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Analysis of urban-rural gradients using satellite data

Joshua D. Greenberg

A dissertation submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2000

Program Authorized to Offer Degree: College of Forest Resources

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ABSTRACT

Analysis of urban-rural gradients using satellite data

By Joshua D. Greenberg

Chairperson of the Supervisory Committee:
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Growing urban populations has sparked concerns over the urbanization impacts to ecosystems. Gradient analysis has been presented as a method of assessing human impacts on the environment, but few studies have used satellite data to provide information for these analyses. In this dissertation techniques to interpret satellite data were used to investigate urban-rural gradients. The combination of a spectral mixing model and V-I-S (vegetation, impervious, soils) model provided information about the land cover in and around several cities. Based on accuracy assessments using ground data, the model output was determined to be an acceptable predictor of land cover values. An analysis of the Seattle Washington urban-rural region revealed a land cover gradient does indeed exist along a distance gradient from the city center. Traditional land use classes, human population and distance to city center were poor predictors of land cover for a specific location, but acceptable for determining large scale trends. Techniques using V-I-S data to provide landscape level analysis were compared with traditional thematic data. In Seattle Washington no relationship was observed between forest patch size or patch shape along the urban rural gradient. Traditional landscape ecology analysis for urban-rural areas is problematic. A data smoothing technique is presented that allows a landscape context to be determined from spatially continuous raster data. Using this approach, small urban forest patches can be distinguished from small rural forest patches. Lastly, the land cover along the urban-rural gradient of eight cities was compared. Within these eight cities the urban land cover was relatively similar even though the rural land cover was dissimilar. Rural vegetation cover was correlated with precipitation and changes in percent vegetation along the gradient were greater for wet environments than dry. The population of a city is correlated with both the extent of the built environment and the rate of change in impervious cover along the gradient. The techniques presented in this dissertation can be used to compare the land cover along the urban rural gradient of different cities, changes over time, and provide information useful in understanding changes in ecosystem processes from urbanization.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION

This dissertation is organized in four chapters investigating the concept of using remotely sensed data to analyze regions in and around cities. Urban areas in the United States only covered 5.7 percent of the non-federal land area in 1997, but since 1992, the national rate of development more than doubled to 3 million acres per year (NRI 1999). Most of this development is not occurring in the city centers, but in the sprawling surrounding metropolitan regions (WRI 1996).

The transformations from undeveloped to developed lands impact natural ecosystem processes. A call by McDonnell and Pickett (1990) to investigate human influences on the environment has prompted a number of urban-rural studies. Instead of measuring ecosystem changes over time, researchers are using gradient analysis techniques to investigate changes over space. Using rural areas to represent pre-settlement conditions, researchers assume that the ecosystem changes that occur with increasing proximity to a city center are due to urbanization.

Figure 0-1 depicts a summary of results from urban-rural studies in New York City. Aspects of urbanization (column A) are described as changes in structural features and biota. The aspects of urbanization directly effect the physical and chemical environment as well as population and community attributes. These in turn are linked to ecosystem effects (column C).

