structure must be identified and quantified in meaningful ways before the interactions between landscape patterns and ecological processes can be understood. The spatial patterns observed in landscapes result from complex interactions between physical, biological, and local factors. Landscape mosaic is a mixture of natural and human managed patches that vary in size, shape, and arrangement, which are describing tools of landscapes in P-M model. Information of tenets of landscape in P-M model, such as size, shape, distance, and connectedness, can be easily stored in digital format, and landscape indices can be calculated in geographic information system (GIS). Early studies on the quantification of landscape structure were mostly for special purpose or lack of analysis tools, thereby the results were limited (Turner, 1990). In recent years, the development of geographic information system (GIS) makes timely temporal and spatial information accessible. Moreover, its capability of spatial analysis and presentation makes it a useful tool for studying landscape spatial structure and landscape change analysis.

Landcover and landuse change analyses and projection provide a tool to assess ecosystem changes and its environmental implications at various temporal and spatial scales (Lambin, 1997). Data sets used in the landscape changes tend to be aerial photographs or satellite images because the study area is usually landscape scale or regional scale. Sometimes it is required to digitize maps in Computer Aided Design system (CAD) or GIS, specially, when dealing with historical landscapes. The next step to analyze land cover changes is to classify the land cover. In the digital data sets, patch-corridor-matrix of each land cover type stores land cover type, size, and location. Once landscapes characteristics are stored, researcher can detect the landscape changes in terms of vegetation type, patch size, landscape structure, configurations and compositions of the landscapes. Consequences of landscape changes can be expressed in several indicators such as biodiversity and nutrient fluxes (Fig. 2.2).

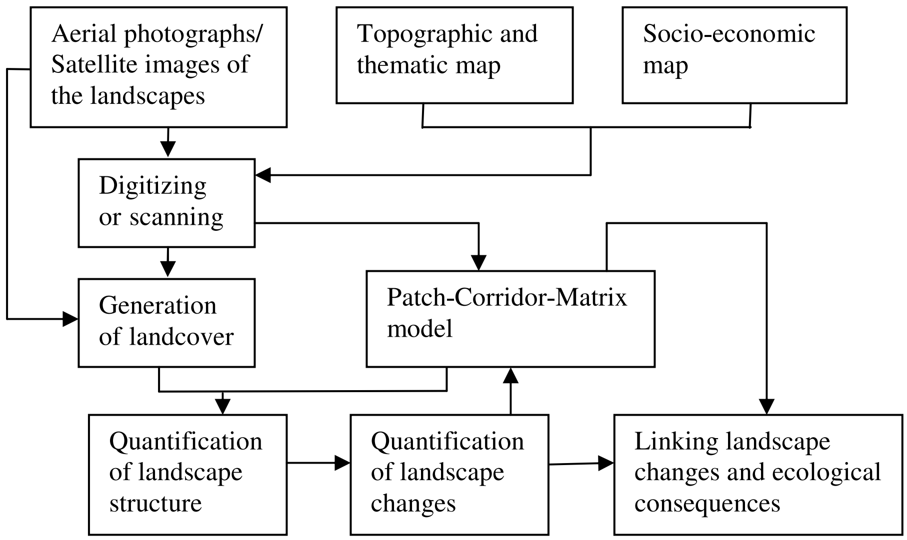


Fig.2.2. General flow of landscape changes study with P-M model (Transformed from Lopez model, 2001).

According to Collinge (1996), in the process of land use changes, native ecosystems are transformed from prairie to agricultural field and from forest to residential development. Land use changes may severely compromise the integrity of ecological system through loss of native species, invasion of exotic species, pronounced soil erosion, and decreased water quality.

4. Fragmentation and Landscape Metrics

4.1. Habitat Fragmentation

The expansion of urban areas causes deforestation and habitat fragmentation. When native vegetation is cleared for development, habitats which were once continuous become divided into separate fragments.

Habitat fragmentation is often defined as a process during which a large expanse of habitat is transformed into a number of smaller patches of smaller total area, isolated from each other by a matrix of habitats unlike the original (Wilcove, 1985). Fragmentation is also defined as the process of breaking up of continuous habitats, resulting in reduced area, increased edge, reduced interior area, increased isolation of patches and increased number of patches and decreased average patch size (Davidson, 1998).

In its strictest sense, fragmentation is the breaking of a whole into smaller pieces (Zipperer, 1993; Forman, 1995a; Bogaert et al., 2000). Therefore, a comprehensive definition can be proposed that habitat fragmentation is the process of breaking up continuous habitats and thereby generating habitat loss, isolation, and edge effects.

Habitat fragmentation is generally thought to have a large, negative effect on biodiversity and is therefore widely viewed as an aspect of habitat degradation (Haila, 2002). Forman (1995a) listed ecological effects of fragmentation in three categories: spatial, species, and other effects (Table 2.1).

Table 2.1
Ecological effects of fragmentation (Excerpted from Forman, 1995a)

	Increase	Decrease	Increase, decrease, or not change
Spatial effects	• Patch density • Inter-patch distance • Boundary length • Stepping stones • Corridors	• Patch size • Connectivity • Interior-to-edge ratio • Maximum size of core • Total interior area	• Patch shape • Fractal dimension * Depending upon the pattern of fragmentation
Species effects	• Isolation • Number of generalists • Number of multihabitat species • Number of edge species • Number of exotic species • Nest predation • Extinction rate	• Dispersal of interior specialists • Large-home-range species • Richness of interior species	
Other effects	• Metapopulation dynamics • Genetic inbreeding	• Internal habitat heterogeneity • The sizes of disturbance patches	• Natural disturbance • Hydrologic flows • Wind movement • Nutrient cycling • Productivity • Gene flow

He argues that spatial attributes such as patch density, inter-patch distance, boundary length, stepping stones, and corridors are commonly reported to increase patch size, connectivity, interior-to-edge ratio, maximum size of core, and total interior area decrease, and patch shape and fractal dimension increase, decrease, or no change, depending upon the pattern of fragmentation. In species effects, he argues that following species effects are common: isolation, number of generalists, multihabitat species, edge species, exotic species, nest predation, extinction rate increase, dispersal of interior specialists, large-home-range species, and richness of interior species decrease. As other effects, increases in metapopulation dynamics and genetic inbreeding are common while decreases in internal habitat heterogeneity and the sizes of disturbance patches are characteristic. Some variables, such as natural disturbance, natural disturbance, hydrologic flows, wind movement, nutrient cycling, productivity, and gene flow, increase, decrease, or remain unchanged.

Small fragments of habitat can only support small populations of fauna and biodiversity is quickly lost from small remnants. Fragments of habitat that are separated from one another are also unlikely to be recolonized. Furthermore, small fragments of habitat do not contain interior habitat. Habitat along the edge of a fragment has a different climate and favors different species to the interior. They are therefore unfavorable for those species which require interior habitat and may lead to the extinction of those species. In sum, fragmentation has effects on species extinction as well as almost all of the ecological patterns and processes.

4.2. Quantification of Landscape Pattern

The quantification of landscape pattern is an area of broad practical interest. Quantitative methods link spatial patterns and ecological processes at broad spatial and temporal scales. The purpose of landscape metrics is to obtain sets of quantitative data that allow a more objective comparison of different landscapes for grouping or differentiation (Antrop, 2000). Interest in measuring landscape pattern has been driven by the premise that ecological processes are linked to and can be predicted from some broad-scale spatial pattern (Baskent and Jordan, 1995; Gustafson, 1998). Because landscape ecology emphasizes the interaction between spatial pattern and ecological process, methods by which spatial patterning can be described and quantified are necessary.

There are numerous practical examples of where knowledge of the pattern is important. First, landscapes change through time, and we may be interested in knowing whether the pattern is different at time t+1 than it was at time t. Furthermore, we may want to know specifically how landscape pattern has changed. Actually landscapes have undergone dramatic change during the past two centuries. Second, we may wish to compare two or more different landscapes or places within a given landscape and determine how different or similar they are. In some cases, a political boundary may result in dramatically different landscape configurations within close proximity. Third, when considering options for land management or development, we may need to evaluate quantitatively the different landscape patterns that result from the alternatives. Spatial analyses have been especially informative when comparing alternative forest harvest strategies. Finally, different aspects of spatial pattern in the landscape may be important for processes such as the movement patterns of organisms, the redistribution of nutrients, or the spread of a natural disturbance. Metrics are required to describe these patterns.

4.3. Components of Categorical Map Patterns and Associated Metrics

Many metrics have been developed to quantify landscape patterns on categorical maps. Such metrics fall into two general categories: those that quantify the composition of the map without reference to spatial attributes, and those that quantify the spatial configuration of the map, requiring spatial information for their calculation (Gustafson, 1998; McGarigal and Marks, 1995).

Composition is easily quantified and refers to features associated with the variety and abundance of patch types within the landscape, but without considering the spatial character, placement, or location of patches within the mosaic. Because composition requires integration over all patch types, composition metrics are only applicable at the landscape level. The principal metrics are number of categories, proportions, and diversity.

Proportional abundance of each-class is one of the simplest and perhaps most useful pieces of information that can be derived relative to the entire map. Diversity measures typically combine two components of diversity: richness, which refers to the number of classes present, and evenness, which refers to the distribution of area among the classes. Dominance is the complement of evenness (evenness=1-dominance), indicating the extent to which the map is dominated by one or a few classes (O'Neill et al., 1988).

Spatial configuration is much more difficult to quantify and refers to the spatial character and arrangement, position, or orientation of patches within the class or landscape (McGarigal, 2002). Some aspects of configuration are measures of the spatial character of the patches themselves, even though the aggregation may be across patches at the class or landscape level. The spatial pattern being represented is the spatial character of the individual patches. The location of patches relative to each other is not explicitly represented. Such metrics, quantified in terms of the individual patches are spatially explicit at the level of the individual patch, not the class or landscape.

Configuration also can be quantified in terms of the spatial relationship of patches and patch types. These aspects of configuration are measures of the placement of patch types relative to other patches, other patch types, or other features of interest. These metrics are spatially explicit at the class or landscape level because the relative location of individual patches within the patch mosaic is represented in some way. There are many aspects of configuration and the literature is replete with methods and indices developed for representing them. The principal aspects of configuration are size, shape, density connectivity, fractal dimension, contagion, and lacunarity.

Patch size distribution and density is the simplest measure of configuration. Patch size represents a fundamental attribute of the spatial character of a patch and patch size distribution can be summarized at the class and landscape levels in a variety of ways (e.g. mean, median, max, variance) or, alternatively, formulated as patch density.

Shape complexity relates to the geometry of patches–whether they tend to be simple and compact, or irregular and convoluted. Due to the difficulty of indexing shape per se, shape metrics generally index overall shape complexity rather than attempt to assign a value to each unique shape. The most common measures of shape complexity are based on the relative amount of perimeter per unit area, usually indexed in terms of a perimeter-to-area ratio, or as a fractal dimension, and often standardized to a simple Euclidean shape (e.g. circle or square).

Contagion measures the extent to which cells of similar class are aggregated. The index is calculated using the frequencies with which different pairs of classes occur as adjacent pixels on the map. This index typically does not distinguish differences in aggregation that may exist for different classes, but summarizes the configuration of all classes. Contagion is appealing because it is a single-valued index used to represent complex interacting patterns.

Lacunarity analysis is a multiscale method used to determine the heterogeneity of a system property represented as a binary response in one, two, or three dimensions (Plotnick et al., 1993). The technique uses a gliding box (moving window) algorithm to describe the probability distribution of the class of interest as the box is passed over the data (a map, a transect, or points). Valuable insight into the spatial heterogeneity of the system and the domains of the scale of variation in that pattern can be achieved by using a number of box sizes and plotting lacunarity as a function of box size (Table 2.2).

Table 2.2
Components of categorical map patterns and associated metrics (Adopted from Gustafson 1998).

Components	Quantification	Measure
Categorical maps (Qualitative)		
Non-spatial (Composition)	• Number of categories • Proportions • Diversity □ Richness □ Evenness □ Dominance	• The number of classes in the map • The proportion of each class relative to the entire map • The number of classes present • The distribution of area among the classes • The extent to which the map is dominated by one or a few classes
Spatial (Configuration)	• Patch-based indices □ Size □ Shape □ Density □ Connectivity □ Fractal dimension • Pixel-based indices □ Contagion □ Lacunarity	 • The patch size which represents a fundamental attributes of the spatial character of a patch • The geometry of patches-whether simple, compact, irregular or convoluted. • The number of patches over unit area. • The functional connections among patches • The constant over a range of measurement scales • The clumpiness of maps • Multiscale method used to determine the heterogeneity of a system property represented as a binary response in one, two, or three dimensions

4.4. Landscape Metrics

The degree of fragmentation can be quantified with landscape metrics such as proportion, size, shape, density, and degree of isolation. Each landscape metrics represents spatial characteristics. In this study Patch Density (PD), Mean Patch Size (MPS), Mean shape Index (MSI), Mean Nearest Neighbor (MNN), Edge Density (ED) and Percent Land (PLAND) were selected.

4.4.1. Patch Density (PD)

Patch density (PD) is a limited, fundamental aspect of landscape structure. It expresses the number of patches of the corresponding patch type by per unit area. This metrics has the same basic utility as the number of patches as an index, except that it expresses the number of patches on a per unit area basis that facilitates comparisons among landscapes of various sizes. The number of patches of a particular habitat type may affect a variety of ecological processes, depending on the landscape context. The number of patches may determine the number of subpopulations in a spatially dispersed population, or metapopulation, for species exclusively associated with that habitat type. The number of subpopulations could influence the dynamics and persistence of the metapopulation (Gilpin and Hanski, 1991). The number of patches can also alter the stability of species interactions and opportunities for coexistence in both predator-prey and competitive systems (Kareiva, 1990). If class area is held constant, then a landscape with a greater density of patches of a target patch type would be considered more fragmented than a landscape with a lower density of patches of that patch type.

The density of patches in the entire landscape mosaic could also serve as a good heterogeneity index because a landscape with greater patch density would have more spatial heterogeneity. Warner (1994) argued the degree of spatial heterogeneity and connectivity within a landscape was positively correlated with species diversity and bird density.

4.4.2. Mean Patch Size (MPS)

Mean patch size (MPS) is the size of individual land cover patches (ha) averaged over all patches of a given class. Area metrics comprising a landscape mosaic is the single most important and useful piece of information contained in the landscape. In general, patch size is considered the foremost predictor of species diversity within a patch (Forman and Godron, 1981) and it has a great deal of ecological utility in its own right.

The bird species richness and the occurrence and abundance of some species are strongly correlated with patch size (Robbins et al., 1989). Herkert (1991) identified grassland patch size to be positively correlated with breeding bird diversity and abundance. Herkert (1994) suggested fields should be at least 50 ha and preferably 100 ha for grassland and forest bird species most sensitive to habitat fragmentation. However, less sensitive species should still benefit from grasslands of three over 20 ha.

Thus, patch size information alone could be used to model species richness, patch occupancy, and species distribution patterns in a landscape. Progressive reduction in the size of habitat fragments is a key component of habitat fragmentation. Thus, a landscape with a smaller mean patch size for the target patch type than another landscape might be considered more fragmented.

4.4.3. Mean Shape Index (MSI)

Mean shape index (MSI) measures the average patch shape, or the average perimeter-to-area ratio, for a particular patch type (class) or for all patches in the landscape. Shape index expresses the complexity of patch shape compared to a standard shape. Patch shape has been shown to influence interpatch processes such as small mammal migration (Buechner, 1989) and woody plant colonization (Hardt and Forman, 1989) and may influence animal foraging strategies (Forman and Godron, 1986). However, the primary significance of shape in determining the nature of patches in a landscape seems to be related to the "edge effect" (McGarigal and Marks, 1995).

4.4.4. Mean Nearest Neighbor Distance (MNN)

Nearest neighbor distance is defined as the distance from a patch to the nearest neighboring patch of the same type, based on edge-to-edge distance. This metrics quantify landscape configuration and can be used for a number of important ecological processes. For example, there has been an increase of mathematical models on population dynamics and species interactions in spatially subdivided populations (Kareiva, 1990), and results suggest that the dynamics of local plant and animal populations in a patch are influenced by their proximity to other subpopulations of the same or competing species. Many authors have claimed that patch isolation explains why fragmented habitats often contain fewer bird species than contiguous habitats (Hayden et al., 1985; Whitcomb et al., 1981). Interpatch distance plays a critical role in island biogeographic theory and in recent conservation efforts for endangered species (Lamberson et al., 1992; McKelvey et al., 1992). Similarly, Forman and Godron (1981) reported distance between patches was an important indicator or possible patch interactions and species diversity.

4.4.5. Edge Density (ED)

Edge density (ED) is the linear distance of edge per unit area of landscape (m/ha). Edge metrics usually are best considered as representing landscape configuration. In landscape ecological investigations, much of the presumed importance of spatial pattern is related to edge effects. The forest edge effect, for example, results primarily from differences in wind and light intensity and quality reaching a forest patch that alter microclimate and disturbance rates (Chen and Franklin, 1990; Gratkowski, 1956; Ranney et al., 1981). These changes, combined with changes in seed dispersal and herbivory, can influence vegetation composition and structure (Ranney et al., 1981).

It is now widely accepted that edge effects must be viewed from an organism-centered perspective because edge effects influence organisms differently; some species have an affinity for edges, some are unaffected, and others are adversely affected.

Most of the adverse effects of forest fragmentation on organisms seem to be either directly or indirectly related to edge effects. Therefore, edge index in a landscape often is the most critical piece of information in the study of fragmentation. Similarly, the total amount of edge in a landscape is directly related to the degree of spatial heterogeneity in that landscape.

4.4.6. Percentage of Landscape (PLAND)

Percentage of landscape (PLAND) quantifies the proportional abundance of each patch type in the landscape. Some ecological properties of a patch can be influenced by the abundance of similar patches in the surrounding landscape. For example, island biogeographic theory predicts that the probability of patch occupancy for some species or species richness is a function of both patch size and isolation (MacArthur and Wilson, 1967).

Numerous studies have indicated that the portion of various land cover types influences numerous species. Warner (1994) found relative amount of grassland as a factor influencing diversity and density of nesting birds, as well as nesting success of pheasants. Perkins et al. (1997) identified the proportion of grass in a hen’s home range was the only landscape variable to be significantly correlated with survival and that hens selected grass habitat and avoided corn and soybean fields. Lots of studies have indicated bobwhite abundance is positively correlated with amount of idle land and pasture land (Brady et al., 1993; Taylor et al., 1999).

However, because percentage of landscape (PLAND) is a relative measure, it may be a more appropriate measure of landscape composition than class area for comparing among landscapes of varying sizes.

4.4.7. Landscape Change and Indispensable Pattern

There is a temporal dimension of variation. Spatial relationships of habitats and organisms can have a profound effect on the ecological phenomena (Turner, 1989). Each land transformation is a series of spatial patterns over time. Land is transformed by multiple spatial processes overlapping in order, including perforation, fragmentation and attrition, which increase habitat loss and isolation, but can transform the spatial patterns and ecological processes (Forman, 1995a). Top-priority patterns for protection, with no known substitute for their ecological benefits, are a few large natural-vegetation patches, wide vegetated corridors protecting water courses, connectivity for movement of key species among large patches, and small patches and corridors providing heterogeneous bits of nature throughout developed areas (Forman, 1995a)

4.5. Measuring Fragmentation

Measurement of fragmentation is crucial for determining its consequences and to develop policy for nature conservation. As defined in section 3.1 fragmentation produces many changes in the landscape that can be quantified: reduced area of certain habitats, increased edge, reduced interior area, increased isolation of patches, and possibly increased number of patches and decreased average patch size. Most of these effects can be measured separately. However, there is no single measure that captures all aspects of fragmentation (Davidson, 1998). This poses problems for efforts to quantitatively evaluate changes in fragmentation or alternative landscape designs. Often a single measure is mistakenly used as an overall measure of fragmentation (Fig. 2.3, Fig 2.4)

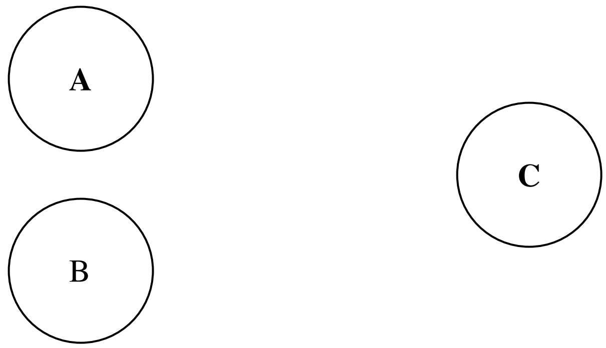


Fig. 2.3. Patches A, B, and C represent equal areas of habitat. Destructing any 1 patch leaves a landscape with equal patch area, interior area, and area-to-edge relationships. Fragmentation indices based on area or edge-to-area relationships do not reveal that a landscape of patches A and B is less isolated than a landscape of A and C or B and C (Davidson, 1998).

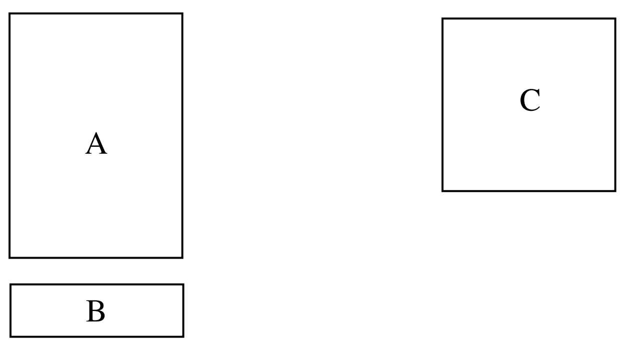


Fig. 2.4. Whether a landscape patches A and B or A and C is less fragmented depends upon the importance of area versus isolation in measuring fragmentation. For different species, total habitat area of habitat isolation may be more or less important in assessing fragmentation (Davidson, 1998).

Davidson (1998) presented two basic solutions to the lack of an overall index of fragmentation. The first is to select the single aspect of fragmentation that is of most concern to the question of interest; the second is to use several measures. Both solutions have their disadvantages. Interpreting single-factor measures of fragmentation is tricky.

Because edge length, patch area, interior area, isolation, and other indicators of fragmentation all interact and may change in contradictory directions as fragmentation proceeds.

The second method, use of multiple measures is most appropriate when concern is for the integrity of the entire ecosystem, rather than the impact on a single species with specific needs. Measuring fragmentation requires balancing different measurements, often in different metrics. So, combination of different measures can not be carried out unambiguously (Davidson, 1998).

In this study, both methods will be used for interpretation of fragmentation overtime of study areas. For the combination of multiple measures, the model for measuring fragmentation proposed by Bogaert et al. (2000) is applied. In this model, fragmentation measure $|\phi|$ combines, using a multidimensional Euclidean distance, 4 main characteristics of fragmented landscape: total habitat area, total habitat perimeter, number of patches, and patch isolation. This model is appropriate to reflect the overall fragmentation status.

4.5.1. Definition of the Single Fragmentation Measure

- Habitat area

A minimum patch area a_{min}, is determined by the size of the square pixels composing the image; the pixel size is then considered as the unit of area measurement (a_{min}=4). The theoretical maximum area of a single patch a_{max}, can be defined using historical data or can be simply set equal to the study area extent a_s. The observed total habitat area value a_{obs} can then be transformed into

$$\alpha = \frac{a_{obs} - a_{min}}{a_{max} - a_{min}} \times 100.$$

The normalized α-index reflects the habitat retention after fragmentation. Large values of α are found for minimally fragmented landscapes.

- Habitat perimeter

To assess boundary length, cumulative patch perimeter p_{obs} is compared with the minimum and maximum perimeter that can be configured for a_{obs}. For raster data, $p_{max}=4\cdot a_{obs}$ and calculation of p_{min} is dependent on a_{obs}. For a_{obs} it is always valid that $j^2 \leq a_{obs} < (j+1)^2$ and $j \in Z_0^+$ (i.e., j is a non-negative integer greater than 0.0). If $a_{obs}=j^2$, then $p_{min}=4\sqrt{a_{obs}}$ and the j^2 pixels form a square figure. If $j^2 < a_{obs} \leq j(j+1)$, then $p_{min}=2(2j+1)$ and a figure is formed composed of a square with j^2 pixels to which $(a_{obs}-j^2)$ pixels are added at one side. For $a_{obs}=j(j+1)$, a rectangle is formed with side lengths j and $j+1$. Finally, if $a_{obs}>j(j+1)$, then $p_{min}=4(j+1)$. The pixels are now added to the rectangle's side of $j+1$ pixels. A normalized value β can then be calculated to assess boundary length, i.e.,

$$\beta = \frac{p_{max} - p_{obs}}{p_{max} - p_{min}} \times 100,$$

and small β values are associated with longer perimeter lengths, i.e., increased degree of fragmentation.

- Number of patches

To quantify number of patches n_{obs}, the theoretical maximum (n_{max}) and minimum number (n_{min}) are used, i.e.,

$$\nu = \frac{n_{\max} - n_{obs}}{n_{\max} - n_{\min}} \times 100,$$

with n_{max}=(a_{obs}/a_{min}) and n_{min}=1.0. The observation of many patches generates lower ν values.

- Patch isolation

Patch isolation is measured using the sum of 2 distances d_{obs}: the smallest of all nearest neighbors and the largest of all farthest neighbors. The distances are measured between all patches and the greatest and least values are retained. For n_{obs} patches, $n_{obs}(n_{obs}-1)$ distances are compared. High and low values of d_{obs} indicate high and low degrees of patch isolation, respectively. The theoretical maximum value d_{max} will be dependent on study area features. For raster images, distances are calculated using row and column numbers and $d_{obs} \geq 2\sqrt{2} = d_{min}$. Normalization of d_{obs} results in δ, i.e.,

$$\delta = \frac{d_{\max} - d_{obs}}{d_{\max} - d_{\min}} \times 100$$

Low δ values are found for extremely isolated patches.

The four indices can be combined to a single measure using a 4-D space composed of 4 orthogonal coordinate axes with origin *O*. Every fragmented patch type f can then be represented by a point or vector ϕ_f in this space denoted as the array (α_f,β_f,ν_f,δ_f), characterized by the vector length $|\phi_f|$ measuring the Euclidean distance to the origin, calculated by

$$|\phi_f| = \sqrt{\alpha_f^2 + \beta_f^2 + \nu_f^2 + \delta_f^2}$$

Points remote of *O* represent habitats with a low degree of fragmentation ($|\phi_f| \approx 200$). The fragmentation index $|\phi|$ does not incorporate interior-to-edge measures or connectivity measures, but all main features of fragmentation are incorporated or can be derived from the components. Analysis of the components can be suggested for policy development to mitigate fragmentation.

4.5.2. Sensitivity Analysis

To know how the metrics perform over a range of fragmentation levels, various types of fragmentation patterns are presented (Bogaert, 2000). Fig. 2.5 illustrates the

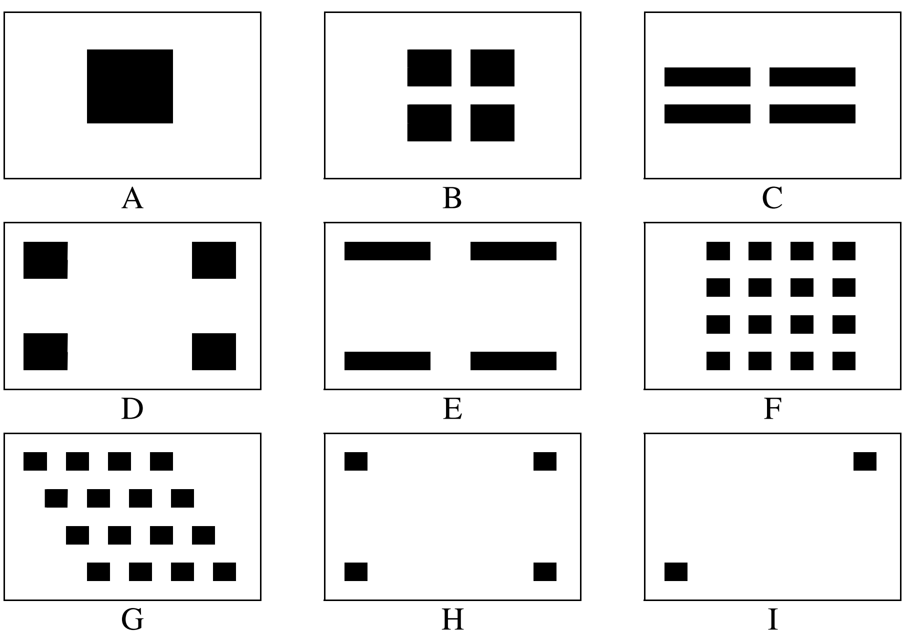


Fig. 2.5. Set of 9 fragmentation patterns for sensitivity analysis (Adopted from Bogaert (2000))

variation in calculated values of α, β, ν, δ, and |ϕ|. Table 2.3 shows the results of calculation. Four parameters vary in the set: 1) total habitat aera, for which the area of pattern A (=a_{obs}(A)) is used as reference, i.e., $a_{obs}(A)= a_{max}$, and for which a_{min} equals the pixel size, i.e., $a_{min}= 1$; 2) total habitat perimeter, with reference values calculated based on the present area; 3) total number of fragments, with $n_{max}=a_{obs}$ and $n_{min}=1$; and 4) patch isolation, with reference values $d_{min}=2\sqrt{2}\approx 2.83$ and d_{max} as observed for pattern I (=d_{obs}(I)), i.e., $d_{max}= d_{obs}(I)= 2\sqrt{12^2+6^2}\approx 26.83$. The following reference values are identical for all patterns: a_{max}, a_{min}, d_{max}, and d_{min}. The reference values p_{max}, p_{min}, n_{max}, and n_{min} are calculated for each pattern separately and are based upon the area (in number of pixels) present. Pattern A is characterized by |ϕ| = 200.00 and pattern I represents the most fragmented situation.

Differences between patterns B-G are caused by changes in perimeter, fragment number and changes in isolation. According to Bogaert (2000), the pattern sequence A-I clearly illustrates the sensitivity of the proposed method to changes in area, perimeter (shape), patch number and isolation. High values are found for the least fragmented patterns, whereas low values are characteristic for the most fragmented habitats (Table 2.3).

Table 2.3
Sensitivity analysis using 9 spatial patterns representing different fragmentation states

Pattern	α	β	ν	δ	|ϕ|
A	100.00	100.00	100.00	100.00	**200.00**
B	100.00	66.67	80.00	91.67	**171.02**
C	100.00	50.00	80.00	91.67	**165.24**
D	100.00	66.67	80.00	40.62	**149.98**
E	100.00	50.00	80.00	41.38	**143.57**
F	100.00	0.00	0.00	68.10	**120.99**
G	100.00	0.00	0.00	47.56	**110.73**
H	20.00	0.00	0.00	30.90	**36.80**
I	6.67	0.00	0.00	0.00	**6.67**

α: area index, β: perimeter index, ν: number of patch index, δ: isolation index, |ϕ|: fragmentation index

5. Urban Sprawl and Local Development Regulation

5.1. Introduction

After World War II, the development of high speed and multiple lane highways allowed workers to smaller towns 20-30 miles from their work. Because the land in these small towns was cheap, these new residents were able to afford to build a house on a much larger parcel of land than was possible in the city. Thus, the suburban communities were far less dense than their urban counterparts. Shortly thereafter, businesses wishing to avoid the high rent of downtown office buildings moved to less dense office parks outside the city. Eventually the demand for suburban land drove up its price. Enterprising land developers then began to buy cheaper land even farther from the city and the same process began again. The low density housing in the suburbs drains the infrastructure. Roads and utilities must be stretched much further to serve the same number of people than they do in the city. Beautiful hilly areas are destroyed and subdivided.

Local governments possess four general kinds of authority that can be used to implement plans: the power to regulate, the power to condemn and exact, the power to spend, and the power to tax. Regulation derives from the police powers to protect public health, safety, welfare, and morals. The most common, and perhaps least popular, regulatory technique used in the United States is zoning. Other techniques, which may be used in conjunction with zoning, include planned unit developments (PUDs), performance standards, design guidelines, critical (or environmentally sensitive) areas protection, wetland and riparian area protection, habitat conservation plans, historic preservation, subdivision regulations, and building codes. Covenants are private contracts that can be used to regulate many of the same features as zoning, design guidelines, and subdivision ordinances (Steiner, 2000).

The government power to regulate human activity is carefully balanced against fundamental freedoms of the individual. Cities and counties derive limited regulatory power from the states, but local governments must use those powers in reasonable ways to achieve public goals without infringing on basic individual rights. Regulations involve rules and restrictions that are used to control what an individual, a family, or a business can do with its property. Such rules and restrictions may also involve how land use on one property affects neighboring areas. Regulations can direct activities from ones with negative consequences to those with positive results. Restrictions and rules help reinforce the responsibilities which accompany property ownership.

5.2. Urban Sprawl

Urban sprawl, evident primarily in rural urban fringe areas, has been frequently viewed as a source of problems, which stem from unplanned, scattered and piecemeal residential and commercial development (Razin, 1998). Conflicting land uses, pressures on agricultural and open space, high costs of service provision, adverse consequences on traffic and public transport, and social disparities are among the more noticeable problems (Thomas, 1990). Municipal fragmentation, frequently associated with urban sprawl, is likely to intensify these problems (Veer, 1994). Backed by *laissez-faire* ideologies, contrasting arguments in favor of urban sprawl challenge notions on its perceived disadvantages (Gordon and Richardson, 1997), and stress its contribution in meeting popular demand for low-density, semi-rural, residential environments, and in avoiding discrimination of new entrants into the housing market. Hence, conflicts between private capital and public planning over development patterns are now endemic in many urban fringe areas (Pacione, 1993).

The debate on urban sprawl in the United States involves contradicting views on whether suburban business ventures at the edge of the metropolis can grow independently of central cities (Garreau, 1988), or whether central cities and their suburbs are highly interdependent. The latter view maintains that suburban sprawl is associated with the decline of central cities and older suburbs, negatively affecting the future of the metropolis (Savitch et al., 1993; Danielson and Wolpert, 1994).

Downs (1998) identified sprawl as follows: 1) unlimited outward extension, 2) low-density residential and commercial settlements, 3) leapfrog development, 4) fragmentation of powers over land use among many small localities, 5) dominance of transportation by private automotive vehicles, 6) no centralized planning or control of land-uses, 7) widespread strip commercial development, 8) great fiscal disparities among localities, 9) segregation of types of land uses in different zones, 10) reliance mainly on the trickle-down or filtering process to provide housing to low-income households. In general, sprawl is defined as dispersed development outside of compact urban and village centers along highways and in rural countryside.

5.3. Local Development Regulations

5.3.1. Zoning

First adopted by the City of New York in 1916, zoning is probably the most common land use instrument used by local governments in the United States today. Its constitutional basis stems from the responsibility of state governments to provide for the health, safety, and welfare of it citizens. As recommended in the Standard Zoning Enabling Act prepared by the U.S. Department of Commerce in 1925, most states delegated the authority to zone and regulate subdivision activity to local governments. Subsequently, in 1926, the Supreme Court ruled that zoning was a legitimate exercise of police power not in violation of the U.S. constitution. As a result, the popularity of zoning soared. By 1930, almost every major city and many small cities and towns had adopted zoning ordinances. These ordinances contained numerous land use categories and specific restrictions on the bulk, setback, and density of urban development for each land use category (Delafons, 1969).

In principle, the purpose of zoning is to assure that land uses in a community are appropriately situated; to provide adequate open space and access to services such as streets, schools, and utility systems; and to protect property values by separating incompatible uses (Moore, 1978). In practice, however, zoning can be used to exclude low-income or minority residents; to attract uses that contribute more to municipal costs than revenues; and to prevent potential new residents from moving into the community (Mills, 1979). Recently, critics of zoning have argued that zoning contributes to urban sprawl (Pendall, 1999; Shen, 1996; Feitelson, 1993; Levine, 1999). These critics suggest that zoning and subdivision regulations are used to lower the density of residential development, create excessive separation between complementary uses, and create an urban fabric dominated by large parking lots, wide streets, and unsightly suburban monotony. Euclidean land-use zoning has particularly been criticized for procedural inadequacies: lax enforcement, favoritism, non-consistency with planning, and excessive rigidity in some cases and undue flexibility in others.

Nowadays the new term “smart growth”, that means policies regarding growth and development that recognize the effects of new growth and development, including the environmental, economic, and social costs, appears.

5.3.2. Planned Unit Developments (PUDs)

A planned unit development (PUD) is comprehensively conceived and contains some mix of residential, commercial, industrial, institutional, and recreational land uses on a single tract of land. Sometimes a PUD ordinance is included as a part of zoning regulations, while at other times it is addressed under separate rules. PUD ordinances offer benefits to both developers and communities. Under PUDs, developers are allowed greater design flexibility and greater densities, while communities are able to protect environmentally sensitive areas or enforce design standards. Frequently, homeowners' associations become responsible. Cullingworth (1997) notes that such associations play an important role in managing commonly held property. Homeowners' associations also become responsible for restrictions and covenants placed on the PUD by the developer. Such restrictions can require that homeowners use only native plants on their lawns and paint their houses certain colors for compatibility.

5.3.3. Performance Standards

Performance standard is a rather broad, generic term that has been defined and applied in several different ways. Basically, the term refers to criteria that are established and must be met before a certain use will be permitted. These criteria, or standards, may be a set of economic, environmental, or social factors or any combination of these factors. Originally, performance standards were used as a means for prescribing specific conditions for observable or scientifically measurable industrial plant emissions. More recently, performance standards have been linked to zoning ordinances in various ways.

Conventional prescriptive zoning ordinances "are based on the principle that most land uses are incompatible and should be separated from one another" (Juster, 1994). In contrast, performance zoning is based on the premise that within broad limits different land uses can coexist with one another" (Juster, 1994)

5.3.4. Design Guidelines and Controls

Design guidelines and controls establish standards for landscape architecture features of new development. Stokes et al. (1997) note that design guidelines "can illustrate what acceptable development in the community should look like, and they can be published by citizens' groups or governmental bodies." The guidelines or control standards are published by the municipality or the county. A proponent for a new development or a change of a building's use must present designs illustrating how they are in compliance with the standards. Usually a design review board, comprised of local experts, is responsible for checking whether the designs are in compliance. The standards address requirements for the site, for proposed structure, and often for off-site features (Shirvani, 1990). Site standards usually include guidelines for parking, circulation, paving, lawns, plantings, drainage, irrigation, signs, fencing, setbacks, and building envelopes.

5.3.5. Subdivision Regulations

The regulation of land subdivision is a fundamental legal tool for municipal guidance of land development. It applies not only to single-family projects, but also to the development of condominiums and to nonresidential subdivisions such as industrial parks.

The purpose of subdivision regulations is to protect the public interest during the laying out of land and the construction of public and private improvements. Like comprehensive or general plans and zoning ordinances, local governments have the authority to enact subdivision regulations through state enabling legislation. Subdivision regulation supplements but does not modify zoning. The use of land, minimum lot size, and bulk of structures to be built in the subdivision all must conform with applicable zoning. Subdivision approval requires that in addition to satisfying all zoning provisions, the proposed development will also meet performance standards for the layout and design of new subdivisions (Platt, 1991).

Subdivision regulations usually have strong enforcement provisions: Deeds to subdivided land may not be recorded or registered, and consequently land may not be sold, until the planning commission forwards an approved copy of a final plat to the county clerk or auditor.

5.3.6. Covenants

Covenants are agreements, usually voluntary, that restrict what can be done with private property. Generally, for a covenant to be imposed, property has to change hands, at which time these agreements appear in the new deed. Typically, covenants are placed on a property by an owner prior to sale. Usually private parties, rather than governments, impose covenants. Covenants are usually backed up by government authority and may be called voluntary covenants, restrictive covenants, or deed restrictions. The purpose of covenants is to place additional rules, regulations and/or restrictions upon the use of land over and above, or not capable of being implemented, in the zoning ordinances, subdivision regulations, or building codes; or in the absence of such ordinances, regulations, or codes.

Often all lots within a subdivision will have covenants attached to the land title that describe and design limitations on houses or other structures such as outbuildings and fences. The same principle has been used to a limited extent to control the use of land in the larger community. For instance, a local government may choose to implement its land-use plan through covenants rather than zoning.

If a covenant is broken, then other landowners affected by the action can bring suit to restore the original covenant-specified condition or receive compensation for damages. Covenants specify who can bring suit, sometimes including local municipalities. Since neighbors find it very difficult to bring suit against each other, often covenants are not enforced. Therefore, the use of voluntary covenants would only be a reasonable means to control the use of land as long as the parties affected by the covenants are willing to see that they are enforced. One way covenants could be made more efficient in land-use control is for a homeowners' or watershed association to be formed, so that complaints are a result of a collective, rather than individual, action (Steiner, 2000).

5.3.7. Landscape Ordinances

Landscape ordinances provide for the preservation of natural features such as wetlands, erodible slopes, special native habitats, and specimen trees (Abbey, 1998). Ordinances protect and enhance property values and aesthetic environments, prevent soil erosion and sedimentation, reduce air pollution, attenuate sound, regulate planting, care, maintenance and repair of trees, shrubs, ground covers and vines, regulate plant removal, and protect rural, suburban and urban water sheds and woodland resources (Tereshkovich, 1990). In some communities, the total context of their ordinances is the protection of the public water supply, whereas in other communities it is the tree canopy that is important to preserve. Though these ordinances may vary from one region to another, from one community to another, they all have a common thread that makes them acceptable to the public (Tereshkovich, 1990).

Landscape ordinances can be found at various levels of government. At the state level there is in some cases a provision in the constitution for an individual's right to "clean air, pure water, and … the preservation of the natural, scenic, historic, and aesthetic values of the environment". At the regional and county level there are a small number of true landscape ordinances, though by necessity they are somewhat broad and general in their legislation. Ordinances are much more common at the local level, where they can be specific in their regulations and may be subdivided by zoning classifications such as residential, commercial, and industrial.

Finally, there are numerous instances where a neighborhood or planned unit development will establish its own landscaping regulations in order to maintain a high level of quality and control over the development. These requirements can be found in restrictive covenants or landscaping associations that are hired to maintain a specific neighborhood or development.

The reasons presently given by cities for establishing landscape ordinances are many, yet the main premise for these ordinances must legally be the protection of the public's health, safety and/or welfare. Some of the reasons used under this main premise are aesthetic in nature and have resulted in regulations such as the planting of shrubs along a fence to soften its visual effect, or the screening of vehicular areas in order to improve the visual quality of the streetscape. Others are based on the need to preserve and protect the environment, and result in regulations requiring water detention and retention areas or restrictions on the clear cutting of sites. Ordinances have been used as a means to improve the quality of the urban community, as well as to protect, enhance and preserve the natural environment of our cities and towns. Landscape ordinances have attempted to maintain certain aesthetic standards and improve the overall quality of the urban environment by controlling such elements as vegetation and landscape buffers.

6. Summary

In this chapter, I reviewed the literature on landscape ecology, landscape ecological planning, patch-corridor-matrix (PM) model, quantitative method in landscape ecology, fragmentation measurement, urban sprawl, and land development regulations.

Literature on landscape ecology provides the basic understanding about landscape ecology and why landscape ecology is important to landscape architecture and urban planning. Landscape metrics and measuring fragmentation were also discussed for the purpose of quantifying landscape structure.

Landscape ordinances come into existence recently in community development. Previous study showed that land development regulation led to a suburban fragmentation and decentralization and pushed development in one direction or another. However, few studies have been conducted on the relationship between landscape pattern and local development regulations.

Ordinances have been used as a means to improve the quality of the urban community, as well as to protect, enhance and preserve the natural environment. More and more communities are requiring that landscape plans be drawn to code and meet various technical requirements that are being enacted by city councils (Abbey, 1999). So, the topic of the relationship between landscape patterns in ecological perspective and land development regulations can be a critical issue in landscape architecture research for better strategies of planning and designing sustainable communities.

CHAPTER III

RESEARCH METHODS AND DATA

1. Introduction

Chapter III contains the research methods and data. First, it sets up a conceptual framework to explore the relationship between landscape structure and local development regulations applied to study areas. Based on the conceptual framework, hypotheses have been derived. The next subchapter presents the biophysical characteristics and applied land development regulations of two study areas. Finally this chapter specifies collected dada and study flow such as data collection, mosaic and color balancing, classification, calculating landscape metrics, and sampling.

2. Conceptual Framework and Hypotheses

2.1. Conceptual Framework

As more and more communities are requiring landscape plans be drawn to code and meet various technical requirements that are being enacted by city councils across the land (Abbey, 1999), the topic of the relationship between urban vegetation patterns from a landscape ecological perspective and local development regulations and ecological planning approach can be a critical issue in landscape architecture research. In this context, this study started with some questions related to development regulations and landscape structure: Are there relationships between local development regulations and guidelines and landscape structures? If they are related, how do local development regulations and guidelines affect landscape structures? More specifically, how do land development regulations and standards affect the landscape metrics? Are there relationships between planning method and fragmentation of urban vegetation? If there are changes in landscape structures after development, do they persist over time?

Comparison analysis was conducted between two areas that had similar pre-development ecological conditions but were developed under vastly different regulatory environments. The Woodlands which was regulated to protect ecological condition and North Houston area which followed traditional subdivision regulations were examined at three different developmental time periods: predevelopment, early development (after 10 years), and matured development (after 30 years).

A study concerning the relationship between landscape structure and local development regulations needs to look at the difference between study areas as well as within each area. Fig. 3.1 illustrates a conceptual framework for this study. This study examines the land cover changes within sites and investigates the difference between sites for the relationship between landscape stricture and planning method and development regulations.

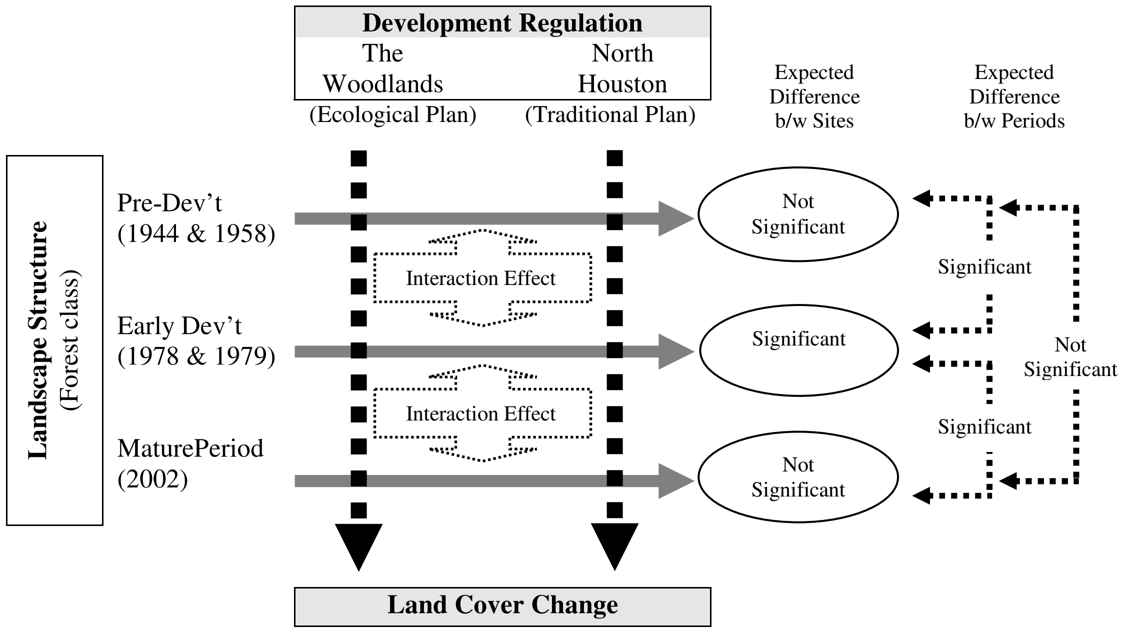


Fig. 3.1. Conceptual framework

2.2. Hypotheses

Based on the above questions and conceptual framework, hypotheses have been made as below:

Hypothesis 1: More restrictive development regulations lead to lower forest habitat fragmentation in the period just after development.

Hypothesis 2: Landscape fragmentation is higher in traditionally planned community than in ecologically planned one.

Hypothesis 3: Over time, re-growth will lead to no differences in fragmentation between regulatory environments.

Hypothesis 4: Different development regulations affect ecological landscape structure differently (Interaction effect).

2.3. Study Flow

The outline of this study flow contains two major streams: 1) Examining the local development regulations and 2) Measuring the landscape structure using GIS (Geographic Information System) and RS (Remote Sensing) analysis (Fig. 3.2).

Development regulations are examined in land platting policy manual, subdivision ordinances, residential development standards, deed restriction, and covenant for the two study areas. Black and white aerial photographs and DOQs (Digital Orthophoto Quadrangles) of two areas were scanned and adjusted in a spatial resolution of 2m and classified using ISOCLASS (Iterative Self-Organizing Data Analysis) technique. The classes consist of forest, grassland, and developed area. Landscape structure was analyzed in FRAGSTAT, a landscape pattern analysis software developed by McGarigal and Marks (1995).

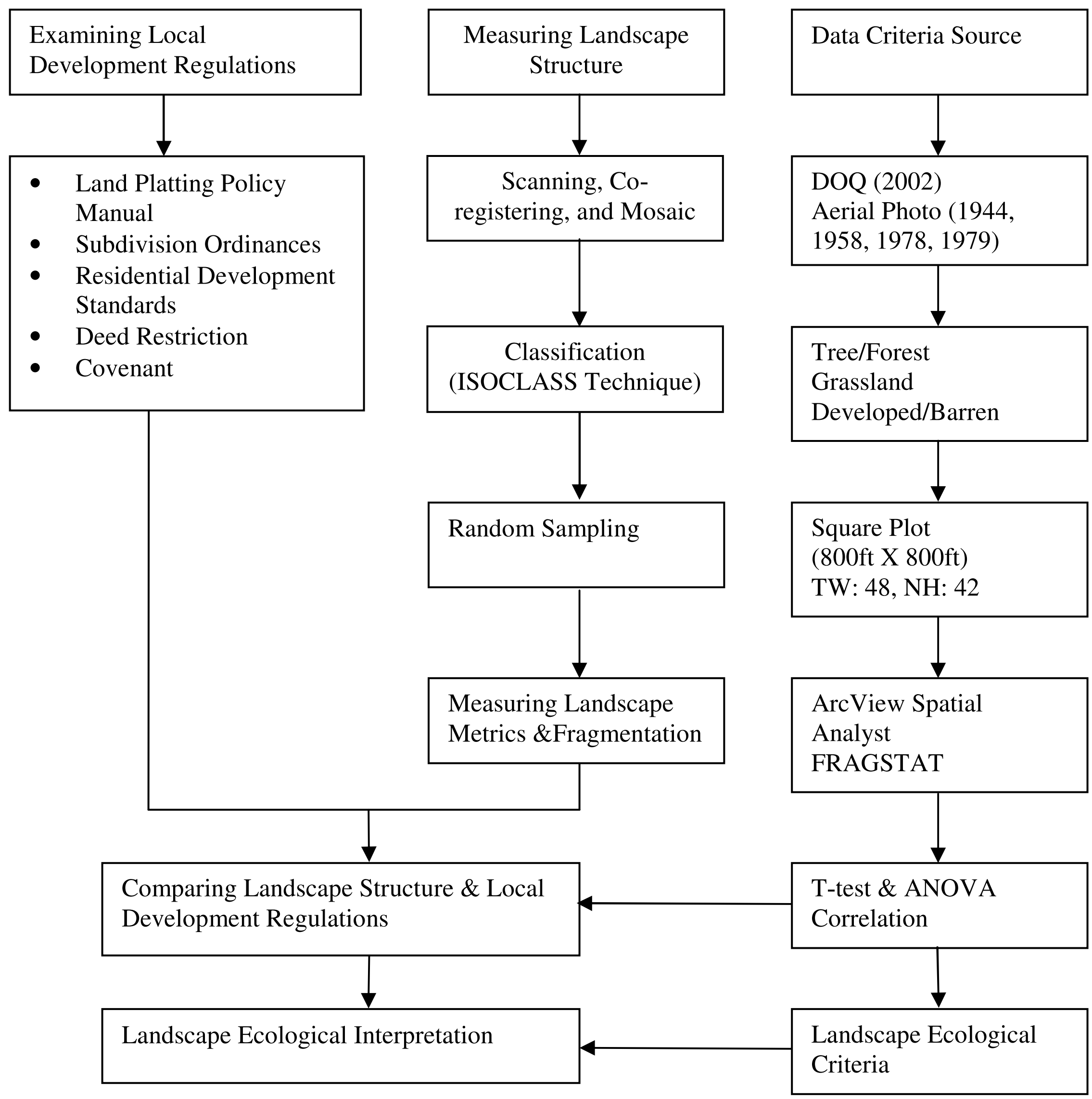


Fig. 3.2. Study flow

3. Research Design

3.1. Study Area

The Woodlands and North Houston area were selected as study areas. The Woodlands is a community west of Interstate Highway 45 and eleven miles south of

Conroe in southern Montgomery County. This area is bounded on the south by Harris County. North Houston area is located north of the Beltway (FM 1960) that is between I-45 and HW 149 (Fig. 3.3).

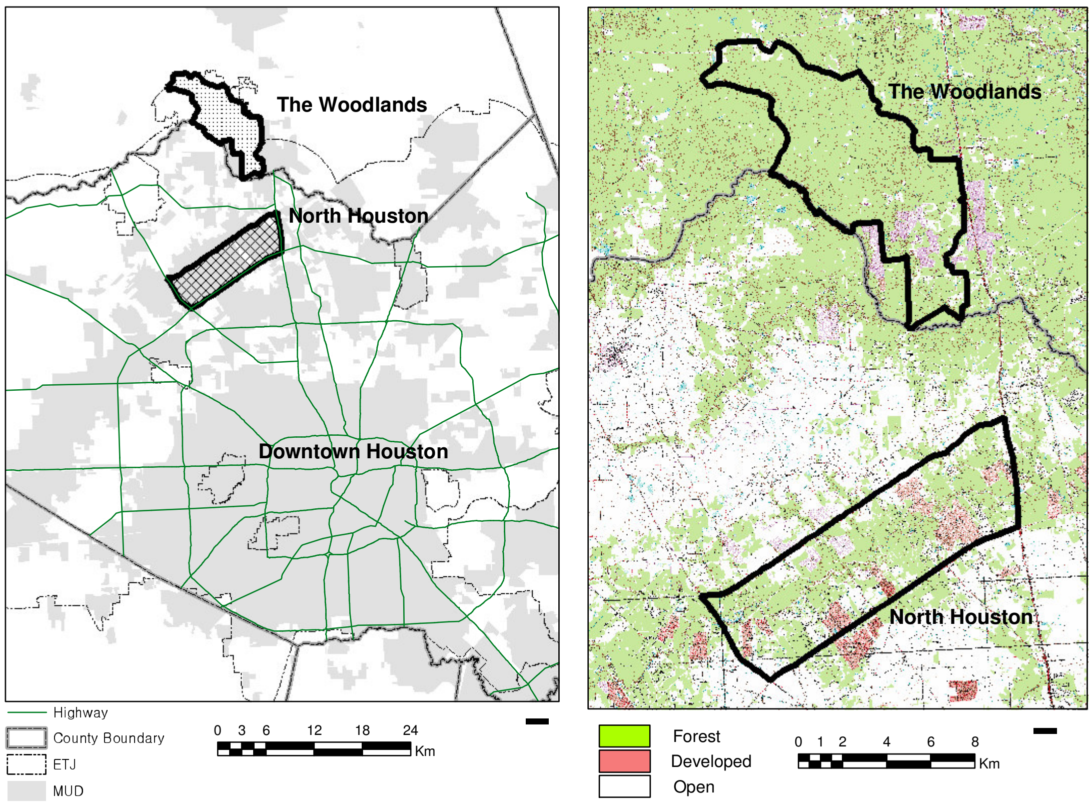


Fig. 3.3. Location map and the digital graphic raster (1975)

3.2. Biophysical Characteristics

3.2.1. Vegetation Types and Ecoregion

Although The Woodlands is located in Montgomery county and North Houston area in Harris county respectively, they are nearly adjacent to each other. The Woodlands is located approximately 27miles north of Houston, Texas, and two areas began development around the early 1970's. Biophysical characteristics such as vegetation, soil, and topography of these areas are very similar. Both areas lie within same vegetation type boundary. Even though North Houston area has a little portion of Crops type and lies adjacent to the different ecoregion, Pine-Hardwood forest type is mainly distributed in both areas (Fig. 3.4).

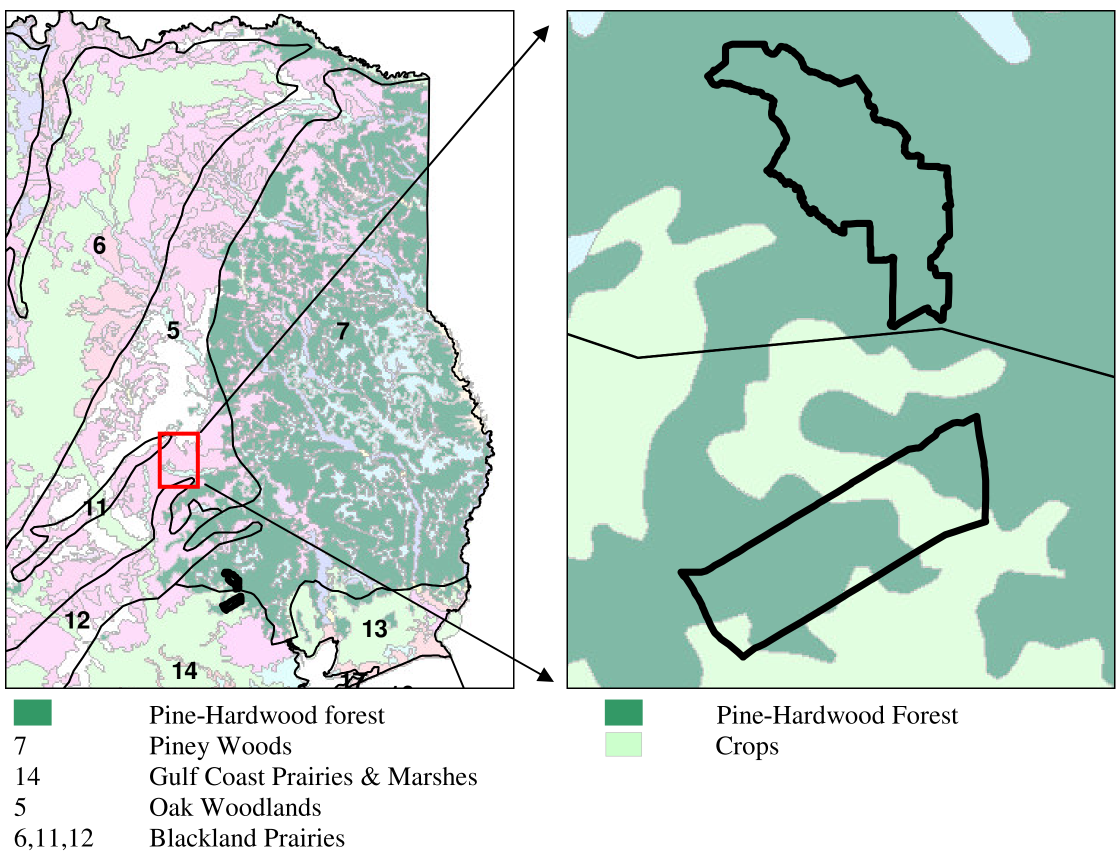


Fig. 3.4. The vegetation types and ecoregion of study areas

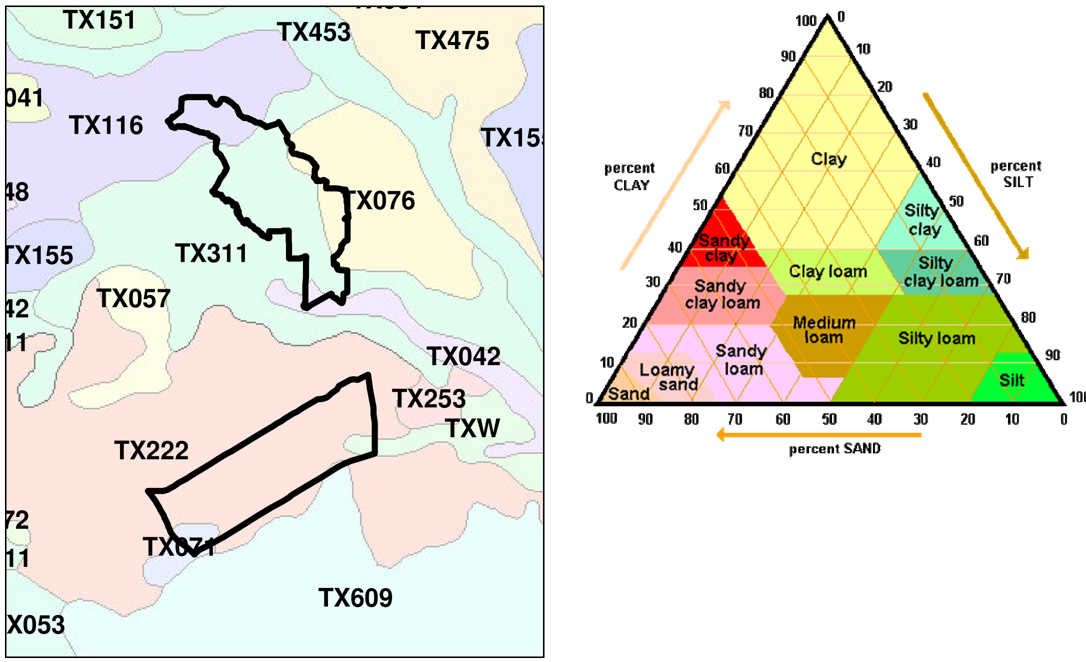
The Pine-Hardwood forest lies within the Piney Woods ecoregion, which extends into Texas for 75 to 125 miles west of the Louisiana border (Fig. 3.4). This area is a nearly level to gently undulating, locally hilly, forested plain. The dominant vegetation type of this area is a mixed pine-hard forest on the uplands and a mixed hardwood forest on the lowlands. Native pines are loblolly (*Pinus taeda*), shortleaf (*P. echinata*), and longleaf (*P. palustris*). Slash pine (*P. elliottii*), a native of the southeastern United States, has been widely planted on thousands of acres. Hardwoods grow in mixed stands with pines in the uplands but are generally dominant along major streams. The principal hardwoods in the region are sweetgum (*Liquidambar styraciflua*), oaks (*Quercus*), water tupelo (*Nyssa aquatica*), blackgum (*N. sylvatica*), magnolias (*Magnolia*), elms (*Ulmus*), cottonwoods (*Populus*), hickories (*Carya*), walnuts (*Juglans*), maples (*Acer)*, American beech (*Fagus grandifolia*), ashes (*Fraxinus*), and baldcypress (*Taxodium distichum*).

3.2.2. Wildlife

Wildlife in these areas include eastern gray and fox squirrels, various species of bats and skunks, and small herbivores such as gophers, mice, rabbits, and armadillos, as well as raccoons, white-tailed deer, opossum, bobcat, coyote, and red and gray fox. Alligators, frogs, toads, and numerous species of snake, including the poisonous copperhead, cottonmouth, coral snakes, and rattlesnake, are found in abundance. A wide variety of birds - mockingbirds, cardinals, doves, quail, blue jays, and roadrunners, to name a few - are also native to the area.

3.2.3. Soil

In the Piney Woods area, upland soils are generally acid, sandy loams and sands over gray, yellow, red, or mottled sandy loam to clay subsoil. Bottomland soils are



TX311 LFS (Loamy Fine Sand)
TX076 SIL (Silt Loam)
TX222 FSL (Fine Sandy Loam)

Fig. 3.5. Soil type

generally light brown to dark gray, acid to calcareous, loamy to clayey alluvial. Acid loamy soils are extensive in the flood plains of minor streams. Study area soils are light-colored and loamy with deep, reddish, clayey to loamy subsoil. Specifically Loamy fine sand and Silt loam are distributed in The Woodlands area and Fine Sandy Loam type soil is mainly distributed in North Houston area (Fig. 3.5).

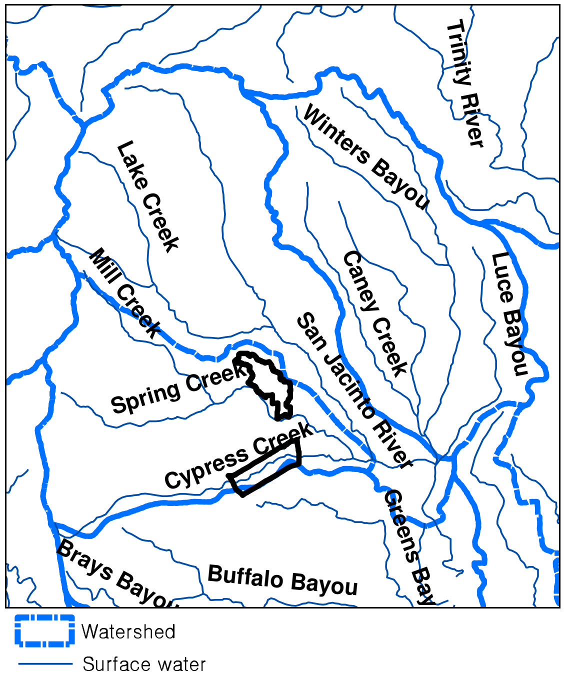
3.2.4. Watershed

Also both areas lie within the same watershed boundary. Spring Creek forms Harris County's northern boundary and, joined by parallel Cypress Creek, becomes the

West Fork of the San Jacinto River. Spring Creek flows adjacent to the south boundary of The Woodlands and Cypress Creek passes through North Houston area (Fig. 3.6). Topography of these two areas is almost flat and average soil surface slope for this area is below 2%.

3.2.5. Climate and Precipitation

The climate is subtropical humid, with warm summers and mild winters. The average annual relative humidity is 73 percent, and the average rainfall is 47.81 inches (Fig. 3.7). The average annual temperature is 68° F. Temperatures in January range from an average low of 39°F to an average high of 61° F and in July range from 72° F to 95° F. The growing season averages 270 days per year, with the last freeze in early March and the first freeze in late November.



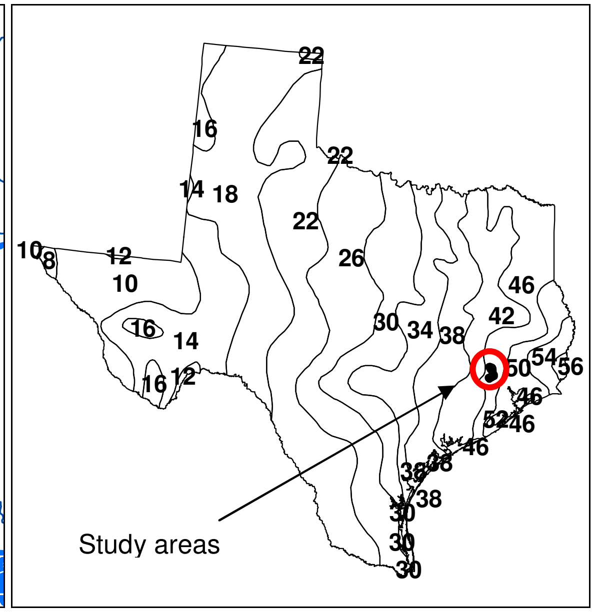


Fig. 3.6. Watershed and surface water

Fig. 3.7. Precipitation (unit: inch)

3.3. Land Development Regulations

Despite the similarities in pre-development environmental aspects, these communities were developed and maintained under two different regulatory environments, ranging from standard, largely permissive subdivision guidelines to highly restrictive ecology-based covenants administered through a homeowner association.

The Woodlands is a master-planned community. According to McHarg (1975), this is the first city plan produced by ecological planning. The Woodlands began development in the 1970s on a site that includes 27,000 acres of old logging forests and ranch land. The population of The Woodlands has increased in average of 3.7 %

annually since 1974. The population in 2002 is 70,050 and in 2007 it is projected 97,000. On-going development of The Woodlands is guided by a group of legally binding covenants and design standard guidelines including landscaping and tree removal.

North Houston area also began development in the early 1970s. Since this area is beyond the city limits of Houston in Harrison County, Municipal Utility Districts (MUD) were created as a financing tool to provide water, sewer and drainage to property within the district's boundary. Property owners who wanted service from the district were required to file a subdivision plat prior to obtaining services.

Before 1960 the southeast and southwest sectors dominated Houston's industrial, residential, and population growth. The northwest area, including northern Harris and southern Montgomery counties, remained essentially rural because of distance from Houston and difficulty of access. Champions, the first major residential project in the region, started slowly because of the time-consuming motor trip through narrow and winding streets. Completion of I-45 early in the decade quickened the pace of Champions' development and contributed to a gradual shift of major population growth away from the southeast-southwest and into the northwest quadrant.

3.3.1. The Woodlands

The "Covenants, Restrictions, Easements, Charges and Liens (the Covenants) of The Woodlands" are recorded in the real property records and are legally binding upon land, landowners and residents in The Woodlands. The Covenants establish homeowner associations to administer and enforce the Covenants, and committees of homeowners and developer appointees to adopt and enforce building and land use standards.

The Woodlands Community Association, Inc. (WCA) and The Woodlands Association, Inc. (TWA) are nonprofit corporations established by the Covenants, which enforce the Covenants and make available to residents and property owners many of the services necessary to live, work, relax, and grow in The Woodlands. Land within WCA is generally located within the eastern/south-eastern portion of The Woodlands and was developed prior to 1994. Land within TWA is generally located within the north western portion of The Woodlands and was developed after 1992 (Fig. 3.8). The Associations operate and maintain parks and hike and bike paths, fund fire protection and emergency medical and rescue services, and contract for police protection, residential trash collection, recycling, street lighting and streetscape maintenance. These covenants specify the Landscape Restrictions (Section 10:02) which state that no tree having a diameter of six inches or more (measured from a point two feet above ground level) is allowed to be removed from any lot without the express written authorization of the Development Standard Committee.

Under authority provided by the Covenants, the Development Standards Committee, and the Development Review Committee have each adopted Residential Development Standards which apply to all improvements on all lots restricted to use as a Single Family Dwelling and to all street rights-of-way. These standards designate the tree removal requirements (1.6), landscaping and yard structures (2.7), and building setback lines (2.1). According to the standards, 40% of the front yard must be trees, shrubbery, flowers, mulch or plants other than turf or grass. No trees, shrubbery, plants or vegetation may be removed which would result in the grassed area exceeding 60% of the front yard. Also, the standard recommends the use of native plant materials for the sense of continuity and consistency in The Woodlands landscape concept and, whenever possible, new planting should make use of ground covers in lieu of grass.

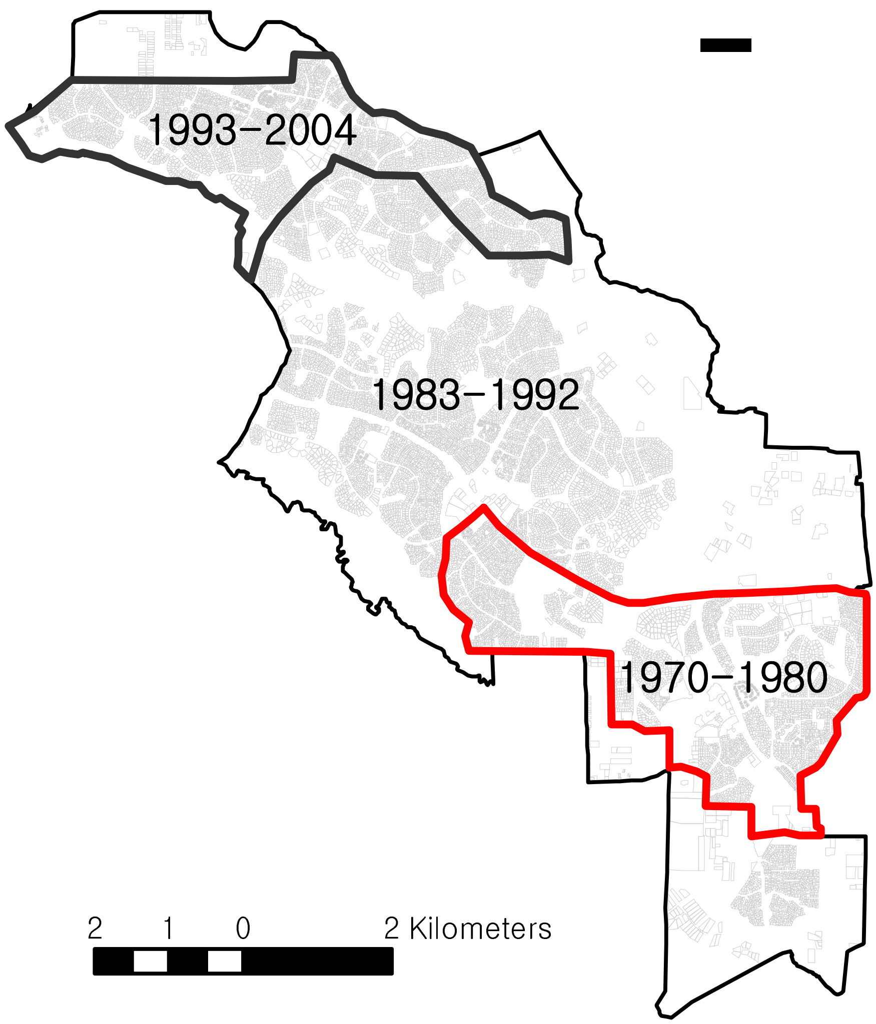
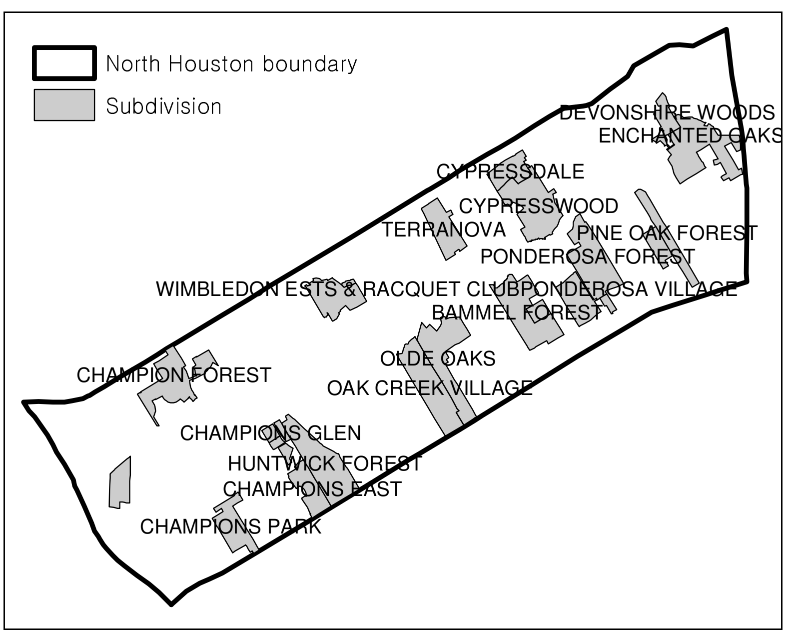


Fig. 3.8. Development period of The Woodlands

3.3.2. North Houston Area

This area started development in the early 1970s. One hundred and eight subdivision plats were filed during the early development period in this area (Fig. 3.9). The City of Houston allowed the developers to file a General Plan and divide the land into phases. The Municipal Utility Districts were created as a financing tool to provide water, sewer and drainage to property within the district's boundary. Property owners who wanted service from the district were required to file a subdivision plat prior to obtaining services. The subdivision plat was reviewed by the City of Houston and approved by the Planning Commission. The county also included development in the review and approval process. At that time, the City of Houston had a "Land Platting Policy Manual" that covered subdivision plats.



SUBDIVISION NAME

- Bammel Forest
- Champion Forest
- Champions Bend Estates
- Champions East
- Champions Park
- Cypressdale
- Cypresswood
- Devonshire Woods
- Enchanted Oaks
- Huntwick Forest
- Oak Creek Village
- Olde Oaks
- Ponderosa Forest
- Prestonwood Forest
- Terranova
- The Hamlet at Champions
- Westador
- Wimbledon Ests & Racquet Club

Fig. 3.9. Subdivision developed between 1970 and 1980

The Houston City Planning Commission was created in 1940 by ordinance passed by the City Council. The details of the action include the creation of the City Planning Department and the powers and duties of the commission and its staff. One of the principal functions of the City Planning Commission has been to perform performance of the duties necessary to comply with the statutes of the state and ordinances of the City of Houston regarding the approval of land subdivision and development plats. This includes the city limits as well as the city's extraterritorial jurisdiction which involves the unincorporated territory extending beyond the city limits a distance of five miles. The "Land Platting Policy Manual" (first edition, 1976), prepared by the Houston City Planning Department, accurately represents the rules, policies, standards, and the City Planning Commission desires to promulgate and implement.

The Covenants of this area say "the owners or occupants of all lots shall at all times keep all weeds and grass thereon cut in a sanitary, healthful and attractive manner" and do not mention the use of native plants and landscaping standard guidelines (Ponderosa Forest Community Improvement Association, 1971).

Fig. 3.10 shows partial view of the study areas. Vegetation pattern of the road median and front yard of residential unit looks very different. Aerial photo also shows different landscape pattern between two sites.

	North Houston	The Woodlands
Road		
Front Yard		
Lot Shape		

Road: The median of North Houston area is maintained by grooming. However The Woodlands area show existing plants are preserved in median as well as side of the street.

Front Yard: 40% of the front yard in The Woodlands is maintained with trees, shrubbery, flowers, mulch or plants other than turf or grass.

Lot Shape: The parcel lot shape of North Houston area shows “cookie-cutter” and vegetation is evenly distributed while The Woodlands area looks like considering existing natural resources.

Fig. 3.10. Comparison of the study areas

4. Study Design and Variables

4.1. Data Collection

Black white aerial photographs in 1944 and 1978 of North Houston area and in 1958 and 1979 of The Woodlands were collected. Digital Orthophoto Quadrangles (DOQs) in 2002 of both areas were acquired. Scanning of the aerial photographs was conducted with a spatial resolution of 2 m. the dots per inch (dpi) were determined depending on the photo scale and desired output image with a pixel dimension of 2× 2m according to the following formula, where *S* is the scale of the aerial photograph.

$$dpi = \frac{S}{2m \times 39.37 inches / m}$$

Aerial photo scales are 1:20,000, 1:22,000, and 1:24,000 respectively, so 251, 276, and 301 dpi were used to scan these aerial photographs with a Microtek Scan Wizard scanner (Microtek Lab, Inc., Carson, CA, Table 3.1).

Table 3.1
Aerial photo scales and scanning resolution

Site	Year	Scale	dpi
The Woodlands	1958	1: 20,000	251
	1979	1: 24,000	301
North Houston	1944	1: 22,000	276
	1978	1: 24,000	301

Scanned aerial photographs were georeferenced using the 1m and 2.5m Digital Orthophoto Quadrangles (DOQs) data. In the US, airphoto images are available as Digital Orthophoto Quarter Quadrangles, known as DOQQs. DOQQ images have already been orthorectified. Namely, geometric distortions caused by the camera and the terrain topography have already been removed. Therefore it combines the image characteristics of a photograph with the geometric qualities of a map. A DOQ image typically covers one quarter of a 1:24,000 scale USGS topographic map plus a little overlap.

All images were mosaicked together and color balanced with ERMapper software. Aerial photographs have a “roll off” of intensity across the photo, and also change chroma due to lens refraction. In other words, the photos often appear darker towards the edges, and have a subtle color shift from the center to the edges, in order to mosaic aerial photographs with no visible seams, these artifacts must be removed. ERMapper uses histogram matching and feathering to minimize seams in mosaics. Feathering is the process of blending the data values in areas where two datasets overlap so that they gradually transition (or “feather”) from one to the other. Histogram matching method is used for color balancing operation. For each color layer, the histogram of each individual aerial photograph is modified to match the specified histogram (Fig. 3.11 and Fig. 3.12).

High-resolution aerial photography and digital ortho-photographs and GIS data were obtained from the Texas Natural Resources Information System (TNRIS) Research and Distribution Center (RDC) and the City of Houston Planning and Development Department, respectively. In addition, the tax attribute database maintained by Harris County Appraisal District (HCAD) and Montgomery County Appraisal District (MCAD) provides information on parcel characteristics, such as the size of building footprints and building year built.

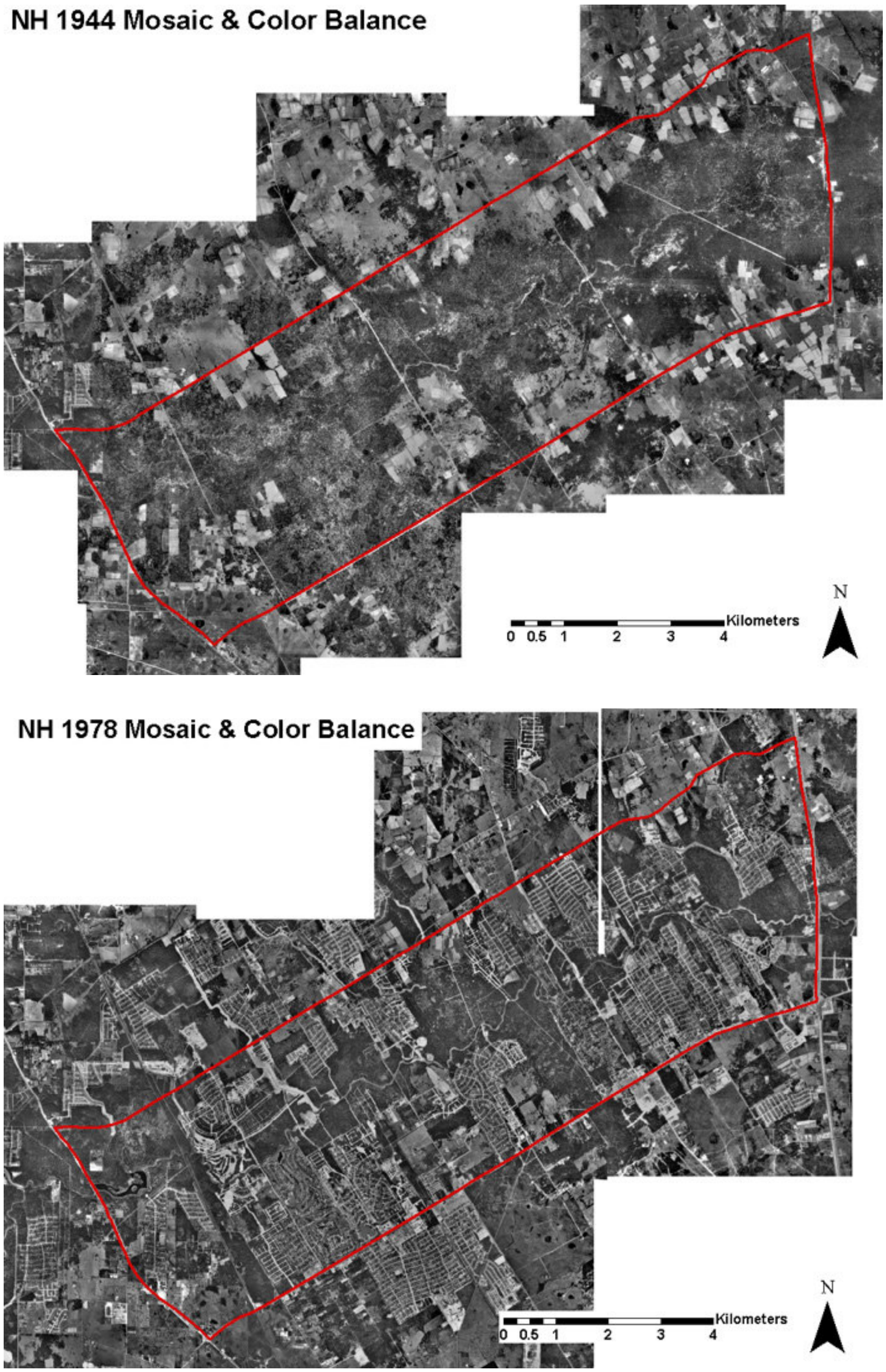


Fig. 3.11. Mosaic and color balanced aerial photograph of North Houston area over time

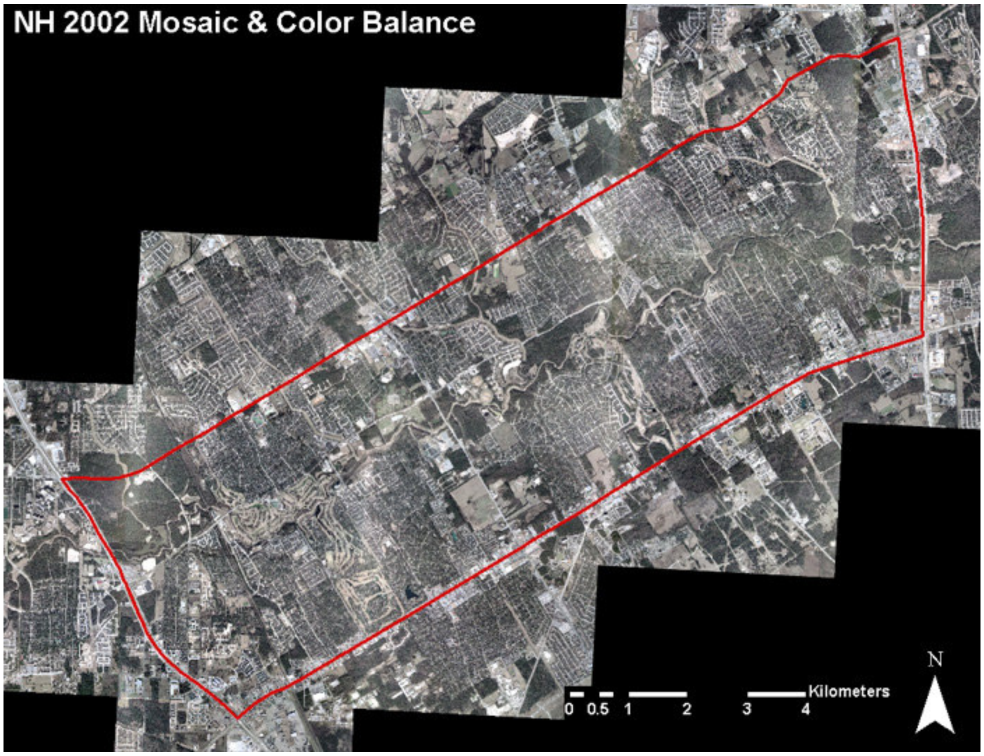
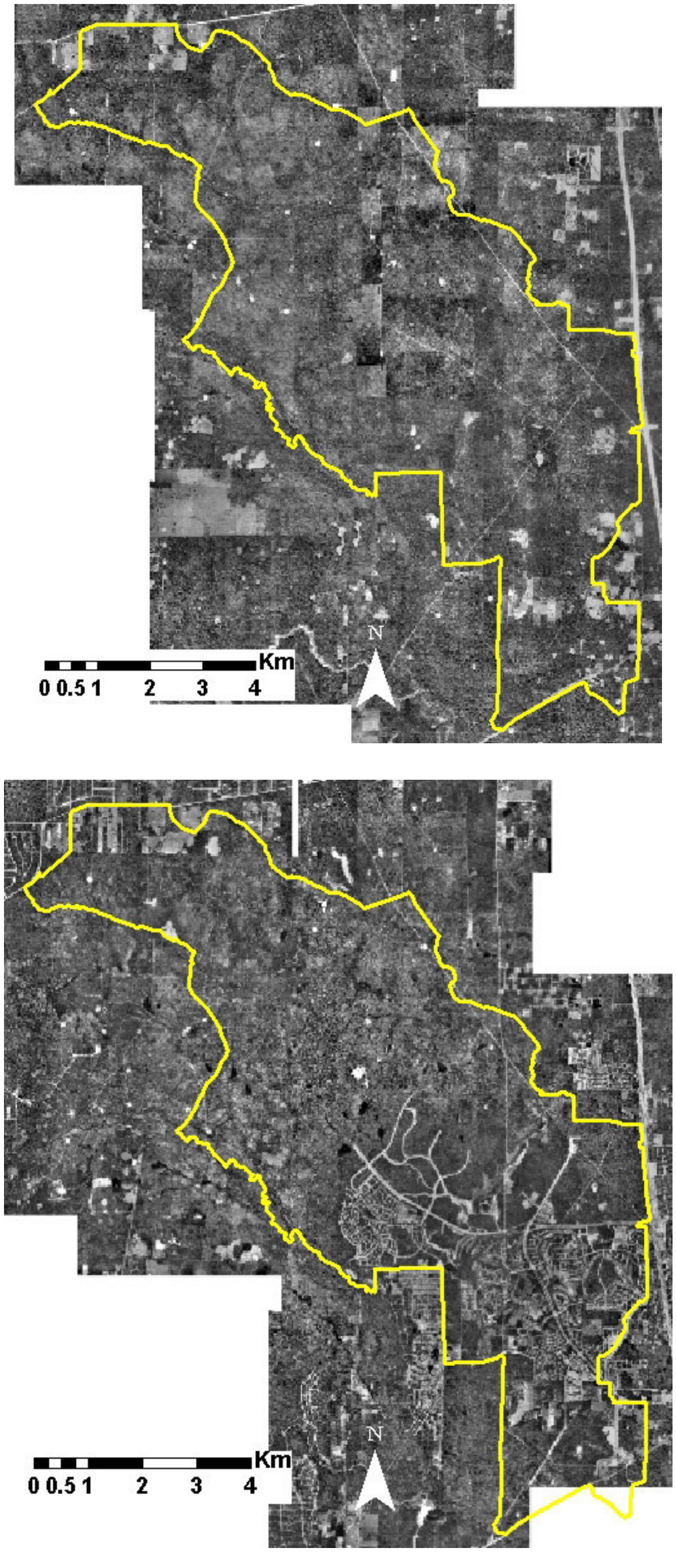


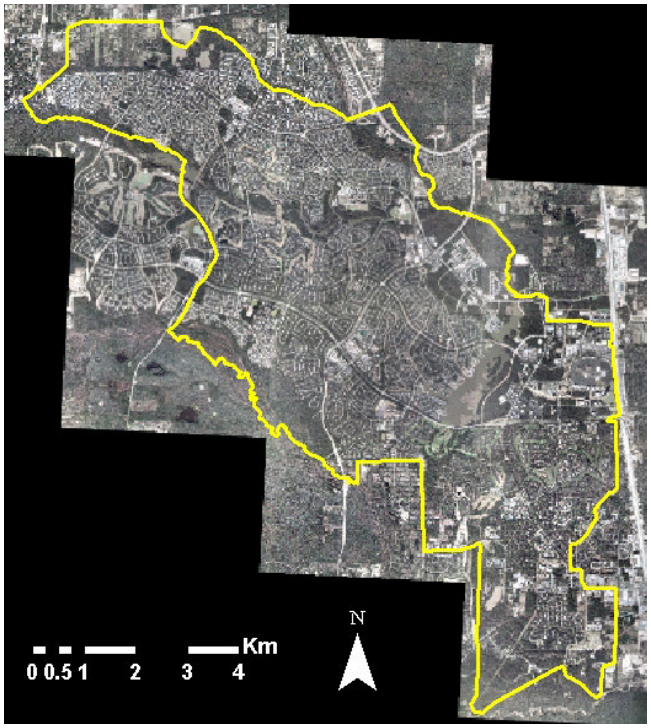
Fig. 3.11. Continued



1958

1979

Fig. 3.12. Mosaic and color balanced aerial photograph of The Woodlands over time



2002

Fig. 3.12. Continued

4.2. Classification

Digital ortho-photographs with 1-foot resolution taken in 2002 and black and white aerial photographs of The Woodlands (1979 and 1958) and North Houston (1978 and 1944) were used to measure landscape structure. The aerial photographs were scanned with a nominal resolution of 2 meters. These scanned images were co-registered, and the spatial scale was verified with ground features of known dimensions. The imagery was classified using an Iterative Self-Organizing Data Analysis Technique (ISOCLASS) that classifies the pixels of each landscape into 40 classes based on their spectral similarity.

The 40 classes generated for each landscape were grouped into three land cover types-Trees/Forest, Grass land and Developed area, based on visual interpretation of the aerial photo images and other field photos (Fig. 3.13, Fig. 3.14, and Fig. 3.15). Also, recognition elements, such as size, shape, shadow, tone and color, texture, pattern, height and depth, site (location), and association, were considered for photo interpretation. The classification system used for this research is modified from the Anderson land-use and land-cover classification system (Table 3.2).

Table 3.2
Reclassification of the classification

Class	Anderson	
	(Level I)	(Level II)
Forest	4. Forest land	41. Deciduous forest land 42. Evergreen forest land 43. Mixed forest land
Grassland	3. Range lands	31. Herbaceous rangelands
Developed/ Barren land	1. Urban or Built up Land	11. Residential 14. Transportation, communication, or utilities
	7. Barren land	73. Sandy areas, except beaches 74. Bare exposed rock

Fig. 3.13. Landscape change of North Houston area

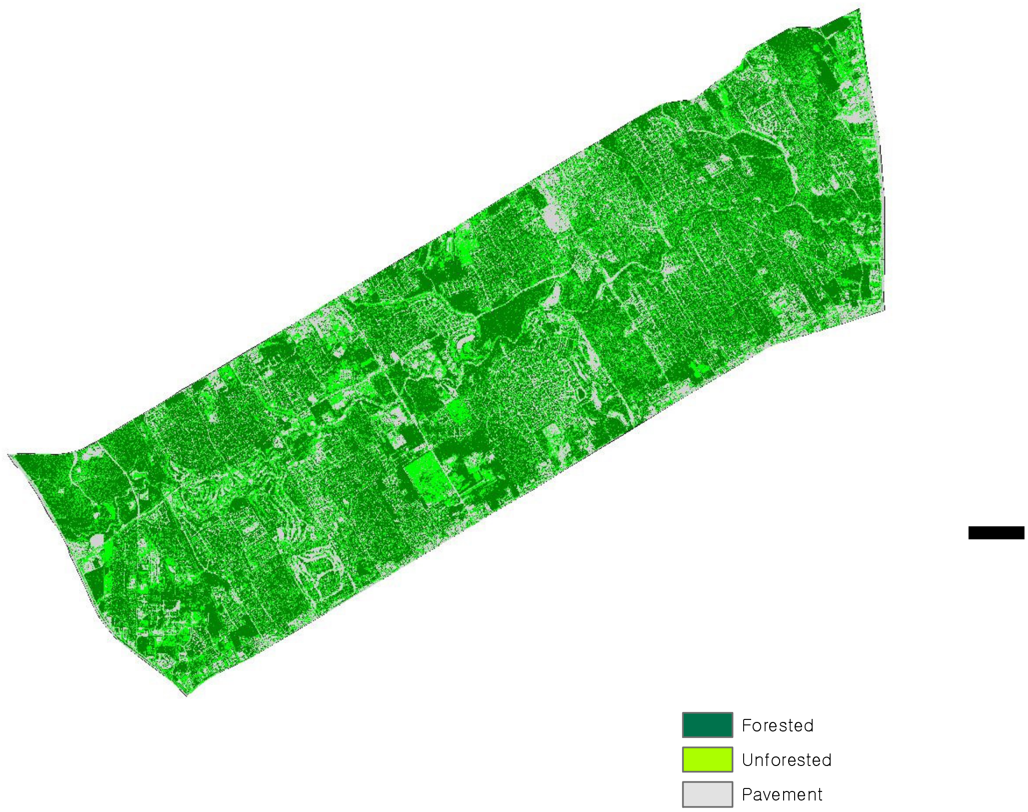


Fig. 3.13. Continued

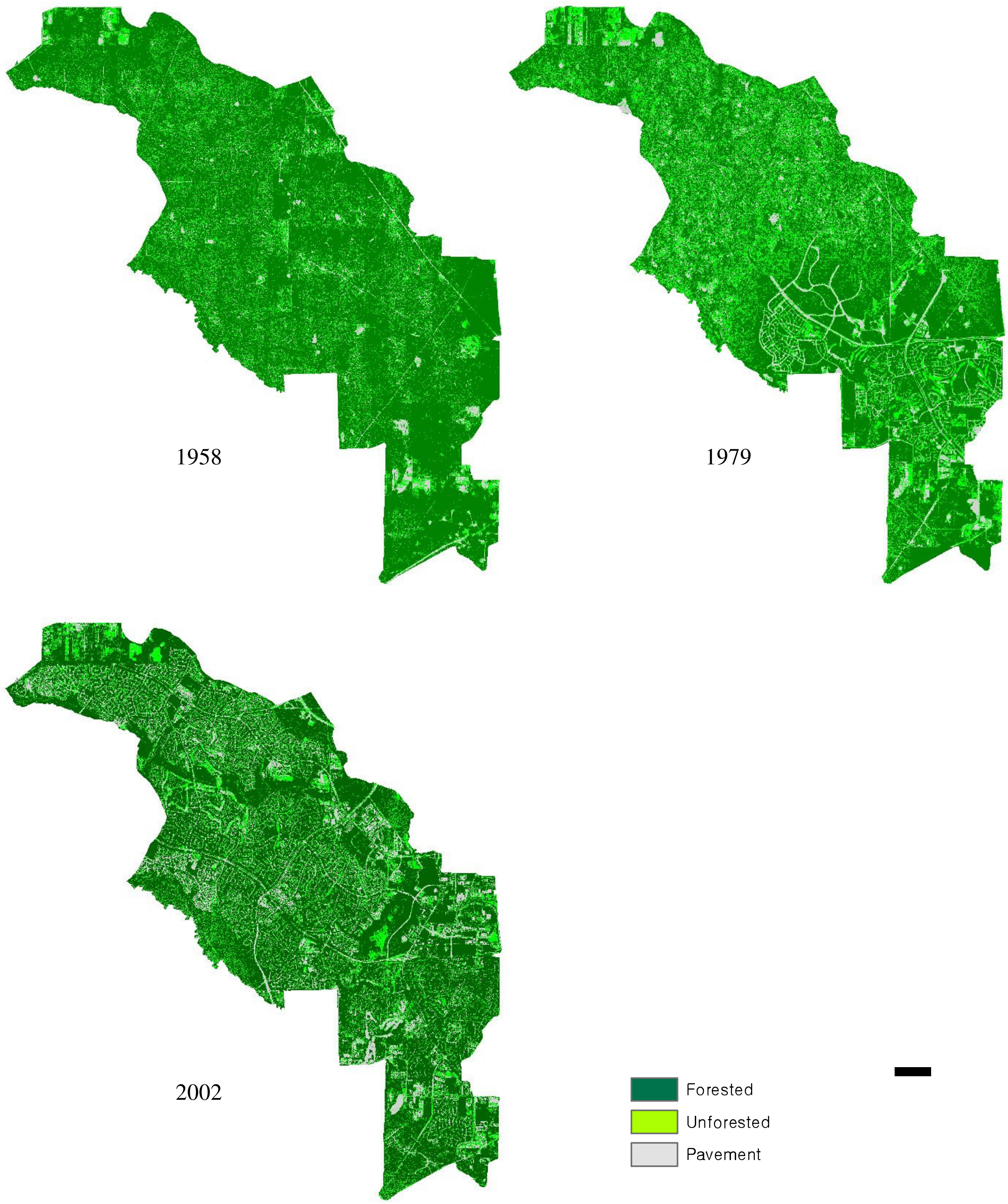


Fig. 3.14. Landscape change of The Woodlands

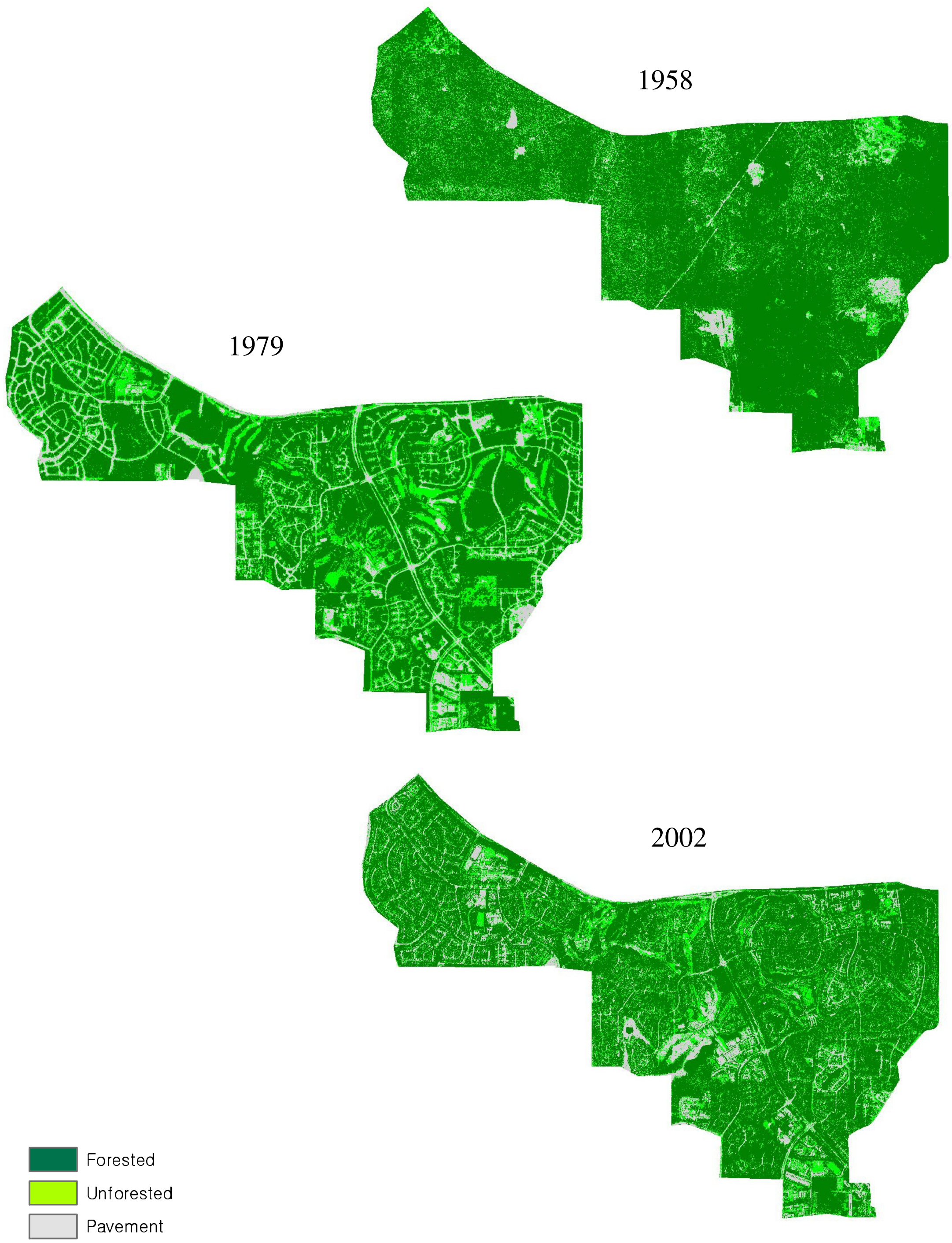


Fig. 3.15. Landscape change of The Woodlands (Early developed area)

4.3. Measures

Twelve attributes of sampling plots were quantified or collected to associate development regulations and standards with landscape structure: lot size of parcel, building footprint, built year of the building, total perimeter of parcels, perimeter adjacent to street, number of parcel, street width, number of intersection, number of cul-de-sac, grooming, tree removal, and native plant.

The landscape structure and their temporal changes were quantified with a number of landscape metrics (Gustafson, 1998). In this study, quantifying the landscape structure and its change over time involves the use of statistics (metrics) that describe the landscape configuration and composition. A set of relevant landscape metrics at the class level was used to quantify the landscape pattern and change. They include Patch Density (PD), Mean Patch Size (MPS), Mean Nearest Neighbor (MNN), Edge Density (ED), Mean Shape Index (MSI), and Percent Land (PLAND) at the class level. What follows is a brief description of each variable and the method employed in its estimation.

- Lot size and number of parcel: The area of parcel measured in square meters and the number of parcels in sampling plot. These serve as direct measures of housing density and were used in the analysis to assess how different levels of housing density influence the landscape structure.
- Building site: The heated area measured in square meters. This measure is related to lot coverage which is the percentage of the property covered by structures including the primary dwelling footprint and accessory buildings such as garages,

carports, tool sheds, etc. Because building footprint is related to the planting area, this measure can be a critical factor for the landscape structure.

- Total perimeter and perimeter adjacent to street: Total length of parcels and the perimeter (width) of the parcel at the point of its adjacency to the street in sampling plot. While total perimeter can also be related to the housing density, the perimeter adjacent to street is a direct determinant of the length of street required to service the parcel.
- Year built: The year building was erected. This measure was used as a control variable in the analysis to account for the variation of landscape structure. In evaluating the relative influences of alternative development regulations, it is essential that the time period of development be almost same (Fig. 3.16).

Fig 3.16. Year built

In addition to these five parcels related variables, three attributes of the street network were measured to assess the contribution of landscape structure.

- Street width: The width of the primary residential street in meters. The street allotment is the portion of the residential street immediately adjacent to the single-family parcel. Wider street widths and perimeter adjacent to street require a greater area of street paving in residential zones, with direct implications for storm water runoff and surface heat retention (Stone, 2004). This measure was used for examining landscape structure, especially edge metrics (Fig. 3.17).

Fig. 3.17. Street width

- Number of intersection and number of cul-de-sacs: the number of street intersections located within 576are (240m×240m) and the number of cul-de-sacs lied within 2300are (480×480m) of the residential parcel. As illustrated in Fig. 3.18, these measures provide quantitative variables that may be used to differentiate standard grid-based street networks from dendrite street networks. As cul-de-sacs are not considered to be intersections, dendrite networks tend to have a much smaller number of intersections per unit of area than a grid-based network. This variable is used to evaluate the effects of the street network pattern on landscape structure.

Number of Intersection of North Houston — Number of Intersection of The Woodlands

Fig. 3.18. Street intersection in dendrite and grid network types

- Grooming, Tree removal, and Native plant: These variables are derived from residential development standards and community deed restriction. Each community has their own covenants and deed restrictions established by homeowner associations. As it is shown on the above photograph (Fig. 3.18), these standards seem to play a critical role for physical settings and also landscape composition and configuration.

Table 3.3 shows the main variables and measures used in this study.

Table 3.3
Main variables and measure

Variables	Measure	Abbreviation
Local Development Regulations		
1. Subdivision ordinance		
(Land platting policy manual)		
Min. lot size	Parcel lot (m^2)	PARCEL
Building footprint	Heated area (m^2)	BLDG
Year built	The year building was erected	YEAR
Total perimeter of parcels	Perimeter (m)	PERI
Perimeter adjacent to street	Adjacent perimeter (m)	ADJPERI
Number of parcel	Number of parcel	NPAR
Street width	Street width (m)	WIDTH
Number of intersection	Number of intersection	INTER
Number of Cul-de-sac	Number of Cul-de-sac	CDS
2. Development Standards		
Grooming	Yes/No	GRM
Tree removal	Max. Diameter (in)	DIA
Native plant	Yes/No	NPLNT
Landscape Metrics		
Area	Mean patch size (ha)	PLAND
Number	Patch density (#/100ha)	PD
Perimeter	Edge density (m/ha)	MPS
Distance	Mean nearest neighbor distance (m)	ED
Shape	Mean shape index	MSI
Proportion	Percentage of landscape (%)	MNN
Fragmentation	Fragmentation index $\lvert\phi\rvert$	FRAG

4.4. Sampling

The objective of this study is to investigate the relationship between local development regulation and guidelines and landscape structure over time for single-family residential area in north Houston areas. Specifically, an analysis of 90 single-family residential plots was presented to assess the impact of land development regulations and standards governing minimum lot size, building footprint, street related characteristics, landscaping, and the tree removal on the landscape structure.

Square plot random sampling was used for the comparison of the landscape structure of the two areas. Plot size, 800ft by 800ft (240m by 240m) was determined by the maximum length for blocks under circumstances of cul-de-sacs in land platting policy manual of the City of Houston (1976). Samples of 48 plots in The Woodlands and 42 plots in North Houston were randomly collected using ArcView Avenue script, “Random Points” and “Poly from Points.” To investigate the relationship between ecological landscape structure and local development regulations over time, 90 reference random sampling plots were selected within early development area (Fig. 3.19).

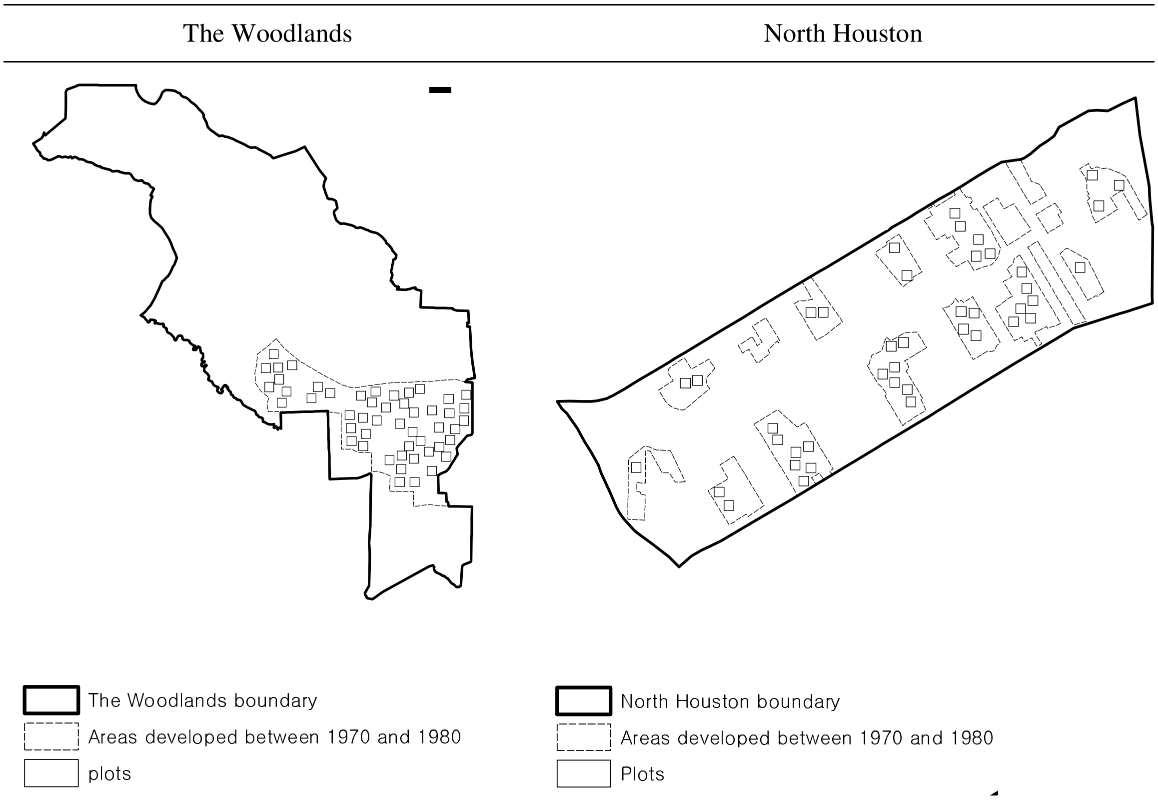


Fig. 3.19. Location of randomly located windows of The Woodlands and North Houston area

Fig. 3.20 shows aerial photos of one of samples representing as of each development period for both study areas and Fig. 3.21 represents classification results of one of the samples.

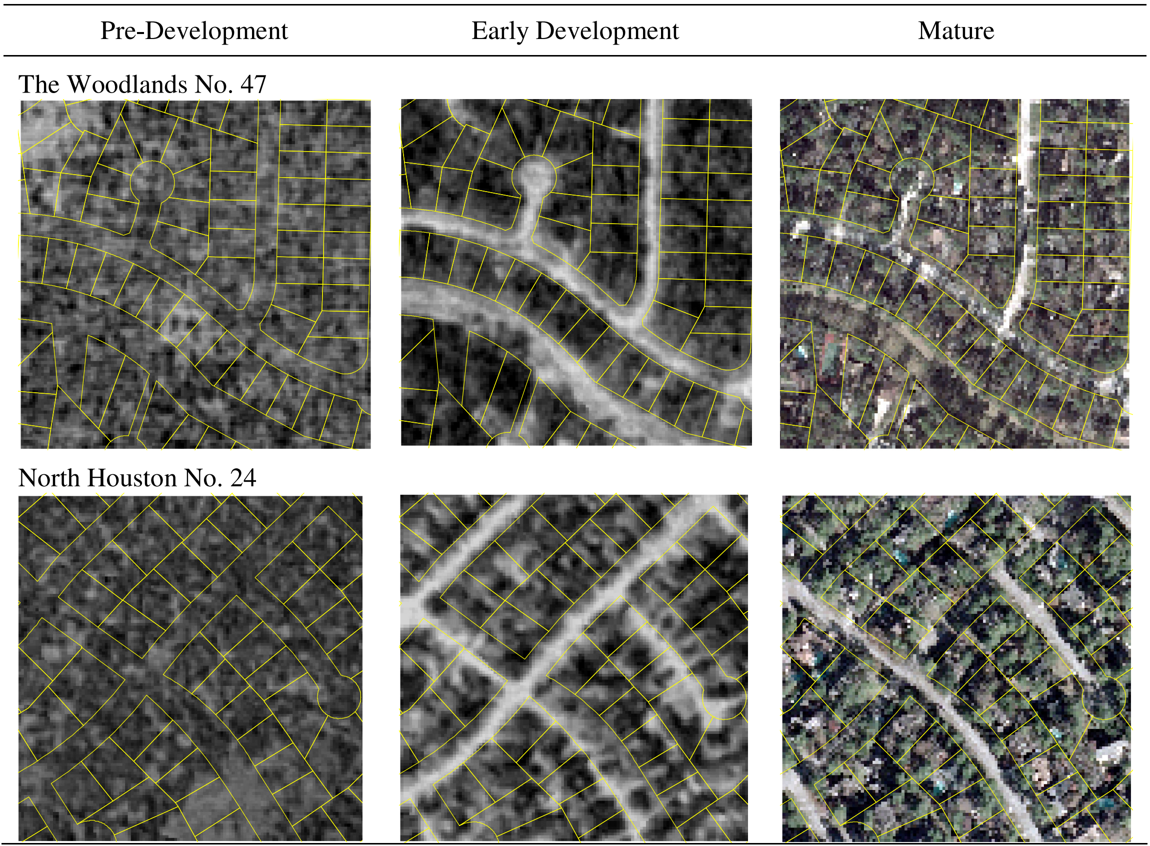


Fig. 3.20. Aerial photograph samples showing landscape changes from pre-development period to present in study areas

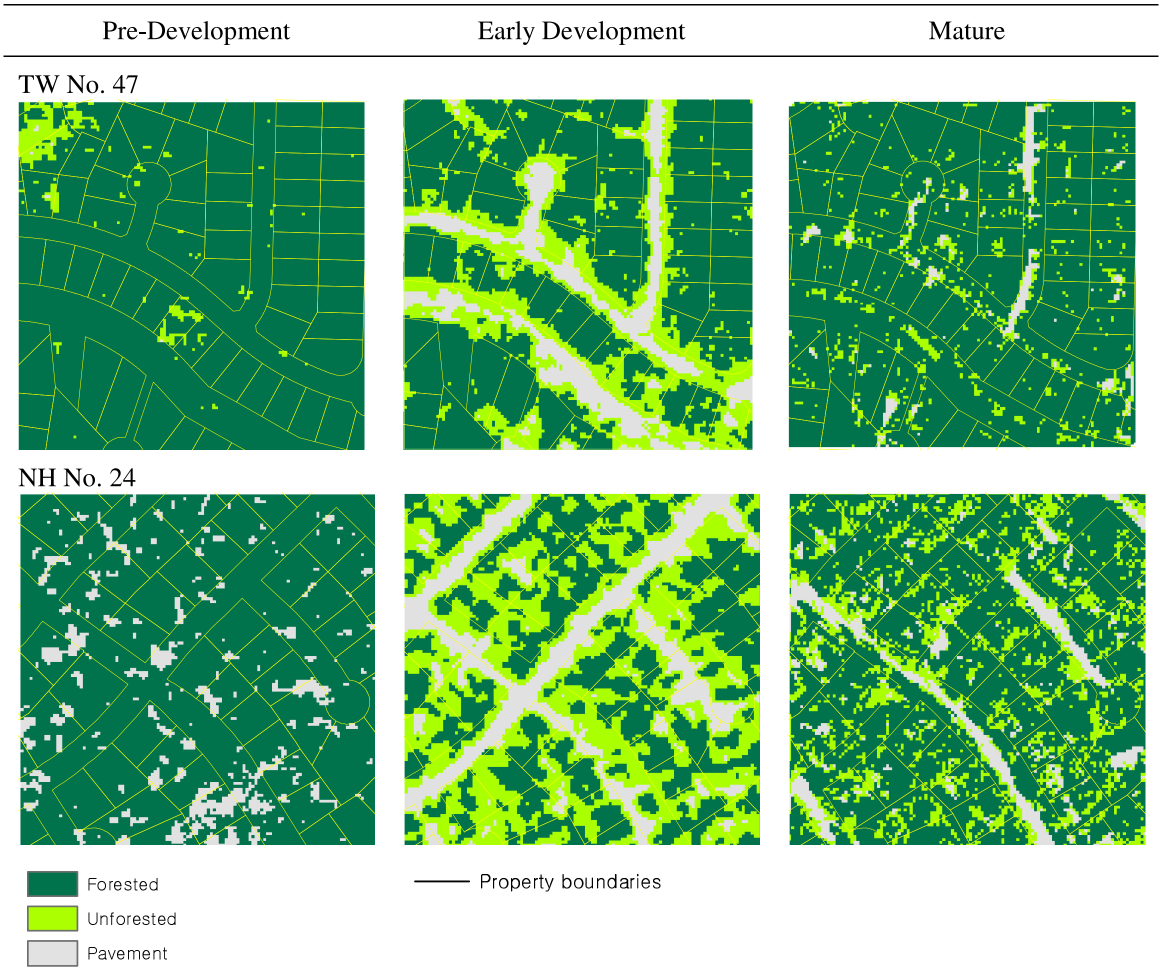


Fig. 3.21. Classification of aerial photograph samples from pre-development period to present in study areas

5. Summary

This chapter discussed the research concept based on the literature review and objectives of study. Some questions related to the development regulations and landscape structure are addressed and hypotheses have been made based on these questions.

Conceptual model of this study was discussed. This is divided into two categories based on the two questions: Is there significant difference with each site over time? Is there significant difference between two sites at each development periods?

The woodlands (regulated to protect ecological condition) and North Houston area (which followed traditional subdivision regulations) were examined at three different developmental time periods; predevelopment, early development (after 10years), and matured development (after 30years).

Aerial photos of each site from the three time periods were classified into forest, grassland, and developed/barren class. Landscape metrics were also selected to compare the landscape structures of two sites. Finally, 42 samples in North Houston area and 48 samples in The Woodlands were collected using ArcView GIS software.

CHAPTER IV

ANALYSIS AND RESULTS

1. Introduction

Chapter IV describes the analysis and results of the hypotheses testing described in Chapter III. This chapter describes the land cover changes of each class, fragmentation measurement, relationship between landscape metrics and land development regulations, and main effect and interaction effect. Specifically, it includes the results of measuring selected landscape metrics and spatial characteristics of study areas. Subchapter 2 states the overall land cover change and the attributes of the parcel lot and street of two study areas. Subchapter 3 discusses the fragmentation status for each development period of two study areas using fragmentation index. Subchapter 4 presents how the landscape metrics changed over three time periods: pre-development period, early development (after 10 years), and matured development (after 30 years). Subchapter 5 discusses the relationship between landscape structure and local development regulations at forest class and main effect and interaction effect using two-way ANOVA.

2. Descriptive Analysis

2.1. Land Cover Changes

Selected metrics were computed for classes within North Houston area and The Woodlands. Even though study areas were classified into forest, grassland, and developed area, the results for forest are particularly emphasized in this study because they play important roles in defining landscape structure and fragmentation within the study areas.

Percentage of landscape (PLAND) provides results of percentage of total landscape covered by all patches of a class. Table 4.1 and the graph in Fig. 4.1 show the changes of proportion of patch types from pre-development period to mature period. Percentage of landscape (PLAND) of forest class in North Houston dropped from 78.45% in 1944 to 40.72% in 1978, while in The Woodlands this value dropped from 85.32% in 1958 to 51.60% in 1979. However, from the late 1970s to 2002, forest cover area increased in both sites while grassland and developed areas decreased. The ratio of forest cover from pre-development to mature period is 73% for North Houston area and 88% for The Woodlands. This ratio represents the proportion of forest cover regained. This indicates that the forest class of The Woodlands area is 15% less lost than that of North Houston.

The percentage of landscape (PLAND) of grassland and developed areas represented similar pattern over time. The proportions of these classes increased from pre-development period to early development period and decreased from early development period to mature condition. The proportion of grassland in North Houston increased from 14.70% in 1944 to 36.59% in 1978, while in The Woodlands this value increased from 9.96% to 31.84%. The ratio of grassland cover from pre-development to mature period is 179% for North Houston area and 147% for The Woodlands. Likewise the ratio of development area is 216% for North Houston area and 179% for The Woodlands during the same time interval (Table 4.1).

Overall, the results of land cover changes represent that forest area decreased significantly at the early development period. However, tree canopy covered much of the grass and developed area class at the mature period.

Table 4.1
Percentage of each cover type on the aerial photograph-based classification for the residential area of North Houston and The Woodlands

PLAND (%)	NH			TW		
	Pre-D (1944)	Early D (1978)	Mature (2002)	Pre-D (1958)	Early D (1979)	Mature (2002)
Forest	78.45	40.72	57.31	85.32	51.60	76.41
Grass	14.70	36.59	26.36	9.96	31.84	14.74
Dev't	7.56	22.68	16.33	4.92	16.55	8.85

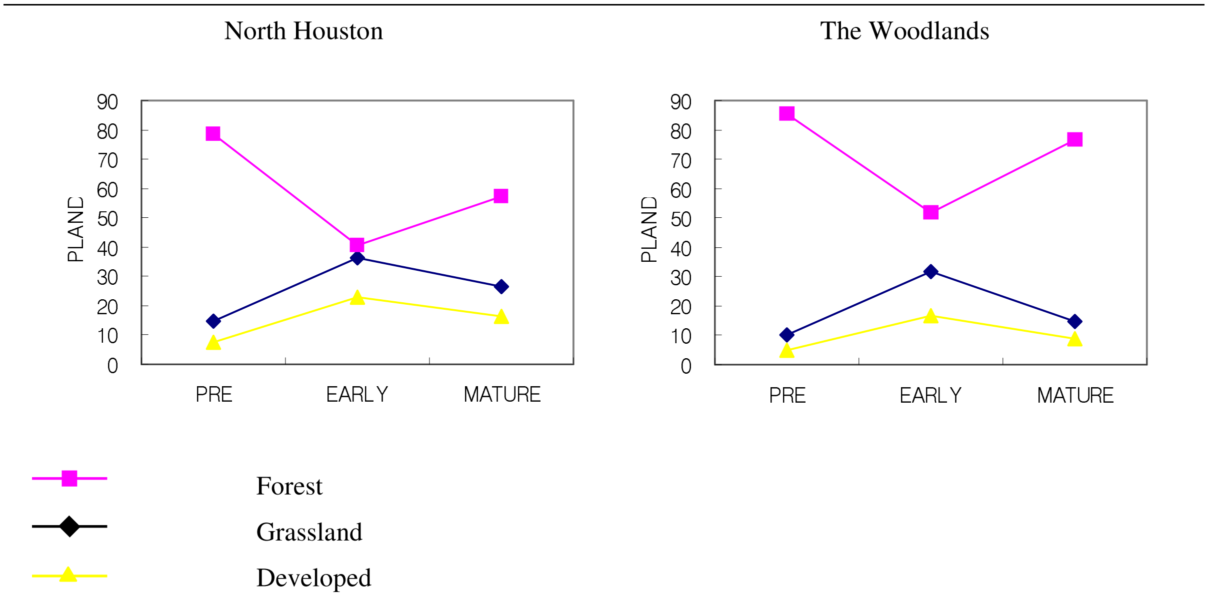


Fig. 4.1. The percentage of cover type of North Houston area and The Woodlands

2.2. Attributes of Parcel Lot and Street

Table 4.2 presents descriptive statistics and *p* values for each of the independent sequential variables in two study areas. There are no significant differences between The Woodlands and North Houston areas in terms of lot size, building footprint, number of parcels, and number of cul-de-sacs. However, significant differences were found with respect to lot perimeter ($p<0.001$), adjacent perimeter to the road ($p<0.001$), street width ($p<0.01$), and number of intersection ($p<0.05$).

Parcel perimeter of North Houston area is 1.34 times higher than that of The Woodlands and perimeter adjacent to the street of North Houston also shows 1.5 times higher value than that of The Woodlands. Street width of North Houston area shows 6% wider than that of The Woodlands and number of intersection also indicates 31% more than that of The Woodlands.

In sum, while parcel lot related attributes such as lot size, building footprint, and number of parcel are not significantly different between The Woodlands and North Houston area, street related variables such as adjacent perimeter to the road, street width,

Table 4.2
Descriptive statistics

Variables	NH		TW		*P*
	Mean	SD	Mean	SD	
Lot size (m^2)	1149.43	485.17	1214.02	628.26	.591
Building footprint (m^2)	258.08	41.70	237.61	85.71	.147
Perimeter (m)	17262.24	2844.58	12929.13	4331.77	**.000**
Adjacent Perimeter (m)	4176.27	944.00	2768.277	1175.42	**.000**
Number of parcel	35.52	10.50	30.93	15.02	.094
Street width	7.714	.557	7.244	.839	**.002**
Number of intersection	2.64	1.21	2.02	1.12	**.013**
Number of Cul-de-sac	3.79	2.63	3.48	2.13	.543

and number of intersection are significantly different between two sites. This indicates that the difference of parcel lot size, building footprint, and number of parcel between traditionally planned community and ecologically developed community is not significant while street pattern and arrangement of parcel lot are significantly different between them.

3. Fragmentation Measurement

Overall, fragmentation produces many quantifiable landscape changes: reduced habitat area, increased edges, reduced interior area, patch isolation, and increased number of patches (Davidson, 1998). Most can be measured separately. However, as it was discussed in Chapter II, there is not a single measure that captures all aspects of fragmentation.

In this study, fragmentation measurement model, proposed by Bogaert et al. (2000) was used for overall fragmentation status. Four main characteristics of this model consist of area, perimeter, number of patch, and patch isolation. These characteristics are matched to selected landscape metrics: mean patch size (MPS), edge density (ED), patch density (PD), mean nearest neighbor distance (MNN), and mean shape index (MSI).

This model incorporates habitat area, patch boundary length, number of fragments present, and isolation of patches. High values indicate the least fragmented patterns, whereas low values are characteristic for the most fragmented habitats.

In Table 4.3, the fragmentation features for each development period for North Houston area (NH) and The Woodlands (TW) are summarized. In the appendix, the calculations for each development time period for two study areas are given in detail.

According to fragmentation index $|\phi|$, early development period in North Houston is denoted as the most fragmented. Pre-development period in both areas is also quantified as having the least degree of fragmentation. Overall, fragmentation index is dominated by a large patch, causing the greatest α, β, and ν values.

Table 4.3
Calculation of α, β, ν, δ, and $|\phi|$ of North Houston area and The Woodlands

Item	North Houston			The Woodlands		
	Pre-D (1944)	Early D (1978)	Mature (2002)	Pre-D (1958)	Early D (1979)	Mature (2002)
a_{obs}	45187.00	23456.00	33010.00	49145.00	29721.00	44010.00
P_{obs}	4820.43	8763.78	13627.81	4759.60	5213.66	9432.52
n_{obs}	22.29	96.69	650.38	9.12	35.54	27.71
d_{obs}	22.90	20.11	16.08	19.70	23.44	23.34
α	78.45	40.72	57.31	85.32	51.60	76.40
β	97.79	91.26	90.18	98.02	96.17	95.10
ν	99.81	98.37	92.13	99.93	99.54	99.76
δ	95.14	95.99	97.20	96.11	94.98	95.01
$\lvert\phi\rvert$	**186.37**	**169.93**	**171.33**	**190.03**	**175.61**	**184.01**

a_{obs}: observed total forest area, p_{obs}: forest patch perimeter, n_{obs}: number of forest patch, d_{obs}: distance of forest patch, α: area index, β: perimeter index, ν: number of patch index, δ: isolation index, $|\phi|$: fragmentation index

Fig. 4.2 shows the change of fragmentation index over time in both study areas. Both areas indicate the most fragmented status in early development period among three time periods. This figure also illustrates that the community having more restrictive development regulations and developed ecologically is recovering more significantly.

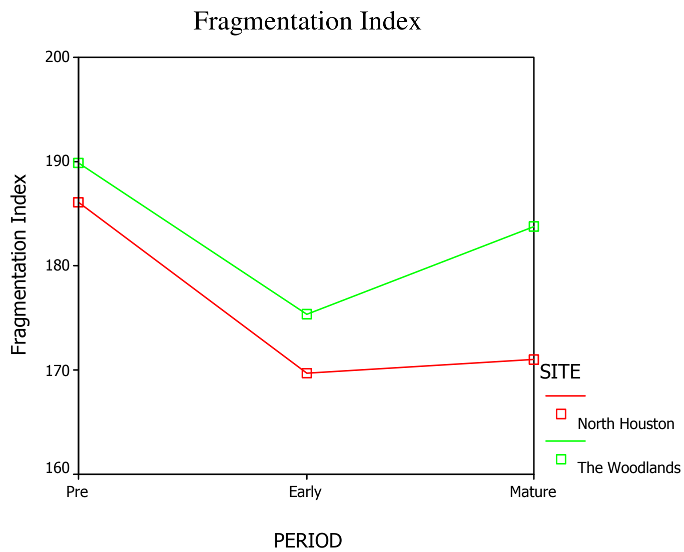


Fig. 4.2. Fragmentation index of three development time period of study areas

4. Landscape Change Described by Selected Metrics

4.1. Forest Cover Change over Time

Fig. 4.3 shows the landscape metrics change over time of forest class. Patch density (PD) of forest in North Houston area increased significantly (4.3 times) during the early development period while relatively less (3.9 times) increased in The Woodlands during the same period. However, this metrics decreased in mature period, 77 % in North Houston and 78% in The Woodlands.

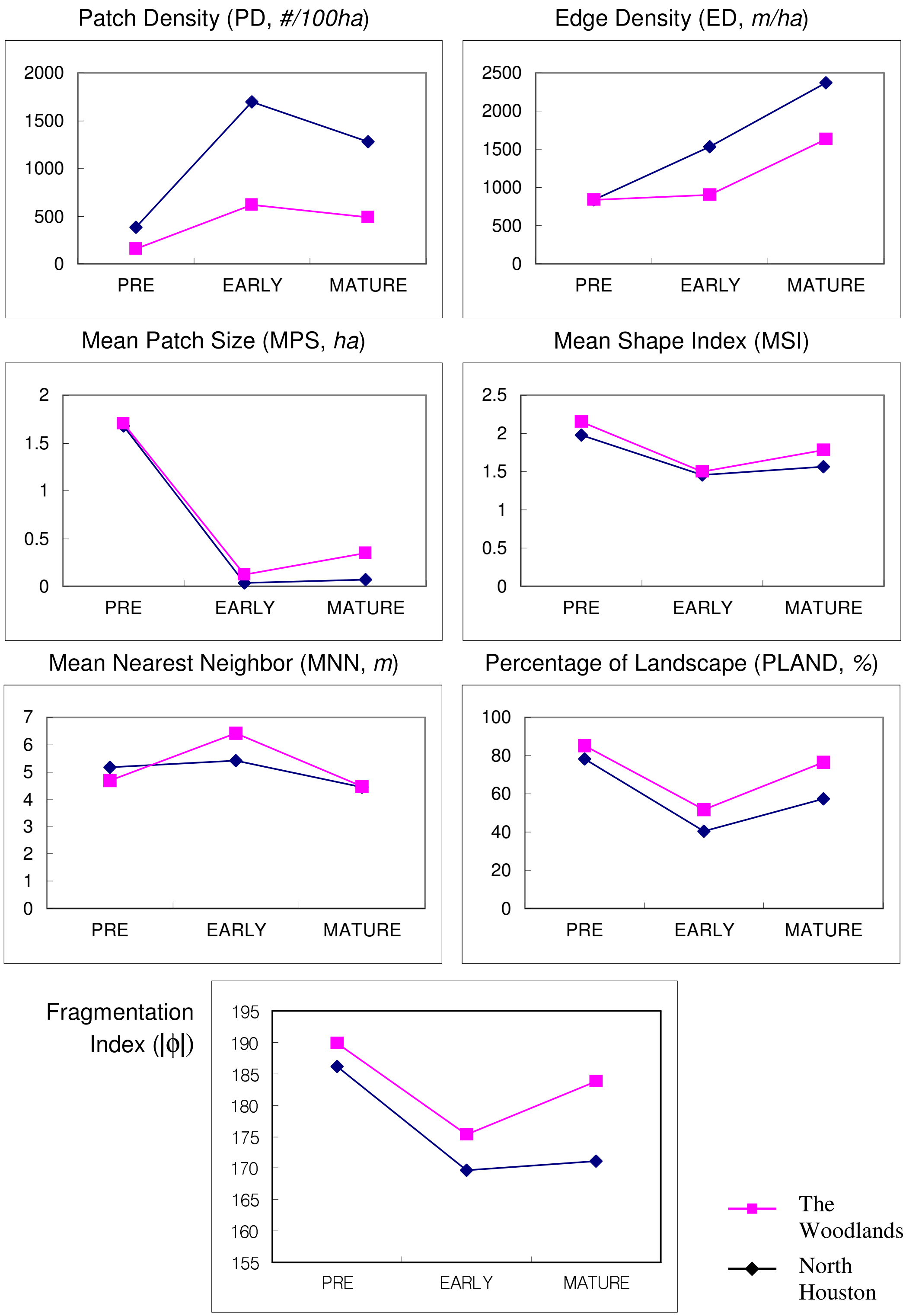


Fig. 4.3. Landscape metrics of forest class through community development time periods

Mean patch size (MPS), mean shape index (MSI), and percentage of landscape (PLAND) metrics show the opposite trend to the patch density (PD); they decrease in early development period and increase after that period. Mean patch size (MPS) in both areas decreased to 4% in North Houston area and 21% in The Woodlands area compared to pre-development period. Mean shape index (MSI) decreased to 73% in North Houston and 70% in The Woodlands at the early development period and regained 79% and 83% respectively at the mature period. Percentage of forest class (PLAND) also decreased to 52% in North Houston and 60% in The Woodlands at the early development period and regained 73% and 95% respectively at the mature period.

Edge density (ED) values of both areas increased continuously over time. This metrics increased 1.8 times and 1.6times during early development period and mature period respectively in North Houston area while increased 1.1 times and 1.8 times in The Woodlands during the same periods. Mean nearest neighbor distance (MNN) metrics show similar trend to the patch density (PD), increasing in early development period and decreasing in mature period.

Fragmentation index ($|\phi|$) in both areas decreased to 91.2% in North Houston area and 92.4% in The Woodlands compared to pre-development period and regained 91.9 % in North Houston area and 96.8% in The Woodlands during mature period respectively.

Table 4.4 presents statistical differences for forest class among three development periods by ANOVA. The result of forest class metrics of the three periods, pre-development, early development, and mature period, in two areas are all significantly different (p<0.001). This indicates landscape structure has continuously transformed over time.

However, the results of comparison of the paired development periods using t-test (pre-development to early development period, early development period to mature period, and mature period to pre-development period) are a little bit different from those

Table 4.4
Forest class metrics of the pre-development, early development, and mature period in two sites with p values for statistical differences among three periods by ANOVA

Metrics	Pre-development		Early development		Mature period		F	*p*
	Mean	SD	Mean	SD	Mean	SD		
North Houston								
PD	386.90	710.18	1678.65	746.21	1291.34	837.72	31.407	.000
ED	836.88	483.05	1521.49	442.05	2365.94	206.22	156.842	.000
MPS	1.68	2.129	.032	.02	.07	.05	24.524	.000
MSI	1.98	1.02	1.45	.10	1.57	.17	8.906	.000
MNN	5.17	1.52	5.43	.99	4.46	.19	10.265	.000
PLAND	78.45	20.76	40.72	11.60	57.31	10.19	67.252	.000
$\|\phi\|$	186.37	11.60	169.93	6.53	171.33	6.48	46.287	.000
The Woodlands								
PD	158.42	239.64	617.04	322.12	481.04	341.49	28.762	.000
ED	826.32	516.83	905.15	209.27	1637.59	349.41	66.559	.000
MPS	1.74	1.74	.12	.10	.36	.74	30.645	.000
MSI	2.17	.89	1.51	.10	1.80	.83	10.465	.000
MNN	4.69	1.16	6.43	1.44	4.47	.34	46.026	.000
PLAND	85.32	12.61	51.60	11.32	76.41	7.74	126.681	.000
$\|\phi\|$	190.03	5.54	175.61	4.69	184.01	3.88	121.168	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

of ANOVA test.

Five landscape metrics out of six indicate the significant difference in the analysis of the difference between pre-development period and early development period (Table 4.5). The mean nearest neighbor distance (MNN) index in North Houston area and edge density (ED) in The Woodlands does not show significant differences during this period.

However, patch density (PD, $p<0.001$), edge density (ED, $p<0.001$), mean patch size (MPS, $p<0.001$), mean shape index (MSI, $p<0.05$), percentage of landscape (PLAND, $p<0.001$), and fragmentation index ($|\phi|$, $p<0.001$) in North Houston area shows significant difference between pre-development and early development period. In The Woodlands, patch density (PD, $p<0.001$), edge density (ED, $p<0.001$), mean patch size (MPS, $p<0.001$), mean shape index (MSI, $p<0.001$), mean nearest neighbor distance (MNN, $p<0.001$), percentage of landscape (PLAND, $p<0.001$), and fragmentation index ($|\phi|$, $p<0.001$) indicate that there are significant differences between this period.

Table 4.5
Statistical differences of the forest class metrics between the pre-development and early development period

Metrics	Pre-development		Early development		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	386.90	710.18	1678.65	746.21	.000
ED	836.88	483.05	1521.49	442.05	.000
MPS	1.68	2.13	.03	.02	.000
MSI	1.98	1.02	1.45	.10	.002
MNN	5.17	1.52	5.43	.99	**.368**
PLAND	78.45	20.76	40.72	11.60	.000
$\|\phi\|$	186.37	11.60	169.93	6.53	.000
The Woodlands					
PD	158.42	239.64	617.04	322.12	.000
ED	826.32	516.83	905.15	209.27	**.331**
MPS	1.74	1.74	.12	.10	.000
MSI	2.17	.89	1.51	.10	.000
MNN	4.69	1.16	6.43	1.44	.000
PLAND	85.32	12.61	51.60	11.32	.000
$\|\phi\|$	190.03	5.54	175.61	4.69	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, $|\phi|$: Fragmentation Index

As discussed in chapter II, nearest neighbor distance is defined as the distance from a patch to the nearest neighboring patch of the same type, based on edge-to-edge distance. Therefore, although forest patches in North Houston area were subdivided into smaller fragments, the mean edge-to-edge distance of these patches did not changed significantly in early development period. It can be presumed that traditionally developed street pattern does not significantly affect mean nearest neighbor distance (MNN).

The Woodlands area was also fragmented in early development period. However, edge density (ED) index does not show significant difference in this area. Edge density

(ED) is edge length on a per unit area and represents landscape configuration. So, The Woodlands, ecologically planned and developed area, presumably was not significantly affected by edge effect. This indicates that the wind and light intensity and quality reaching a forest patch that alter microclimate and disturbance rates in early development period are not significantly different from pre-development status.

Table 4.6 shows the statistical difference between early development period and mature period for the forest class metrics. In both areas, all landscape metrics indicate significant differences between two periods. However, the level of significance (p-value) indicates the different weight of evidence between two study areas.

In North Houston area, patch density (PD, $p<0.05$), edge density (ED, $p<0.001$), mean patch size (MPS, $p<0.001$), mean shape index (MSI, $p<0.001$), mean nearest neighbor distance (MNN, $p<0.001$), percentage of landscape (PLAND, $p<0.001$), and fragmentation index ($|\phi|$, $p<0.001$) show significant differences between early development and mature period and edge density (ED, $p<0.001$), mean nearest neighbor distance (MNN, $p<0.001$), percentage of landscape (PLAND, $p<0.001$), and fragmentation index ($|\phi|$, $p<0.001$) in The Woodlands also significant differences during same periods.

It can be described that landscape metrics of traditionally developed area which had the less restrictive development regulation changed much more than those of ecologically developed area which had the more restrictive development regulation. So, it can be assumed that forest crown cover affecting the calculation of metrics grows fast over time in traditionally developed community.

Table 4.6
Statistical differences of the forest class metrics between the early development and mature period

Metrics	Early development		Mature period		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	1678.65	746.21	1291.34	837.72	**.028**
ED	1521.49	442.05	2365.94	206.22	.000
MPS	.03	.02	.07	.05	.000
MSI	1.45	.10	1.57	.17	.000
MNN	5.43	.99	4.46	.19	.000
PLAND	40.72	11.60	57.31	10.19	.000
$\|\phi\|$	169.93	6.53	171.33	6.48	.000
The Woodlands					
PD	617.04	322.12	481.04	341.49	**.048**
ED	905.15	209.27	1637.59	349.41	.000
MPS	.12	.10	.36	.74	**.032**
MSI	1.51	.104	1.80	.83	**.021**
MNN	6.43	1.44	4.47	.34	.000
PLAND	51.60	11.32	76.41	7.74	.000
$\|\phi\|$	175.61	4.69	184.01	3.88	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, $|\phi|$: Fragmentation Index

In case of the analysis of differences between pre-development period and mature period, only mean nearest neighbor distance (MNN) metrics of The Woodlands indicate there is no significant difference. This can be presented that ecologically planned and developed area may recover faster with a view point of isolation than traditionally developed one does (Table 4.7).

In North Houston area, patch density (PD, $p<0.001$), edge density (ED, $p<0.001$), mean patch size (MPS, $p<0.001$), mean shape index (MSI, $p<0.001$), mean nearest neighbor distance (MNN, $p<0.001$), percentage of landscape (PLAND, $p<0.001$), and fragmentation index ($|\phi|$, $p<0.001$) show significant differences between early development and mature period and patch density (PD, $p<0.001$), edge density (ED, $p<0.001$), mean shape index (MSI, $p<0.001$), percentage of landscape (PLAND, $p<0.001$), and fragmentation index ($|\phi|$, $p<0.001$) in The Woodlands also show significant differences during same periods.

Table 4.7
Statistical differences of the forest class metrics between the pre-development and mature period.

Metrics	Pre-development		Mature period		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	386.90	710.18	1291.34	837.72	.000
ED	836.88	483.05	2365.94	206.22	.000
MPS	1.68	2.13	.07	.05	.000
MSI	1.98	1.02	1.57	.17	.014
MNN	5.17	1.52	4.46	.19	.012
PLAND	78.45	20.76	57.31	10.19	.000
$\|\phi\|$	186.37	11.60	171.33	6.48	.000
The Woodlands					
PD	158.42	239.64	481.04	341.49	.000
ED	826.32	516.83	1637.59	349.41	.000
MPS	1.74	1.74	.36	.74	.000
MSI	2.17	.89	1.80	.83	.038
MNN	4.69	1.16	4.47	.34	**.226**
PLAND	85.32	12.61	76.41	7.74	.000
$\|\phi\|$	190.03	5.54	184.01	3.88	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, $|\phi|$: Fragmentation Index

5. Relationship between Landscape Structure and Local Development Regulations

The forest class-level landscape metrics of North Houston area and The Woodlands in pre-development period indicated that there were no significant differences between two sites with a level of significance of p=0.05 (Table 4.8). As discussed above, this indicates that biophysical characteristics of two study areas, such as vegetation type, soil, climate, watershed, and precipitation, are very similar.

However, in the early development period all metrics showed significant differences between two areas. Patch density (PD) and edge density (ED) of North Houston area showed higher values and mean shape index (MSI), mean nearest neighbor distance (MNN), and percentage of landscape (PLAND) indices indicated lower values than those of The Woodlands. Patch density (PD) value of forest class in North Houston area was 2.7 times higher than that of The Woodlands and mean patch size (MPS) value was 3.7 times lower than that of The Woodlands. Edge density (ED) value of in North Houston has also 1.7 times higher than that of The Woodlands and mean shape index (MSI), mean nearest neighbor distance (MNN), and percentage of landscape (PLAND), are 96%, 84%, and 79% of those of The Woodlands respectively.

As discussed previously, the number of patches and area metrics are very important indicators to understand landscape structure. Progressive reduction in the size of habitat fragments is a key component of habitat fragmentation.

Patch size affects the occurrence and abundance of some species and it is important

Table 4.8
Forest class metrics of North Houston and The Woodlands in pre-development, early development, and mature period, with *p* values for statistical difference between the two sites by t-test.

Metrics	North Houston		The Woodlands		*p*
	Mean	SD	Mean	SD	
Pre-development					
PD	386.90	710.18	158.42	239.64	**.052**
ED	836.88	483.05	826.32	516.83	**.921**
MPS	1.68	2.13	1.74	1.74	**.887**
MSI	1.98	1.02	2.17	.89	**.347**
MNN	5.17	1.52	4.69	1.16	**.135**
PLAND	78.45	20.76	85.32	12.61	**.067**
$\|\phi\|$	186.37	11.60	190.03	5.54	.029
Early development					
PD	1678.65	746.21	617.04	322.12	.000
ED	1521.49	442.05	905.15	209.27	.000
MPS	.032	.02	.12	.10	.000
MSI	1.45	.10	1.51	.10	.012
MNN	5.43	.99	6.43	1.44	.000
PLAND	40.72	11.60	51.60	11.32	.000
$\|\phi\|$	169.93	6.53	175.61	4.69	.000
Mature period					
PD	1291.34	837.72	481.04	341.49	.000
ED	2365.94	206.22	1637.59	349.41	.000
MPS	.07	.05	.36	.74	.010
MSI	1.57	.17	1.80	.83	**.071**
MNN	4.46	.19	4.47	.34	**.838**
PLAND	57.31	10.19	76.41	7.74	.000
$\|\phi\|$	171.33	6.48	184.01	3.88	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, $|\phi|$: Fragmentation Index

in species diversity and species distribution pattern. Number of patch also determines the number of subpopulations and it can alter the stability of species interactions and opportunities for coexistence. The patch density is a good indicator for spatial heterogeneity.

In mature period the landscape indices indicate less significant difference between two areas compared to the early development period. In this period mean shape index (MSI) and mean nearest neighbor distance (MNN) of forest class showed no significant difference between two areas with a level of significance of p=0.05.

Patch density (PD) value of forest class in North Houston area is still 2.7 times higher than that of The Woodlands and mean patch size (MPS) value is 5.2 times lower than that of The Woodlands. Edge density (ED) of North Houston area is 1.4 times higher and percentage of landscape (PLAND) is 1.3 times lower than those of The Woodlands.

This result indicates that forest class in North Houston is more fragmented than that of The Woodlands. As they were in the early development period, patch density (PD) and edge density (ED) values of North Houston area were higher than those of The Woodlands while mean patch size (MPS), mean shape index (MSI), mean nearest neighbor distance (MNN), and percentage of landscape (PLAND) values were lower than those of The Woodlands (Table 4.8).

Table 4.9 shows that some spatial characteristics variables such as lot size and building footprint are not significantly correlated with the selected six landscape metrics and, likewise, mean nearest neighbor distance (MNN) metrics also is not correlated with all spatial characteristics variables. However, this table presents that street related factors such as perimeter adjacent to the road, street width, and number of intersection play important roles to the spatial pattern.

Lot perimeter and road adjacent perimeter are correlated with patch density (PD), edge density (ED), and percentage of landscape (PLAND) metrics and street width is correlated with edge density (ED), mean patch size (MPS), mean shape index (MSI), and percentage of landscape (PLAND) metrics. Number of intersection and number of cul-de-sac variable are correlated with edge density (ED) and patch density (PD) metrics respectively.

Perimeter of parcel lot shows positive relationships with patch density (PD, r=.246) and edge density (ED, r=.430) and negative relationships with percentage of landscape (PLAND, r=-.351). Perimeter adjacent to the street shows similar pattern with lot

Table 4.9
Correlation coefficients of landscape metrics of forest class with spatial characteristics

	PD	ED	MPS	MSI	MNN	PLAND	$\|\phi\|$
Lot size (m^2)	-.005	.071	-.071	-.101	-.074	.053	.041
Building footprint (m^2)	.076	.151	-.123	-.114	-.148	-.115	-.098
Perimeter (m)	.246*	.430**	.114	.184	-.126	-.351**	-.304**
Adjacent perimeter (m)	.243*	.496**	-.112	-.013	-.136	-.431**	-.359**
Number of parcel	.096	.140	.197	.241*	-.047	-.148	-.132
Street width	.202	.214*	-.229*	-.218*	-.019	-.289**	-.258*
Number of intersection	-.033	.211*	-.069	.004	-.129	-.147	-.076
Number of Cul-de-sac	-.224*	.024	.055	.095	-.147	.117	.166
Development standards	-.548**	.783**	.259*	.182	.021	.732**	.641**

*p<.05. **p<.01. N=90.
PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, and $|\phi|$: Fragmentation Index

perimeter. It indicates positive relationships with patch density (PD, r=.243) and edge density (ED, r=.496) and negative relationships with percentage of landscape (PLAND, r=-.431).

Number of parcel is shown to be positively related with mean shape index (MSI, r=.241) and number of intersection is positively related with edge density (ED, r=.211). Street width shows positive relationships with edge density (ED) with a correlation coefficient of .214 and negative relationships with mean patch size (MPS, r=-.229), mean shape index (MSI, r=-.218), and percentage of landscape (PLAND, r=-.289). Number of cul-de-sac is also showed to be negatively related with patch density (PD=-.224).

Development standards, such as grooming, tree removal, and native plant show significantly positive relationships with edge density (ED, r=.783), mean patch size (MPS, r=.259), and percentage of landscape (PLAND, r=.732) and negative relationships with patch density (PD, r=-.548).This result shows that development standard is less correlated with shape complexity and neighboring patch distance.

As shown in table 4.2, significant differences between two study areas exist in spatial attributes such as perimeter (p<0.001), adjacent perimeter to the road (p<0.001), street width (p<0.01), and number of intersection (p<0.05). These street related spatial attributes show a good correlation with selected landscape metrics (Table 4.9).

Analysis of covariance (ANCOVA) was used to control the source of variation due to the planning method. Covariates are perimeter of parcel lot, adjacent perimeter to the road, street width, and number of intersection. Table 4.10 shows covariates having significant correlation with landscape metrics do not significantly affect the group differences. Unlike as the results of t-test (Table 4.8), the mean difference of MSI (mean shape index) between two areas at mature period is statistically significant, $F(1,84)=4.664$, $p<.05$.

Table 4.10
Forest class metrics of North Houston and The Woodlands in early development and mature period, with *p* values for statistical difference between the two sites by ANCOVA.

Metrics	North Houston		The Woodlands		F	*p*
	Mean	SD	Mean	SD		
Early development						
PD	1678.65	746.21	617.04	322.12	41.07**	.000
ED	1521.49	442.05	905.15	209.27	38.29**	.000
MPS	.032	.022	.119	.100	23.88**	.000
MSI	1.45	.10	1.51	.104	10.41**	.002
MNN	5.43	.99	6.43	1.44	12.89**	.001
PLAND	40.72	11.60	51.60	11.32	4.66**	.034
|ϕ|	169.93	6.53	175.61	4.69	13.61**	.000
Mature period						
PD	1291.34	837.72	481.04	341.49	24.38**	.000
ED	2365.94	206.22	1637.59	349.41	79.40**	.000
MPS	.07	.05	.36	.74	6.73*	.011
MSI	1.57	.17	1.80	.83	4.66*	.034
MNN	4.46	.19	4.47	.34	**.28**	**.599**
PLAND	57.31	10.19	76.41	7.74	58.27**	.000
|ϕ|	171.33	6.48	184.01	3.88	35.16**	.000

*$p<.05$. **$p<.01$. N=90.
PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, |ϕ|: Fragmentation Index

Table 4.11 represents the analysis of covariance for statistical difference of landscape metrics. In early development period, the results of the ANCOVA indicated that there were significant differences between patch density (PD, $p<.001$), edge density (ED, $p<.001$), mean patch size (MPS, $p<.001$), mean shape index (MSI, $p<.001$), mean nearest neighbor distance (MNN, $p<.001$), percentage of landscape (PLAND, $p<.05$), and fragmentation index ($p<.001$) controlling for parcel perimeter, perimeter adjacent to the street, street width, and number of intersection. They showed that perimeter element appeared to affect edge density (ED) mean difference significantly ($p<.05$), attributes of perimeter, adjacent perimeter, and number of intersection appeared to affect mean patch size (MPS) mean difference significantly ($p<.01$, $p<.01$, $p<.05$ respectively), and number of intersection appeared to affect mean nearest neighbor distance (MNN) mean difference significantly ($p<.05$).

In mature period, the results of the analysis of covariance indicated that there were significant differences between patch density (PD, $p<.001$), edge density (ED, $p<.001$), mean patch size (MPS, $p<.05$), mean shape index (MSI, $p<.01$), percentage of landscape (PLAND, $p<.001$), and fragmentation index ($p<.001$) controlling for parcel perimeter, perimeter adjacent to the street, street width, and number of intersection. During this period, number of intersection appeared to affect patch density (PD) mean difference significantly ($p<.05$), attributes of perimeter, adjacent perimeter, and number of intersection appeared to affect mean patch size (MPS) mean difference significantly ($p<.01$, $p<.01$, $p<.05$ respectively), and parcel perimeter appeared to affect mean shape index (MSI) mean difference significantly ($p<.05$)

Table 4.11
Analysis of covariance for statistical difference of two sites

	PD			ED			MPS		
	df	F	p	df	F	p	df	F	p
Early development period									
Perimeter	1	.670	.415	1	4.417*	.039	1	7.121**	.009
Adjacent perimeter	1	.001	.974	1	1.013	.317	1	10.056**	.002
Street width	1	.006	.938	1	.166	.685	1	.189	.665
Number of intersection	1	.123	.727	1	.304	.583	1	5.950*	.017
Groups	1	41.065***	.000	1	38.297***	.000	1	23.884***	.000
Mature period									
Perimeter	1	.003	.957	1	.276	.601	1	12.323**	.001
Adjacent perimeter	1	.180	.673	1	1.806	.183	1	3.977*	.049
Street width	1	2.012	.160	1	.446	.506	1	1.754	.189
Number of intersection	1	5.533*	.021	1	.263	.610	1	.804	.373
Groups	1	24.376***	.000	1	79.401***	.000	1	6.725*	.011

*p<.05. **p<.01. ***p<.001. N=90.
PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size

	MSI			MNN			PLAND		
	df	F	p	df	F	p	df	F	p
Early development period									
Perimeter	1	2.438	.122	1	1.123	.292	1	2.926	.091
Adjacent perimeter	1	.446	.506	1	3.663	.059	1	.028	.868
Street width	1	.233	.630	1	.219	.641	1	.650	.422
Number of intersection	1	3.084	.083	1	4.323*	.041	1	1.658	.201
Groups	1	10.409**	.002	1	12.898**	.001	1	4.661*	.034
Mature period									
Perimeter	1	10.897**	.001	1	.637	.637	1	.336	.336
Adjacent perimeter	1	2.349	.129	1	.766	.766	1	.167	.167
Street width	1	3.107	.082	1	.666	.666	1	.254	.254
Number of intersection	1	1.428	.235	1	.510	.510	1	.108	.108
Groups	1	4.664*	.034	1	.599	.599	1	.000***	.000

*p<.05. **p<.01. ***p<.001. N=90.
MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

Table 4.11 Continued

	|ϕ|		
	df	F	p
Early development period			
Perimeter	1	.136	.136
Adjacent perimeter	1	.985	.985
Street width	1	.495	.495
Number of intersection	1	.332	.332
Groups	1	.000***	.000
Mature period			
Perimeter	1	.526	.526
Adjacent perimeter	1	.260	.260
Street width	1	.193	.193
Number of intersection	1	.050*	.050
Groups	1	.000***	.000

*p<.05. **p<.01. ***p<.001. N=90.
|ϕ|: Fragmentation Index

6. Main Effect and Interaction Effect

This study is interested in the landscape structure over time when different development guidelines and planning method are applied. Below are the questions about how factors affect the landscape structure.

1. Does development time period have an effect on landscape structure?
2. Do development guidelines have an effect on landscape structure?
3. Do different development guidelines affect landscape structure differently? (interaction effect)

The first factor is time period and has three levels: pre-development, early development, and mature period. The second factor is designated as group and has two levels: traditionally developed community (North Houston) and ecologically planned community (The Woodlands) using more restrictive development guidelines. The

Table 4.12
Descriptive statistics of patch density (PD)

Metrics	Pre-development		Early development		Mature period		Total Mean
	Mean	SD	Mean	SD	Mean	SD	
North Houston	386.90	710.18	1678.65	746.21	1291.34	837.72	**1118.96**
The Woodlands	158.42	239.64	617.04	322.12	481.04	341.49	**418.83**
	265.05		**1112.46**		**859.18**		

dependent variables are the landscape structure indices consisting of patch density (PD), edge density (ED), mean patch size (MPS), mean shape index (MSI), mean nearest neighbor distance (MNN), and percentage of landscape (PLAND).

6.1. Two Way ANOVA and Interaction (2 × 3)

Main effects are differences in means over levels of one factor collapsed over levels of the other factor. The interaction is ignored for this part. For example, the main effect of site is simply the difference between the means of patch density (PD) for the two levels of site, ignoring or collapsing over development period. As shown in the table 4.12, the main effect of site is whether the two marginal means associated with the site factor are different. In this case these means were 1118.96 and 418.83 and the differences between these means were statistically significant. As shown in the table 4.12, the main effect of period is also significant. This effect refers to the differences in the three marginal means associated with period. In this case the values for these means were 265.05, 1112.46, and 859.18 and the differences between them may be attributed to a real effect.

The interaction effect is the effect that one factor has on the other factor. It is a change in the simple main effect of one variable over levels of the second. An A × B or A by B interaction is a change in the simple main effect of B over levels of A or the change in the simple main effect of A over levels of B. In either case the cell means cannot be modeled simply by knowing the size of the main effects. An additional set of parameters must be used to explain the differences between the cell means. These parameters are collectively called an interaction.

The interaction effect is most easily seen in the graph. If the lines describing the simple main effects are not parallel, then a possibility of an interaction exists. As can be seen from Fig. 4.4, the possibility of a significant interaction exists because the lines are not parallel. The presence of an interaction was confirmed by the statistical significance in Table 4.13.

Table 4.13 shows significances of effects between two sites and three development periods for the selected landscape indices. Patch density (PD), edge density (ED) and

Table 4.13
Significances of between-subjects effects for pre-development, early development, and mature period.

Metrics	Site	Period	Site × Period
PD	.000	.000	.000
ED	.000	.000	.000
MPS	**.308**	.000	**.773**
MSI	**.051**	.000	**.659**
MNN	**.173**	.000	.000
PLAND	.000	.000	.006
$\|\phi\|$	.000	.000	**.093**

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, and $|\phi|$: Fragmentation Index percentage of landscape (PLAND) show significant main effects of site and period and interaction effects. However, only main effect of period exists in mean patch size (MPS) and mean shape index (MSI) while combined effect of site and period exists in mean nearest neighbor (MNN) index.

Two things can be observed in this analysis. The first is that the main effect of period is possibly significant, because the means have different heights. Second, the interaction is possibly significant because the simple main effects of period in North Houston and The Woodlands are different from the main effect of period.

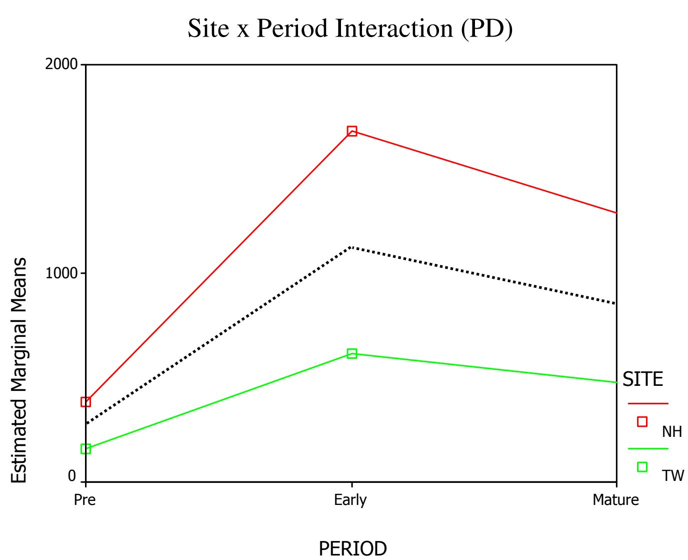


Fig. 4.4. Profile plot of the development period by group level interaction

6.2. Two Way ANOVA and Interaction (2 × 2)

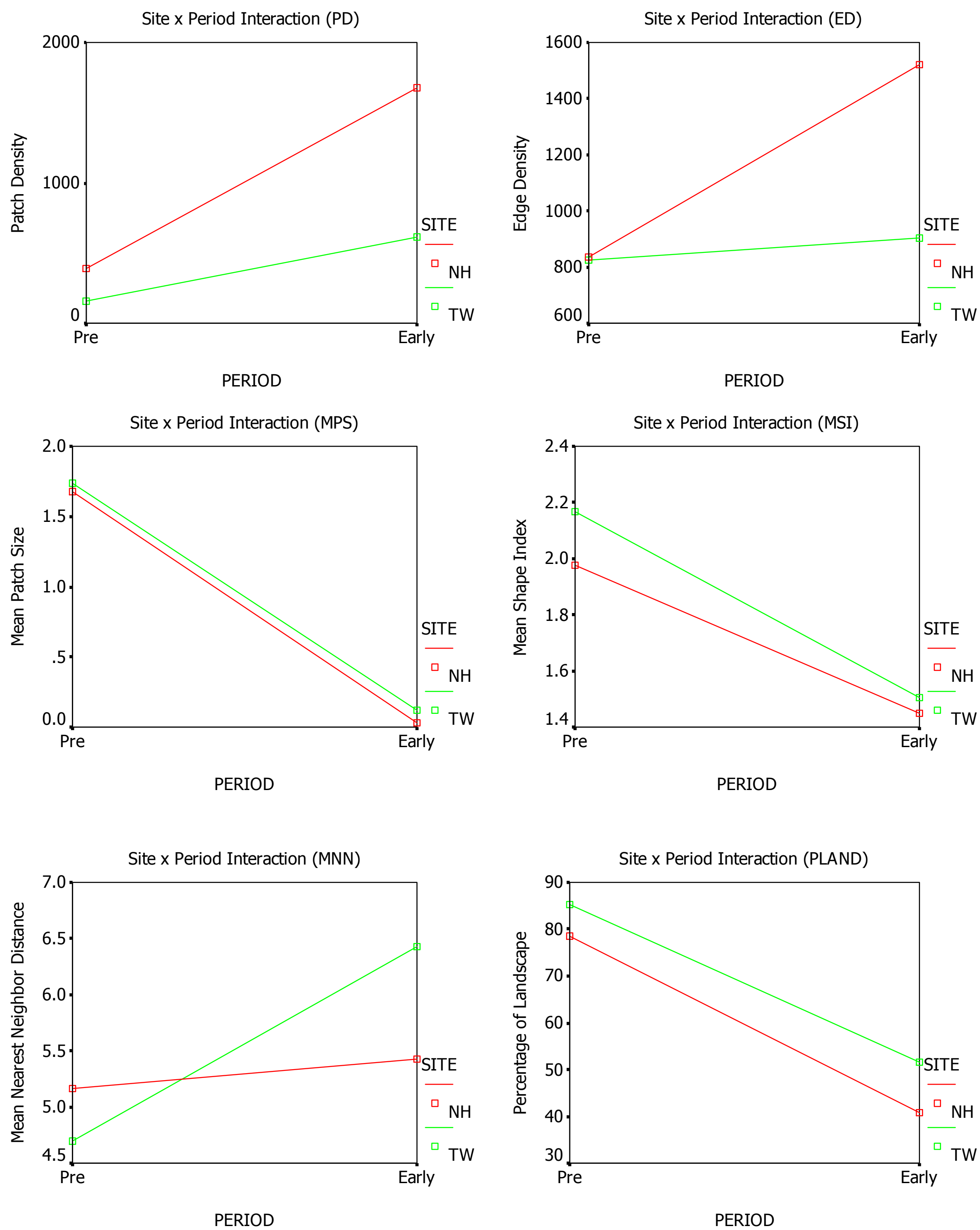
Table 4.13 shows the results of two-way ANOVA for pre-development and early development period. Main effect and interaction effect of site and period are significant in patch density (PD) and edge density (ED) while main effect of period and interaction effect exist in mean nearest neighbor (MNN).

As can be seen from the graph of Fig. 4.5, the lines describing the simple main effects are not parallel in patch density (PD), edge density (ED), and mean nearest neighbor (MNN) between pre-development and early development period. This indicates the possibility of a significant interaction exists. This presence of an interaction was confirmed by the significant interaction with *p* value ($p<0.001$). However, mean patch size (MPS) and mean shape index (MSI) are statistically related to period factor alone with a significance level of $p<0.001$ in this period. In percentage of landscape (PLAND), even though main effects of site and period exist ($p<0.001$), interaction effect is not significant (Table 4.14).

Table 4.14
Significances of between-subjects effects for pre-development and early development period

Metrics	Site		Period		Site × Period	
	F	*p*	F	*p*	F	*p*
PD	64.222	.000	118.223	.000	26.783	.000
ED	24.065	.000	35.690	.000	22.471	.000
MPS	.128	**.721**	63.833	.000	.005	**.942**
MSI	1.479	**.226**	34.126	.000	.442	**.507**
MNN	1.729	**.190**	24.339	.000	13.155	.000
PLAND	16.919	.000	274.146	.000	.862	**.354**
|ϕ|	28.237	.000	217.989	.000	1.873	**.173**

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, |ϕ|: Fragmentation Index



NH: North Houston
TW: The Woodlands

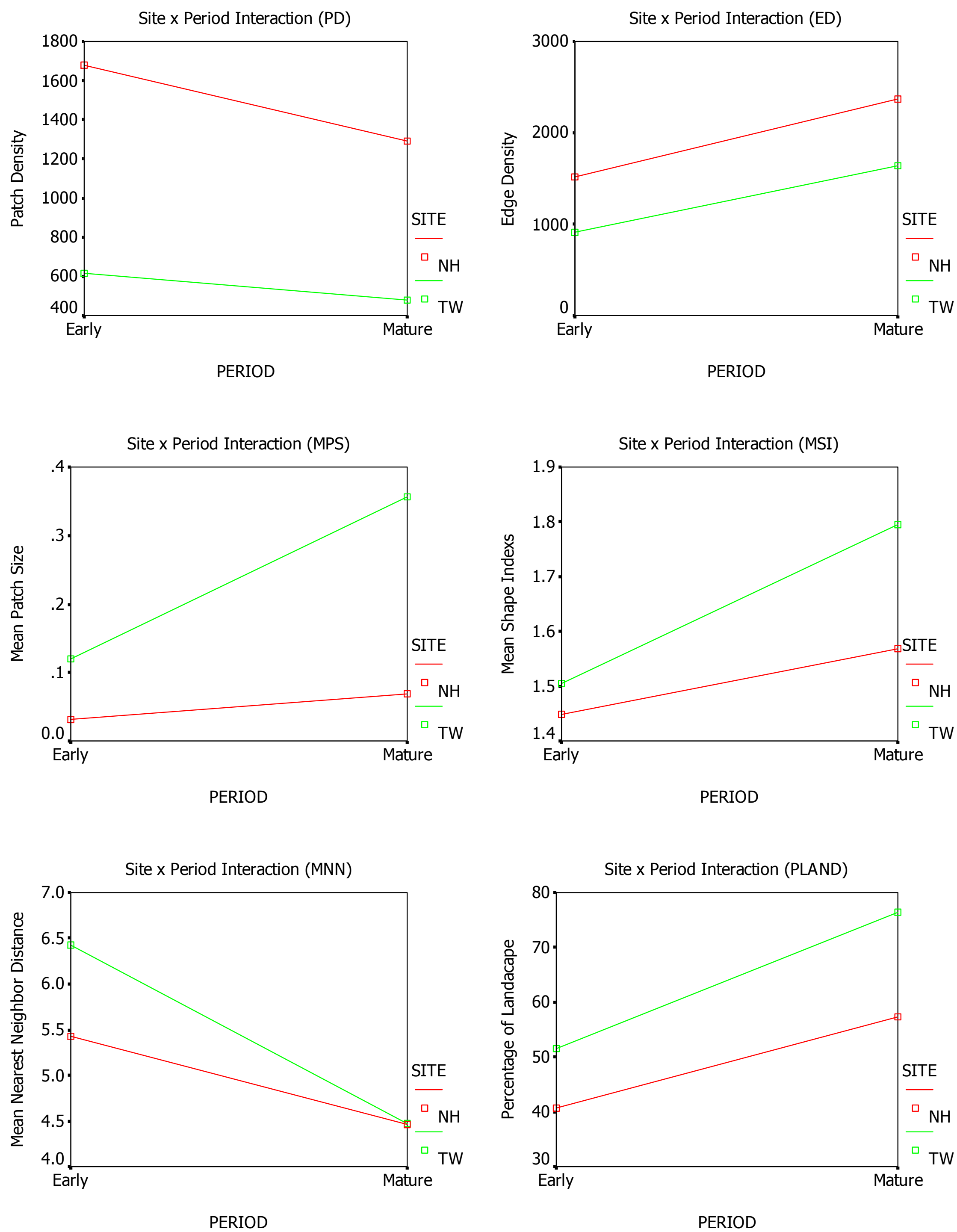
Fig. 4.5. Site by period interaction between pre-development and early period

Table 4.15 indicates the significances of between-subjects effects for early development and mature period. In all of the selected metrics, main effects of site and period are significant (*p*<0.001). This effect refers to the differences between the two marginal means associated with site or period. However, the combined effect of period and site factor exists significantly in mean nearest neighbor (MNN, *p*<0.001) and percentage of landscape (PLAND, *p*=0.008). Fig. 4.6 describes the simple main effects of site and period. The lines are not parallel in mean patch size (MPS), mean shape index (MSI), and mean nearest neighbor distance (MNN) and show possibility that a significant interaction might exist. Statistically, however, interaction effect exists only in mean nearest neighbor distance (MNN, *p*<0.001) and percentage landscape (PLAND, *p*=0.008) metrics (Table 4.15).

Table 4.15
Significances of between-subjects effects for early development and mature period

Metrics	Site		Period		Site × Period	
	F	*p*	F	*p*	F	*p*
PD	111.476	.000	8.712	.004	2.009	**.158**
ED	203.077	.000	279.261	.000	1.409	**.237**
MPS	10.636	.001	5.719	.018	2.995	**.085**
MSI	4.547	.034	9.450	.002	1.662	**.199**
MNN	13.831	.000	116.009	.000	13.191	.000
PLAND	95.094	.000	181.347	.000	7.149	.008
|ϕ|	98.414	.000	121.887	.000	.618	.433

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, |ϕ|: Fragmentation Index



NH: North Houston
TW: The Woodlands

Fig. 4.6. Site by period interaction between early development and mature period

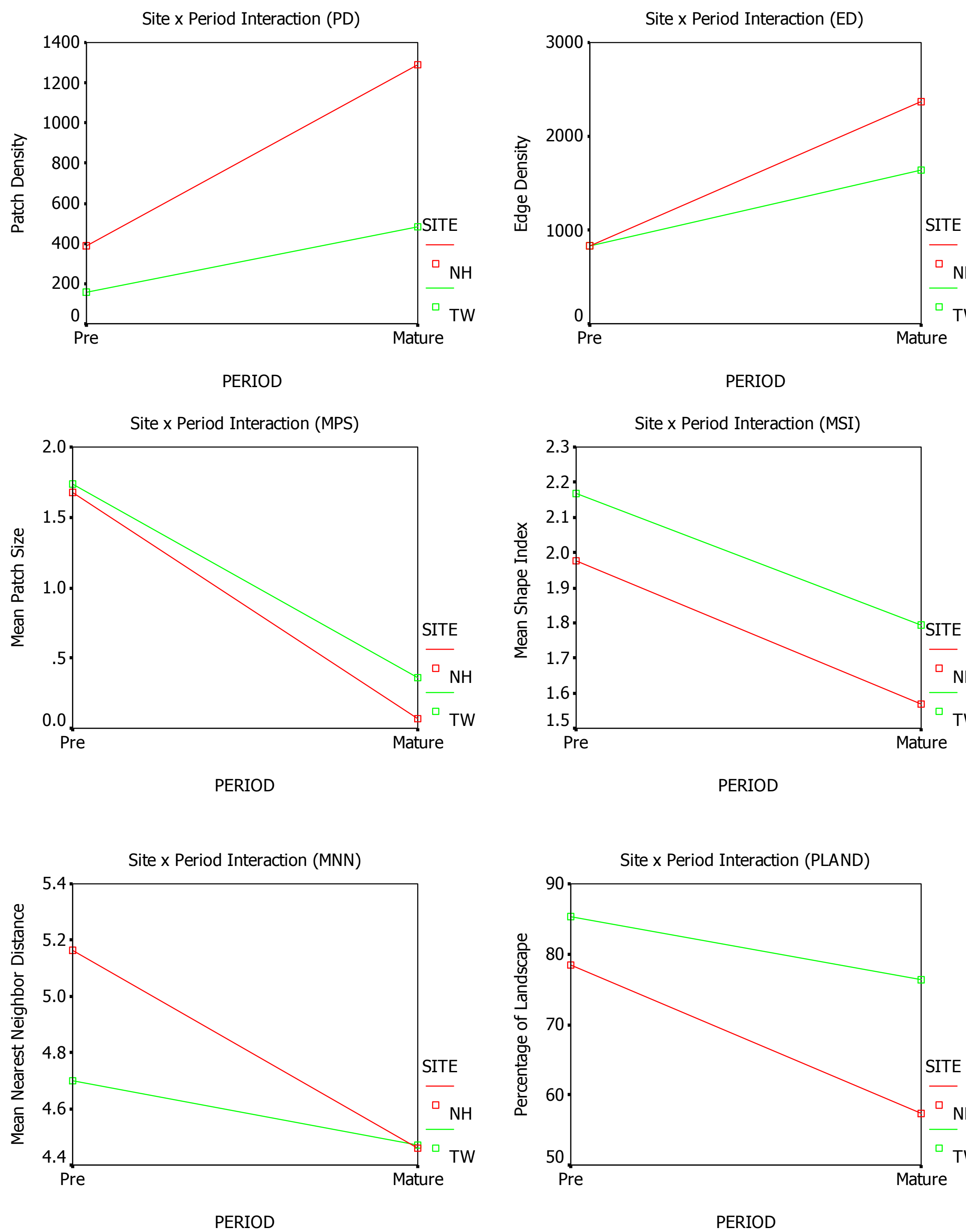
Table 4.16 shows the significance of between-subjects effects for pre-development and mature period. Main effect and interaction effects exist in patch density (PD, $p<0.001$), edge density (ED, $p<0.001$), and percentage of landscape (PLAND, $p=0.003$). This means site and period are significantly related to the patch density (PD), edge density (ED), and percentage of landscape (PLAND) and two factors interact each other.

However, only period has a significant effect for mean patch size (MPS, $p<0.001$), mean shape index (MSI, $p=0.001$), and mean nearest neighbor (MNN, $p=0.002$). Also, Fig. 4.7 illustrates simple main effects of site and period variables. Even though mean nearest neighbor (MNN) seems to exist interaction effect due to line slope, $F_{0.05}$ value (2.724) is not greatly exceeded. Statistically, therefore, interaction effect does not exist in this metrics.

Table 4.16
Significances of between-subjects effects for pre-development and mature period

Metrics	Site		Period		Site × Period	
	F	*p*	F	*p*	F	*p*
PD	36.907	.000	51.499	.000	11.578	.001
ED	36.356	.000	364.709	.000	34.308	.000
MPS	.664	**.416**	49.733	.000	.292	**.590**
MSI	3.018	**.084**	10.472	.001	.022	**.881**
MNN	2.462	**.119**	10.327	.002	2.724	**.101**
PLAND	41.247	.000	55.254	.000	9.141	.003
$\|\phi\|$	35.991	.000	46.419	.000	3.920	.049

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape, $|\phi|$: Fragmentation Index



NH: North Houston
TW: The Woodlands

Fig. 4.7. Site by period interaction between pre-development and mature period

7. Summary

This chapter discussed the analysis and results based on the hypotheses and study objectives. Selected metrics were computed for classes within two study areas. Percentage of landscape (PLAND) of forest cover, which indicates the proportion of forest class area, revealed that the forest area of North Houston area (48%) decreased more significantly than that of The Woodlands (39%). Traditionally planned community has more fragmented forest patches and more disadvantages for biodiversity than ecologically planned community does.

The result from parcel lot and street pattern analysis, showed that parcel related variables, i.e. lot size, building footprint, and number of parcels, are not significantly different. So it can be interpreted that planning method does not significantly affect to housing density even though street related variables are significantly different between two areas.

Overall fragmentation measurement was conducted single measurement model incorporated area, boundary length, number, and isolation (Bogaert et al., 2000). Fragmentation index indicates that early development period in North Houston is the most fragmented and pre-development period in The Woodlands is the least fragmented. It also shows that traditionally developed community recovers more slowly than ecologically developed one does.

For comparing the difference of selected landscape metrics between pre-development period and early development period, the mean nearest neighbor distance (MNN) index in North Houston area and edge density (ED) in The Woodlands do not show significant differences. It can be presumed that traditionally developed street pattern does not significantly affect mean nearest neighbor distance (MNN) while ecologically planned and developed area presumably does not significantly affect edge density (ED).

The statistical difference between early development period and mature period for the forest landscape metrics indicates that in North Houston area, all landscape metrics except patch density (PD) show significant difference between two periods. The results of The Woodlands, however, shows patch density (PD), mean patch size (MPS) and mean shape index (MSI) are not significantly different.

In case of the analysis of difference between pre-development period and mature period, selected landscape metrics indicates significant difference except mean nearest neighbor distance (MNN) metrics of The Woodlands.

The analysis of the difference between sites in three development periods states that there are no significant differences between two study areas for pre-development period. This can be assumed that biophysical characteristics of two areas are very similar. However, in the early development period all metrics indicate significant differences. In mature period, even though mean shape index (MSI) and mean nearest neighbor distance (MNN) are not significantly different, the others show significant difference between two sites.

In analysis of correlation between spatial characteristics and landscape metrics, street related factors such as perimeter adjacent to the road, street width, and number of intersection play important roles to the spatial pattern. Especially, development standards, designating grooming, tree removal, and native plant are significantly correlated with almost all of the landscape metrics.

Two-way ANOVA analysis describes the main effect and interaction effect of site and development period factors in three development periods. In pre-development and early development period, main effect of period exists in all selected metrics and interaction effect of site and period exist in patch density (PD), edge density (ED), and mean nearest neighbor distance (MNN). For the analysis of early development and mature period, main effect of site and period exist in all landscape metrics while interaction effects exist in mean nearest neighbor distance (MNN) and percentage of landscape (PLAND). The result for pre-development and mature period shows that main effect and interaction effects exist in patch density (PD), edge density (ED), and percentage of landscape (PLAND) while main effect of period exists in mean patch size (MPS), mean shape index (MSI), and mean nearest neighbor (MNN).

CHAPTER V

CONCLUSION AND RECOMMENDATION

1. Conclusion

The objective of this study was to investigate the relationship between ecological landscape structure and local development regulations over time. Comparison analysis was conducted between two areas that had similar pre-development ecological conditions but were developed under vastly different regulatory environments.

This study started with some basic questions: are there any relationships between local development regulations and ecological landscape structure? More specifically, the question is; whether there are relationships between development regulations, guidelines, and planning method and fragmentation of urban vegetation. Subsequent questions are; if there are relationships, how local development regulations affect landscape structures and how planning and development method affect the fragmentation of urban vegetation. In addition, if the landscape structure differences exist, how the differences would change over time?

Based on these questions four hypotheses were made; 1) More restrictive development regulations lead to lower forest habitat fragmentation in the period just after development, 2) Over time, re-growth will lead to no differences in fragmentation between regulatory environments, and 3) Different development regulations affect landscape structure differently (Interaction effect).

1.1. More restrictive development regulations lead to lower forest habitat fragmentation in the period just after development: Hypothesis 1

As discussed above, two study areas were very similar in biophysical characteristics at pre-development period. There is no significant difference between North Houston area and The Woodlands for comparison of landscape indices in pre-development period. Most selected landscape metrics and fragmentation index, however, has shown the significant differences in the analysis of the difference between pre-development period and early development period. This suggests a direct relationship between different regulatory environments and landscape structures.

The forest patches of both areas were fragmented as a result of the residential development during 1970s. However, the change ratio of landscape metrics of forest class and the level of significance (*p*-value) indicates that the community having more restrictive development regulations shows less changed landscape metrics than the community having normal development regulations does.

Patch density (PD) of forest class in North Houston increased 4.3 times during the early development period while it increased 3.9 times in The Woodlands during the same period. Mean patch size (MPS), mean shape index (MSI), percentage of landscape (PLAND), and fragmentation index decreased to: 4% in North Houston area and 21% in The Woodlands, 73% in North Houston area and 70% in The Woodlands, 52% in North Houston area and 60% in The Woodlands, and 91.2% in North Houston area and 92.4% in The Woodlands respectively. Edge density (ED) values increased 1.8 times in North

Houston area and 1.1 times in The Woodlands and mean nearest neighbor distance (MNN) metrics showed similar trend in patch density (PD).

Two landscape metrics, mean nearest neighbor distance (MNN) in North Houston and edge density (ED) in The Woodlands did not show significant difference. It can be presumed that traditional regulations do not significantly affect isolation index and more restrictive development regulations do not cause edge effect significantly.

This study suggests that development standards made by homeowner association or community association are most significantly correlated with the landscape metrics. Development standards have shown positive relationships over mean patch size (MPS), percentage of landscape (PLAND), and fragmentation index ($|\phi|$) with a correlation coefficient of 0.255, 0.732, and 0.641. These are also negative relationships over patch density (PD) and edge density (ED) with a correlation coefficient of -0.548 and -0.783 respectively.

Street pattern related variables such as adjacent perimeter to road, street width, and the number of intersection are more closely correlated with landscape structure than parcel related variables such as lot size, building footprint, or the number of parcels. Stone Jr. (2004) argues that total parcel impervious area increases significantly with increments in lot size. According to the results of this study, however, parcel lot size does not significantly affect landscape structure. Even though the code of ordinances (subdivision Sec 42-183) designates the minimum lot size for a single family residential lot in an urban area as 3,500 square feet (325 m^2), mean parcel sizes in both areas are much larger (North Houston: 1,149 m^2, The Woodlands: 1,214 m^2) than required minimum lot size is. Therefore, the minimum limits of lot size are not so meaningful in single family residential development of these study areas.

In sum, the more restrictive regulations such as grooming, tree removal, and native plant have fewer negative effects on ecological landscape condition than less restrictive ones.

1.2. Landscape fragmentation is higher in traditionally planned community than in ecologically planned one: Hypothesis 2

The results of analysis of covariance (ANCOVA) indicates that there are significant differences between two study areas. Covariates having a significant correlation with landscape metrics and are significantly different between two sites were used. Unlike as the results of t-test, mean shape index (MSI) shows significant difference at mature period with a level of significance of p=.05. Level of significance without covariates in mean shape index (MSI) indicates p=.071 while probability value of ANCOVA represents p=.034. It can be assumed that the effects of covariates, parcel perimeter, perimeter adjacent to the street, street width, and number of intersection are statistically significant in shape irregularity. However, they do not significantly affect the group differences overall.

According to the single measurement model for fragmentation, traditional planning method causes more fragmented landscape structure than ecological planning method does. The Woodlands produced by ecological planning and governed by more restrictive development regulations shows ecologically structured environments and less fragmented forest pattern. The single measure fragmentation index showing general fragmentation status indicates 169.93 in North Houston area and 175.61 in The Woodlands during early development period.

At the same period, patch density (PD) and mean patch size (MPS) of The Woodlands is 2.7 times lower and 3.7 times higher than those of North Houston area respectively. These metrics are significantly related with the number of subpopulations in a spatially dispersed population (Gilpin and Hanski, 1991) and species richness and species distribution pattern in a landscape and spatial fragmentation (Forman, 1995; Davidson, 1998; Bender et al., 1998). Edge density (ED) of North Houston area in early development period is 1.7 times higher than that of The Woodlands. This represents that ecologically planned residential area with more restrictive development regulations is less fragmented and more spatially heterogeneous.

Mean shape index (MSI), mean nearest neighbor distance (MNN), and percentage of landscape (PLAND) in North Houston area during early development period are lower than those in The Woodland. Mean shape index (MSI) indicating shape complexity showed that the change ratio of North Houston area (73%) for early development period was higher than that of The Woodlands (70%) and regained 79% and 83% respectively during the mature period. These results represent that ecologically planned community with the strict regulations have more complex landscape shape and recovers more easily. Therefore, it provides better environments for small mammal migration, woody plant colonization, and animal foraging strategies.

1.3. Over time, re-growth will lead to no differences in fragmentation between regulatory environments: Hypothesis 3

Since aerial photograph was used for the analysis of landscape structure, tree crown coverage was an important determinant in estimating metrics. Because classification was conducted without considering under story shrub, no significant difference was expected between two study areas 30 years after early development. Even though the landscape indices of the mature period indicate significant difference between two areas, these are less significant compared to those of the early development period. Especially, fragmentation index indicates that fragmentation status of ecologically planned community recovers more significantly than that of traditionally planned community in mature period.

Results of the aerial photograph-based classification in The Woodlands and North Houston area showed that proportion of forest class decreased from the pre-development to the early development period and increased after the early development. The decreases of forest class in the early development period resulted mainly from the residential development of the early 1970s. The increase of forest cover in mature period can be assumed to be the result of the tree growth with age.

Two landscape indices, mean shape index (MSI) and mean nearest neighbor distance (MNN), showed no significant difference between two areas in mature period. Patch density (PD), edge density (ED), mean patch size (MPI), and percentage of landscape (PLAND) metrics of mature period indicated significant differences between two areas with a significant level of $p<0.001$, which showed similar behavior as those of early development period did.

In sum, The Woodlands area developed through ecologically planned method and maintained by restrictive maintenance guidelines showed more ecologically structured landscape pattern. This indicates that planning approach and development regulation and guidelines may significantly affect the landscape structure and physical setting.

1.4. Different development regulations affect landscape structure differently (Interaction effect): Hypothesis 4

The results of two way ANOVA indicate that significant interaction effects exist in some landscape metrics and fragmentation index during three development period.

In early development period, significant interaction effect exist in patch density (PD) and edge density (ED) with a significance level of $p<.001$. As discussed in landscape change over time section, patch density (PD) and edge density (ED) were changed 4.3 times and 1.8 times in North Houston area while 3.9 times and 1.1 times in The Woodlands respectively in early development period. This indicates that North Houston area experienced significantly greater fragmentation in this phase.

However, there are no significant differences in rate of change during maturation. Patch density (PD), edge density (ED), mean patch size (MPS), mean shape index, and fragmentation index do not show significant interaction effect in mature period. In the long run, comparison between pre-development period and mature period reveals that traditional development experiences greater increases in patch density (PD) and edge density (ED) but decreases in overall forested land proportion.

2. Discussion and Recommendation

Knowing the landscape structure and how it affects landscape processes are important in establishing development plan and managing the developed lands. This study traced land cover changes over three time periods through the analysis of several landscape metrics and explored the relationship between local development regulation and landscape structure in The Woodlands and North Houston area. The aerial photographs were scanned, co-registered, and classified using Self-Organizing Data Analysis Technique (ISOCLASS) and subsequent spatial analyses were conducted by using ArcInfo, ArcView Spatial Analyst and FRAGSTATS spatial pattern analysis program.

Through the statistical comparison of two areas, which had similar pre-development conditions, this study revealed that planning approach and development guidelines could affect the landscape pattern. This study provides the quantified landscape configuration and composition of the effects of development regulations on landscape structure.

According to this study, the critical factors that produce more ecological environments are the specific development standards such as front yard grooming, and native plant and tree removal requirements. Especially, it was proved that 40% vegetation planting of the front yard and strict tree preservation standard may be significantly related to the vegetation community as well as landscape structure. The ecologically planned community shows a less fragmented forest pattern and more restrictive development guidelines result in more ecologically structured environments. Within this context performance zoning, cluster design, and landscape ecological planning can be considered for environmentally friendly community.

Understanding how elements of local development regulations affect ecological landscape patterns is important for landscape architects, planners, and administrators because it can lead to better strategies for planning and designing sustainable communities.

The limitation of this study is the use of 2-D data sets. Since aerial photograph was used for analysis of landscape structure, vegetation structure could not be considered. Therefore, if vegetation structure were added to this study, the result would be more specific and precise for the interpretation of ecologically planned community. This study has focused on the relationship between local development regulation and landscape structure. Further study about the effects of landscape structure or spatial pattern on human activity such as play, walking, cycling, and picnic can be conducted. Then it can be proved that the local development regulation plays an importance role in providing livable community.

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APPENDIX

1. Selected Landscape Metrics

Patch Density (PD)

- Formula $$PD = \frac{n_i}{A}(10{,}000)(100)$$
- Units: Number per 100 hectares.
- Range: PD > 0, without limit.
- Description: PD equals the number of patches of the corresponding patch type (NP) divided by total landscape area, multiplied by 10,000 and 100 (to convert to 100 hectares).
- Ecological Meaning: The number of individual patches of a particular type per unit area of landscape (#/100 ha).
  Patch density is a measure of spatial heterogeneity (McGarigal and Marks 1995). Warner (1994) reported the degree of spatial heterogeneity and connectivity within a landscape was positively correlated with species diversity and bird density. Forman and Godron (1981) concluded distance between patches was an important indicator of possible patch interactions and species diversity.

Edge Density (ED)

- Formula $$ED = \frac{\sum_{k=1}^{m'} e_{ik}}{A}(10{,}000)$$
- Units: Meters per hectare.
- Range: ED ≥ 0, without limit.
- Description: ED equals the sum of the lengths (m) of all edge segments involving the corresponding patch type, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares).
- Ecological Meaning: The linear distance of edge per unit area of landscape (m/ha).
  Edge habitat was long thought to be beneficial for wildlife; however, recent studies have revealed an association between edge density and both nest predation (Wilcove 1985) and nest parasitism (Yahner 1988). Predation was found to be the foremost factor influencing fledging success of avian species (Patterson and Best 1996), with predation causing 40-50

percent of mortality near edge compared to 5-10 percent away from edge (Gates and Gysel 1978). Although risk of predation and parasitism is higher near edge (Gates and Gysel 1978, Yahner 1988), so is nest density of open-nesting passerines, with more than 50 percent of nests found within ±15 m of the edge (Gates and Gysel 1978). These high nest densities near edge were responsible in part for the increased nest predation and parasitism (Gates and Gysel 1978).

In contrast to unfavorable associations with nest predation and parasitism, increased edge density benefits species requiring mixed cover types. The importance of edge as a habitat component for bobwhite (Brady et al. 1993) was demonstrated by a study in which nearly 60 percent of nests were located within 5 m of an observable change in cover pattern (Klimstra and Roseberry 1975). Baxter and Wolfe (1972) found a strong positive correlation between frequency of cover type change and bobwhite abundance. Regretfully, clean farming practices have led to decreased edge density, through the loss of fencerows (Vance 1976, Klimstra 1982).

Mean Patch Size (MPS)

- Formula

$$MPS = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}\left(\frac{1}{10{,}000}\right)$$

- Units: Hectares.
- Range: MPS > 0, without limit.
- Description: The range in MPS is limited by the grain and extent of the image and the minimum patch size in the same manner as patch area (AREA).
- Ecological Meaning: Size of individual land cover patches (ha) averaged over all patches of a given class.

In general, patch size is considered the foremost predictor of species diversity within a patch (Forman and Godron 1981). Herkert (1991) found grassland patch size to be positively correlated with breeding bird diversity and abundance, although Swanson et al. (1999) found no relationship between diversity and grassland area on Conservation Reserve Program lands. Herkert et al. (1993) recommended fields be at least 50 ha (125 ac) and preferably 100 ha (250 ac) for grassland and forest bird species most sensitive to habitat fragmentation. However, less sensitive species should still benefit from grasslands of three ≥ 20 ha (50 ac) (Herkert et al. 1993). Metrics for mean patch size are shown below the two figures.

Mean Shape Index (MSI)

- Formula $$MSI = \frac{\sum_{j=1}^{n}\left(\frac{0.25 p_{ij}}{\sqrt{a_{ij}}}\right)}{n_i}$$
- Units None.
- Range MSI ≥ 1, without limit.
- Description MSI = 1 when all patches of the corresponding patch type are square (raster); MSI increases without limit as the patch shapes become more irregular.
- Ecological Meaning Patch shape has been shown to influence interpatch processes such as small mammal migration (Buechner, 1989) and woody plant colonization (Hardt and Formank 1989) and may influence animal foraging strategies (Forman and Godron, 1986). However, the primary significance of shape in determining the nature of patches in a landscape seems to be related to the "edge effect" (McGarigal, 1995).

Mean Nearest Neighbor Distance (MNN)

- Formula $$MNN = \frac{\sum_{j=1}^{n'} h_{ij}}{n'_i}$$
- Units Meters.
- Range MNN > 0, without limit.
- Description MNN is defined as the distance from a patch to the nearest neighboring patch of the same type, based on edge-to-edge distance.
- Ecological Meaning This metrics quantify landscape configuration and can be used for a number of important ecological processes.

Percentage of Landscape (PLAND)

- Formula $$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$$
- Units Percent.
- Range 0 < PLAND ≤ 100
- Description PLAND approaches 0 when the corresponding patch type

(class) becomes increasingly rare in the landscape. PLAND = 100 when the entire landscape consists of single patch type; that is, when the entire image is comprised of a single patch.

- Ecological Meaning

Numerous species are influenced by the portion of various land cover types within their home range. Warner (1994) identified relative amount of grassland as a factor influencing diversity and density of nesting birds, as well as nesting success of pheasants. Similarly, Perkins et al. (1997) found the proportion of grass in a hen's home range was the only landscape variable to be significantly correlated with survival and that hens selected grass habitat and avoided corn and soybean fields. Numerous studies have indicated bobwhite abundance is positively correlated with amount of idle land and pasture land (Exum et al. 1982, Brady et al. 1993, Taylor et al. 1999), whereas increased acreage of soybeans has been shown to negatively affect bobwhite populations (Exum et al. 1982). The illustrations below show an increase from Figure A to Figure B in the proportion of rural grassland (light green) at the expense of row crop (orange), resulting from habitat manipulation.

2. Landscape Fragmentation Measurement

The calculations for the fragmentation of two sites with three development time period are elaborated.

- Fragmentation Index of pre-development period (North Houston area)

Considering a_s=a_{max}=57,600, a_{min}=4, and a_{obs}=45,187, α can be calculated as

$$\alpha = \frac{a_{obs} - a_{\min}}{a_{\max} - a_{\min}} \times 100 = \frac{45{,}187 - 4}{57{,}600 - 4} \times 100 = 78.45$$

To calculate β, p_{obs}=4,820.43 and p_{max}=4·a_{obs}=4×45,187=180,748 are calculated. For a_{obs} can be calculated that 212^2<45,187<213^2 with 212=j: hence a_{obs}>j(j+1)=45,156, which implies p_{min}= 4(j+1) = 4(212+1)=852. Using p_{obs}, p_{min}, and p_{max}, β is calculated as

$$\beta = \frac{p_{\max} - p_{obs}}{p_{\max} - p_{\min}} \times 100 = \frac{180{,}748 - 4{,}820.43}{180{,}748 - 852} \times 100 = 97.79$$

Using n_{max}=a_{obs}/a_{min} =45,187/4=11,296.75, n_{obs}=22.29 and n_{min}=1, ν is calculated by

$$\nu = \frac{n_{\max} - n_{obs}}{n_{\max} - n_{\min}} \times 100 = \frac{11{,}296.75 - 22.29}{11{,}296.75 - 1} \times 100 = 99.81$$

Map analysis showed that d_{obs}=7.41+15.48=22.90. The square shape of the study area causes the maximum distance to be given by the distance between two pixels placed in diagonally opposite corners, i.e. $119\sqrt{2}$; the minimum distance between two patches equals $2\sqrt{2}$, which is the center-to-center distance of two pixels that touch at one corner. Hence, $d_{\max} = 119\sqrt{2} + 119\sqrt{2} = 336.58$ and $d_{\min} = 2\sqrt{2} + 2\sqrt{2} = 5.41$. δ can be calculated as

$$\delta = \frac{d_{\max} - d_{obs}}{d_{\max} - d_{\min}} \times 100 = \frac{336.58 - 21.73}{336.58 - 5.66} \times 100 = 95.14$$

Using α=78.45, β=97.79, ν=99.81, and δ=95.14, |ϕ| is calculated as

$$|\phi| = \sqrt{78.45^2 + 97.79^2 + 99.81^2 + 95.14^2} = 186.37$$

- Fragmentation index of early development period (North Houston area)

Considering a_s=a_{max}=57,600, a_{min}=4, and a_{obs}=23,456, α can be calculated as

$$\alpha = \frac{a_{obs} - a_{min}}{a_{max} - a_{min}} \times 100 = \frac{23,456 - 4}{57,600 - 4} \times 100 = 40.72$$

To calculate β, p_{obs}=8,763.78 and p_{max}=4·a_{obs}=4×23,456=93,824 are calculated. For a_{obs} can be calculated that 153^2<23,456<154^2 with 153=j: hence a_{obs}<$j(j+1)$=23,562, which implies p_{min}= 2(2j+1) = 2(2×153+1)=614. Using p_{obs}, p_{min}, and p_{max}, β is calculated as

$$\beta = \frac{p_{max} - p_{obs}}{p_{max} - p_{min}} \times 100 = \frac{93,824 - 8,763.78}{93.824 - 614} \times 100 = 91.26$$

Using n_{max}=a_{obs}/a_{min} =23,456/4=5,864, n_{obs}=96.69 and n_{min}=1, ν is calculated by

$$\nu = \frac{n_{max} - n_{obs}}{n_{max} - n_{min}} \times 100 = \frac{5,864 - 96.69}{5,864 - 1} \times 100 = 98.37$$

Map analysis showed that d_{obs}=7.82+12.28=20.11. The square shape of the study area causes the maximum distance to be given by the distance between two pixels placed in diagonally opposite corners, i.e. $119\sqrt{2}$; the minimum distance between two patches equals $2\sqrt{2}$, which is the center-to-center distance of two pixels that touch at one corner. Hence, $d_{max} = 119\sqrt{2} + 119\sqrt{2} = 336.58$ and $d_{min} = 2\sqrt{2} + 2\sqrt{2} = 5.41$. δ can be calculated as

$$\delta = \frac{d_{max} - d_{obs}}{d_{max} - d_{min}} \times 100 = \frac{336.58 - 18.94}{336.58 - 5.66} \times 100 = 95.99$$

Using α=40.72, β=91.26, ν=98.37, and δ=95.56, |ϕ| is calculated as

$$|\phi| = \sqrt{40.72^2 + 91.26^2 + 98.37^2 + 95.99^2} = 169.93$$

- Fragmentation index of mature period (North Houston area)

Considering a_s=a_{max}=57,600, a_{min}=4, and a_{obs}=33,010, α can be calculated as

$$\alpha = \frac{a_{obs} - a_{\min}}{a_{\max} - a_{\min}} \times 100 = \frac{33{,}010 - 4}{57{,}600 - 4} \times 100 = 57.31$$

To calculate β, p_{obs}=13,627.81 and p_{max}=4·a_{obs}=4×33,010=132,040 are calculated. For a_{obs} can be calculated that 181^2<33,010<182^2 with 181=j: hence a_{obs}>$j(j+1)$=32,942, which implies p_{min}= 4(j+1) = 4(181+1)=728. Using p_{obs}, p_{min}, and p_{max}, β is calculated as

$$\beta = \frac{p_{\max} - p_{obs}}{p_{\max} - p_{\min}} \times 100 = \frac{132{,}040 - 13{,}627.81}{132{,}040 - 728} \times 100 = 90.18$$

Using n_{max}=a_{obs}/a_{min} =33,010/4=8,252.50, n_{obs}=650.38 and n_{min}=1, ν is calculated by

$$\nu = \frac{n_{\max} - n_{obs}}{n_{\max} - n_{\min}} \times 100 = \frac{8{,}252.50 - 650.38}{8{,}252.50 - 1} \times 100 = 92.13$$

Map analysis showed that d_{obs}=7.64+8.43=16.08. The square shape of the study area causes the maximum distance to be given by the distance between two pixels placed in diagonally opposite corners, i.e. $119\sqrt{2}$; the minimum distance between two patches equals $2\sqrt{2}$, which is the center-to-center distance of two pixels that touch at one corner. Hence, $d_{\max} = 119\sqrt{2} + 119\sqrt{2} = 336.58$ and $d_{\min} = 2\sqrt{2} + 2\sqrt{2} = 5.41$. δ can be calculated as

$$\delta = \frac{d_{\max} - d_{obs}}{d_{\max} - d_{\min}} \times 100 = \frac{336.58 - 14.91}{336.58 - 5.66} \times 100 = 97.20$$

Using α=57.31, β=90.18, ν=92.13, and δ=96.78, |ϕ| is calculated as

$$|\phi| = \sqrt{57.31^2 + 90.18^2 + 92.13^2 + 97.20^2} = 171.33$$

- Fragmentation index of pre - development period (The Woodlands)

Considering a_s=a_{max}=57,600, a_{min}=4, and a_{obs}=49,145, α can be calculated as

$$\alpha = \frac{a_{obs} - a_{\min}}{a_{\max} - a_{\min}} \times 100 = \frac{49{,}145 - 4}{57{,}600 - 4} \times 100 = 85.32$$

To calculate β, p_{obs}=4,759.60 and p_{max}=4·a_{obs}=4×49,145=196,580 are calculated. For a_{obs} can be calculated that 221^2<49,145<222^2 with 221=j: hence a_{obs}<j(j+1)=49,062, which implies p_{min}= 2(2j+1) = 2(2×221+1)=886. Using p_{obs}, p_{min}, and p_{max}, β is calculated as

$$\beta = \frac{p_{\max} - p_{obs}}{p_{\max} - p_{\min}} \times 100 = \frac{196{,}580 - 4{,}759.60}{196{,}580 - 886} \times 100 = 98.02$$

Using n_{max}=a_{obs}/a_{min} =49,145/4=12,286.25, n_{obs}=9.12 and n_{min}=1, ν is calculated by

$$\nu = \frac{n_{\max} - n_{obs}}{n_{\max} - n_{\min}} \times 100 = \frac{12{,}286.25 - 9.12}{12{,}286.25 - 1} \times 100 = 99.93$$

Map analysis showed that d_{obs}=7.41+12.28=19.70. The square shape of the study area causes the maximum distance to be given by the distance between two pixels placed in diagonally opposite corners, i.e. $119\sqrt{2}$; the minimum distance between two patches equals $2\sqrt{2}$, which is the center-to-center distance of two pixels that touch at one corner. Hence, $d_{\max} = 119\sqrt{2} + 119\sqrt{2} = 336.58$ and $d_{\min} = 2\sqrt{2} + 2\sqrt{2} = 5.41$. δ can be calculated as

$$\delta = \frac{d_{\max} - d_{obs}}{d_{\max} - d_{\min}} \times 100 = \frac{336.58 - 18.53}{336.58 - 5.66} \times 100 = 96.11$$

Using α=85.32, β=98.02, ν=99.93, and δ=95.69, |φ| is calculated as

$$|\phi| = \sqrt{85.32^2 + 98.02^2 + 99.93^2 + 96.11^2} = 190.03$$

- Fragmentation index of early - development period (The Woodlands)

Considering a_s=a_{max}=57,600, a_{min}=4, and a_{obs}=29,721, α can be calculated as

$$\alpha = \frac{a_{obs} - a_{\min}}{a_{\max} - a_{\min}} \times 100 = \frac{29{,}721 - 4}{57{,}600 - 4} \times 100 = 51.60$$

To calculate β, p_{obs}=5,213.66 and p_{max}=4·a_{obs}=4×29,721=118,884 are calculated. For a_{obs} can be calculated that $172^2<29{,}721<173^2$ with 172=j: hence $a_{obs}<j(j+1)$=29,756, which implies p_{min}= 2(2j+1) = 2(2×172+1)=690. Using p_{obs}, p_{min}, and p_{max}, β is calculated as

$$\beta = \frac{p_{\max} - p_{obs}}{p_{\max} - p_{\min}} \times 100 = \frac{118{,}884 - 5{,}213.66}{118{,}884 - 690} \times 100 = 96.17$$

Using n_{max}=a_{obs}/a_{min} =29,721/4=7,430.25, n_{obs}=35.54 and n_{min}=1, ν is calculated by

$$\nu = \frac{n_{\max} - n_{obs}}{n_{\max} - n_{\min}} \times 100 = \frac{7{,}430.25 - 35.54}{7{,}430.25 - 1} \times 100 = 99.54$$

Map analysis showed that d_{obs}=7.51+15.92=23.44. The square shape of the study area causes the maximum distance to be given by the distance between two pixels placed in diagonally opposite corners, i.e. $119\sqrt{2}$; the minimum distance between two patches equals $2\sqrt{2}$, which is the center-to-center distance of two pixels that touch at one corner. Hence, $d_{\max} = 119\sqrt{2} + 119\sqrt{2} = 336.58$ and $d_{\min} = 2\sqrt{2} + 2\sqrt{2} = 5.41$. δ can be calculated as

$$\delta = \frac{d_{\max} - d_{obs}}{d_{\max} - d_{\min}} \times 100 = \frac{336.58 - 22.27}{336.58 - 5.66} \times 100 = 94.98$$

Using α=85.32, β=98.02, ν=99.93, and δ=95.69, |ϕ| is calculated as

$$|\phi| = \sqrt{51.60^2 + 96.17^2 + 99.54^2 + 94.98^2} = 175.61$$

- Fragmentation index of mature period (The Woodlands)

Considering a_s=a_{max}=57,600, a_{min}=4, and a_{obs}=44,010, α can be calculated as

$$\alpha = \frac{a_{obs} - a_{\min}}{a_{\max} - a_{\min}} \times 100 = \frac{44{,}010 - 4}{57{,}600 - 4} \times 100 = 76.40$$

To calculate β, p_{obs}=9432.52 and p_{max}=4·a_{obs}=4×44,010=176,040 are calculated. For a_{obs} can be calculated that 209^2<44,010<210^2 with 209=j: hence a_{obs}>$j(j+1)$=43,890, which implies p_{min}= 4(j+1) = 4(209+1)=840. Using p_{obs}, p_{min}, and p_{max}, β is calculated as

$$\beta = \frac{p_{\max} - p_{obs}}{p_{\max} - p_{\min}} \times 100 = \frac{176{,}040 - 9{,}432.52}{176{,}040 - 840} \times 100 = 95.10$$

Using n_{max}=a_{obs}/a_{min} =44,010/4=11,002.50, n_{obs}=27.71 and n_{min}=1, ν is calculated by

$$\nu = \frac{n_{\max} - n_{obs}}{n_{\max} - n_{\min}} \times 100 = \frac{11{,}002.50 - 27.71}{11{,}002.50 - 1} \times 100 = 99.76$$

Map analysis showed that d_{obs}=7.41+15.92=23.34. The square shape of the study area causes the maximum distance to be given by the distance between two pixels placed in diagonally opposite corners, i.e. $119\sqrt{2}$; the minimum distance between two patches equals $2\sqrt{2}$, which is the center-to-center distance of two pixels that touch at one corner. Hence, $d_{\max} = 119\sqrt{2} + 119\sqrt{2} = 336.58$ and $d_{\min} = 2\sqrt{2} + 2\sqrt{2} = 5.41$. δ can be calculated as

$$\delta = \frac{d_{\max} - d_{obs}}{d_{\max} - d_{\min}} \times 100 = \frac{336.58 - 22.17}{336.58 - 5.66} \times 100 = 95.01$$

Using α=76.40, β=95.10, ν=99.76, and δ=94.59, |ϕ| is calculated as

$$|\phi| = \sqrt{76.40^2 + 95.10^2 + 99.76^2 + 95.01^2} = 184.01$$

3. Land Cover Change (Grassland and Developed/Barren class)

- *Grassland*

Fig. 1 shows the landscape metrics change over time of grassland class. All of metrics in this class show the opposite trend to those of forest class. Patch density (PD) of grassland in North Houston area increased a little at the early development period while decreased in The Woodlands during the same period. However, this metrics increased significantly in mature period, 2.6 times in North Houston and 6.05 times in The Woodlands. Mean patch size (MPS), mean shape index (MSI), and percentage of landscape (PLAND) metrics of grassland class increased in early development period and decreased after that period.

Edge density (ED) values of both areas increased continuously over time. This metrics increased 2.0 times and 1.2 times during early development period and mature period respectively in North Houston area while increased 1.4 times and 1.3 times in The Woodlands during the same periods. Mean nearest neighbor distance (MNN) metrics decreased over time.

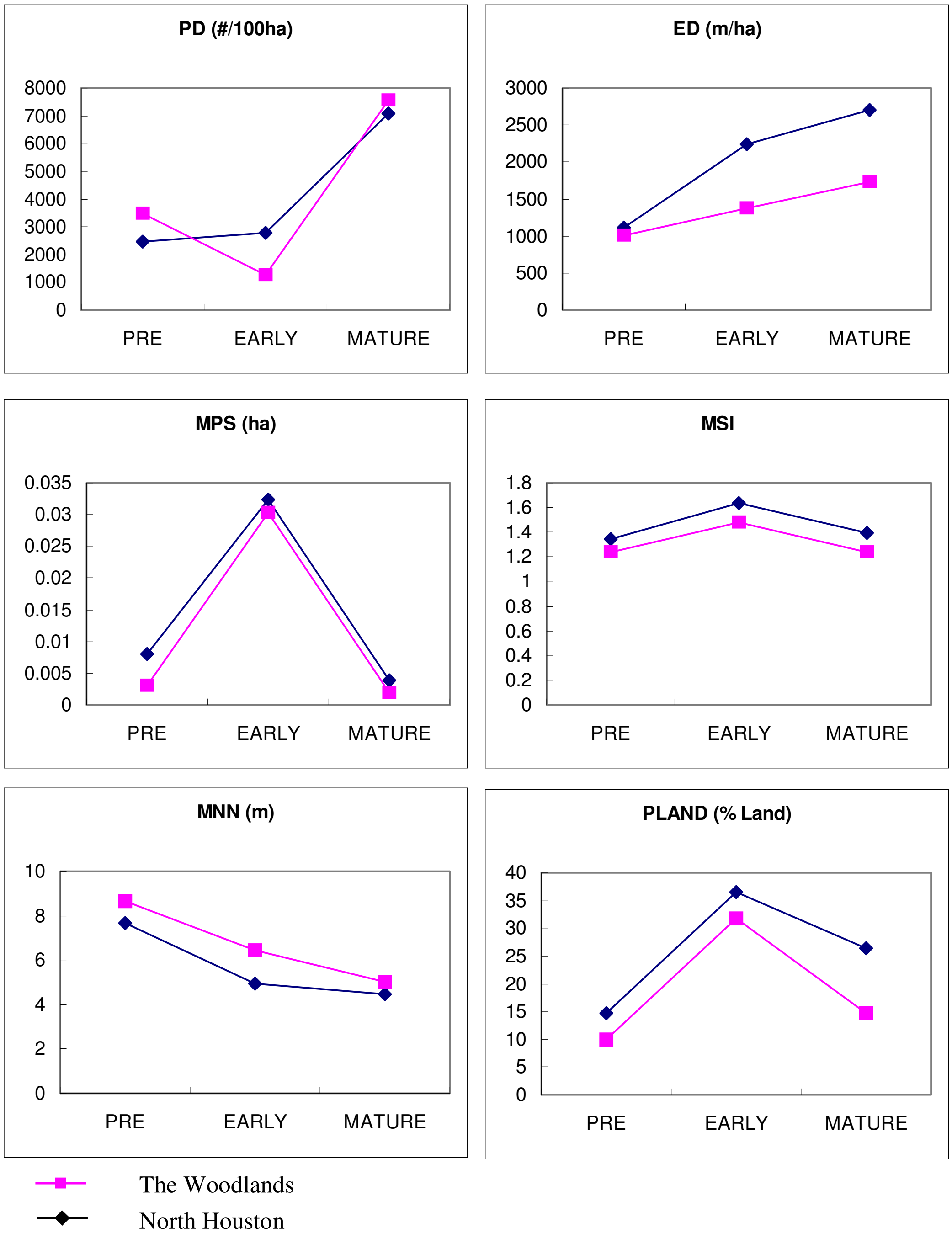

Fig. 1. Landscape metrics of grassland class through community development time periods

Table 1 presents statistical differences for grassland class among three development periods by ANOVA. The results of grassland class metrics of the three periods in two areas are all significantly different as those of forest class are.

Table 1
Grassland class metrics of the pre-development, early development, and mature period in two sites with p values for statistical differences among three periods by ANOVA

Metrics	Pre-development		Early development		Mature period		F	*p*
	Mean	SD	Mean	SD	Mean	SD		
North Houston								
PD	2479.75	1287.95	2750.49	1622.28	7072.59	1118.55	151.000	.000
ED	1111.82	709.71	2226.45	535.52	2702.86	356.89	91.536	.000
MPS	.008	.014	.033	.048	.0039	.0015	12.346	.000
MSI	1.34	.16	1.64	.21	1.39	.069	42.030	.000
MNN	7.65	2.96	4.93	.71	4.47	.13	40.139	.000
PLAND	14.70	12.81	36.59	9.68	26.36	4.58	54.194	.000
The Woodlands								
PD	3459.56	1883.79	1256.87	560.21	7607.42	1351.23	263.218	.000
ED	998.04	627.55	1369.97	263.37	1735.19	394.51	31.613	.000
MPS	.0029	.0026	.0304	.0147	.0019	.00074	167.054	.000
MSI	1.24	.100	1.48	.166	1.24	.046	71.740	.000
MNN	8.75	6.66	6.45	.830	5.01	.37	11.379	.000
PLAND	9.96	7.03	31.84	7.59	14.74	4.65	148.049	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

Below are the results of comparison of the paired development periods using t-test: pre-development to early development period, early development period to mature period, and mature period to pre-development period.

All landscape metrics except patch density (PD) in North Houston area indicate the significant difference in the analysis of the comparison between pre-development period and early development period (Table 2). This indicates that the number of grassland patches was not significantly affected in traditionally planned and developed community.

The landscape metrics of The Woodlands area for grassland class were significantly different in early development period. As in the case of forest class, grassland also seems to transform due to the land development.

Table 2
Statistical differences of the grassland class metrics between the pre-development and early development period.

Metrics	Pre-development		Early development		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	2479.75	1287.95	2750.49	1622.28	**.399**
ED	1111.82	709.71	2226.45	535.52	.000
MPS	.008	.014	.033	.048	.002
MSI	1.34	.16	1.64	.21	.000
MNN	7.65	2.96	4.93	.71	.000
PLAND	14.70	12.81	36.59	9.68	.000
The Woodlands					
PD	3459.56	1883.79	1256.87	560.21	.000
ED	998.04	627.55	1369.97	263.37	.000
MPS	.0029	.0026	.0304	.0147	.000
MSI	1.24	.100	1.48	.166	.000
MNN	8.75	6.66	6.45	.830	.022
PLAND	9.96	7.03	31.84	7.59	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

Table 3 shows the analyses of difference between early development period and mature period. It indicates all landscape metrics of grassland class are significantly different.

Table 3
Statistical differences of the grassland class metrics between the early development and mature period.

Metrics	Early development		Mature period		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	2750.49	1622.28	7072.59	1118.55	.000
ED	2226.45	535.52	2702.86	356.89	.000
MPS	.033	.048	.0039	.0015	.000
MSI	1.64	.21	1.39	.069	.000
MNN	4.93	.71	4.47	.13	.000
PLAND	36.59	9.68	26.36	4.58	.000
The Woodlands					
PD	1256.87	560.21	7607.42	1351.23	.000
ED	1369.97	263.37	1735.19	394.51	.000
MPS	.0304	.0147	.0019	.00074	.000
MSI	1.48	.166	1.24	.046	.000
MNN	6.45	.830	5.01	.37	.000
PLAND	31.84	7.59	14.74	4.65	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

In case of the analysis of difference between pre-development period and mature period, mean patch size (MPS) and mean shape index (MSI) are not significantly different in North Houston area while only mean shape index (MSI) is not significantly different in The Woodlands. So we can assume that shape complexity can be recovered over time (Table 4).

Table 4
Statistical differences of the grassland class metrics between the pre-development and mature period.

Metrics	Pre-development		Mature period		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	2479.75	1287.95	7072.59	1118.55	.000
ED	1111.82	709.71	2702.86	356.89	.000
MPS	.008	.014	.0039	.0015	**.071**
MSI	1.34	.16	1.39	.069	**.067**
MNN	7.65	2.96	4.47	.13	.000
PLAND	14.70	12.81	26.36	4.58	.000
The Woodlands					
PD	3459.56	1883.79	7607.42	1351.23	.000
ED	998.04	627.55	1735.19	394.51	.000
MPS	.0029	.0026	.0019	.00074	.011
MSI	1.24	.100	1.24	.046	**.991**
MNN	8.75	6.66	5.01	.37	.000
PLAND	9.96	7.03	14.74	4.65	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

- *Developed/Barren Area*

Fig. 2 shows the landscape metrics change over time of developed/barren class. All of metrics in this class show similar trends as those of grassland class. Patch density (PD) of developed class in North Houston area increased a little at the early development period while decreased in The Woodlands during the same period. However, this metrics increased significantly in mature period, 3.4 times in North Houston and 2.0 times in The Woodlands.

Mean patch size (MPS), mean shape index (MSI), and percentage of landscape (PLAND) metrics of developed/barren class increase in early development period and decrease after that period. Edge density (ED) values of both areas increased continuously over time. This metrics increased 1.3 times and 3.3 times during early development period and mature period respectively in North Houston area while increased 1.4 times and 2.4 times in The Woodlands during the same periods. Mean nearest neighbor distance (MNN) metrics decreased over time.

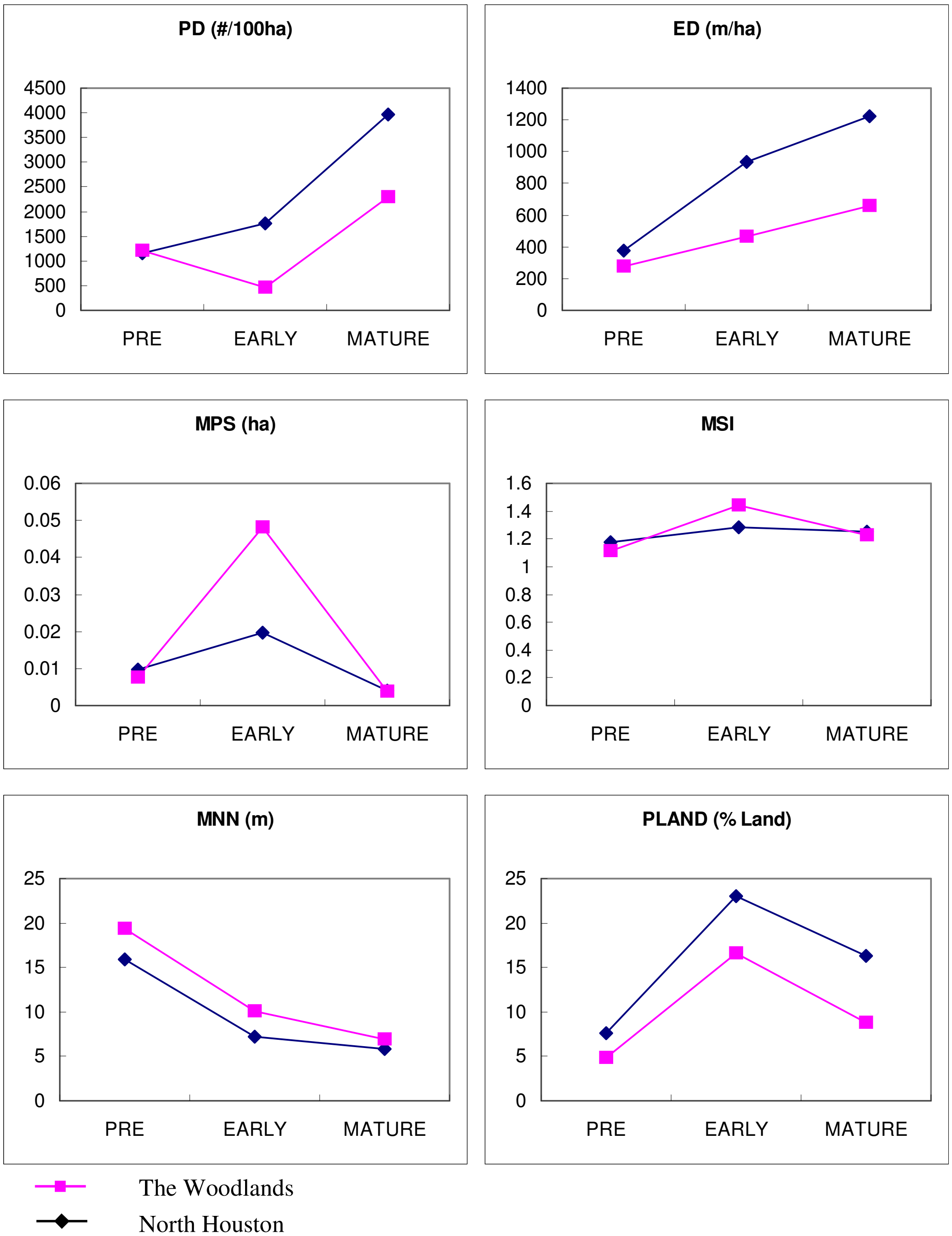

Fig. 2 Landscape metrics of developed/barren class through community development time periods

Table 5 presents statistical differences for developed/barren class among three development periods by ANOVA. The results of this class metrics of the three periods, pre-development, early development, and mature period in two areas are all significantly different as those of forest class and grassland class.

Table 5
Developed/Barren class metrics of the pre-development, early development, and mature period in two sites with p values for statistical differences among three periods by ANOVA

Metrics	Pre-development		Early development		Mature period		F	*p*
	Mean	SD	Mean	SD	Mean	SD		
North Houston								
PD	1158.17	945.98	1737.77	783.18	3955.03	780.95	127.064	.000
ED	375.58	376.28	925.18	321.45	1221.97	450.86	48.768	.000
MPS	.0098	.024	.019	.030	.0041	.0020	5.319	.000
MSI	1.177	.112	1.28	.059	1.25	.069	18.100	.000
MNN	15.92	18.43	7.24	1.62	5.83	.78	10.980	.000
PLAND	7.56	9.93	22.68	9.13	16.33	8.36	27.402	.000
The Woodlands								
PD	1188.48	989.07	470.56	246.21	2337.96	713.73	83.561	.000
ED	274.22	228.22	465.69	165.03	661.19	262.34	35.657	.000
MPS	.0078	.027	.048	.047	.0037	.0015	29.483	.000
MSI	1.11	.098	1.44	.184	1.22	.047	85.072	.000
MNN	19.76	34.47	10.10	5.19	6.89	1.05	5.330	.006
PLAND	4.92	8.73	16.55	7.78	8.85	4.59	31.636	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

Below are the results of comparison of the paired development periods using t-test: pre-development to early development period, early development period to mature period, and mature period to pre-development period.

Table 6 shows the analysis of difference between pre-development period and early development period. Mean patch size (MPS) of North Houston and mean nearest neighbor distance (MNN) metrics of The Woodlands indicate there are no significant differences between two development periods.

Table 6
Statistical differences of the developed/barren class metrics between the pre-development and early development period.

Metrics	Pre-development		Early development		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	1158.17	945.98	1737.77	783.18	.004
ED	375.58	376.28	925.18	321.45	.000
MPS	.0098	.024	.019	.030	**.107**
MSI	1.177	.112	1.28	.059	.000
MNN	15.92	18.43	7.24	1.62	.006
PLAND	7.56	9.93	22.68	9.13	.000
The Woodlands					
PD	1188.48	989.07	470.56	246.21	.000
ED	274.22	228.22	465.69	165.03	.000
MPS	.0078	.027	.048	.047	.000
MSI	1.11	.098	1.44	.184	.000
MNN	19.76	34.47	10.10	5.19	**.073**
PLAND	4.92	8.73	16.55	7.78	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

However, the analyses of difference between early development period and mature period present all landscape metrics of grassland class are significantly different (Table 7).

Table 7
Statistical differences of the developed/barren class metrics between the early development and mature period.

Metrics	Early development		Mature period		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	1737.77	783.18	3955.03	780.95	.000
ED	925.18	321.45	1221.97	450.86	.001
MPS	.019	.030	.0041	.0020	.002
MSI	1.28	.059	1.25	.069	.028
MNN	7.24	1.62	5.83	.78	.000
PLAND	22.68	9.13	16.33	8.36	.001
The Woodlands					
PD	470.56	246.21	2337.96	713.73	.000
ED	465.69	165.03	661.19	262.34	.000
MPS	.048	.047	.0037	.0015	.000
MSI	1.44	.184	1.22	.047	.000
MNN	10.10	5.19	6.89	1.05	.000
PLAND	16.55	7.78	8.85	4.59	.000

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

In case of the analysis of difference between pre-development period and mature period, mean patch size (MPS) of the both areas indicates that there is no significant difference (Table 8).

Table 8
Statistical differences of the developed/barren class metrics between the pre-development and mature period.

Metrics	Pre-development		Mature period		*p*
	Mean	SD	Mean	SD	
North Houston					
PD	1158.17	945.98	3955.03	780.95	.000
ED	375.58	376.28	1221.97	450.86	.000
MPS	.0098	.024	.0041	.0020	**.165**
MSI	1.177	.112	1.25	.069	.001
MNN	15.92	18.43	5.83	.78	.002
PLAND	7.56	9.93	16.33	8.36	.000
The Woodlands					
PD	1188.48	989.07	2337.96	713.73	.000
ED	274.22	228.22	661.19	262.34	.000
MPS	.0078	.027	.0037	.0015	**.314**
MSI	1.11	.098	1.22	.047	.000
MNN	19.76	34.47	6.89	1.05	.017
PLAND	4.92	8.73	8.85	4.59	.007

PD: Patch Density, ED: Edge Density, MPS: Mean Patch Size, MSI: Mean Shape Index, MNN: Mean Nearest Neighbor, PLAND: Percentage of Landscape

VITA

Jinki Kim

ADDRESS

Wonhyoro 2Ga 14, Yongsan-Gu, Seoul, Korea

EDUCATION

Michigan State University, East Lansing, MI.
Master of Art in Interdisciplinary Studies in Social Science: global Applications, 1998.

Seoul National University, Seoul, Korea
Master of Landscape Architecture in Graduate School of Environmental Studies, 1985.

Seoul National University, Seoul, Korea
Bachelor of Science in Landscape Architecture, 1983.

ACADEMIC AND PROFESSIONAL WORK EXPERIENCE

Sep. 2000 – May. 2005	:	Teaching Assistant, Department of Landscape Architecture and Urban Planning, College of Architecture, Texas A&M University, College Station, TX.
Jan. 1987 – Aug. 2000	:	Landscape Architect, Korea Land Corporation, Sungnam, Korea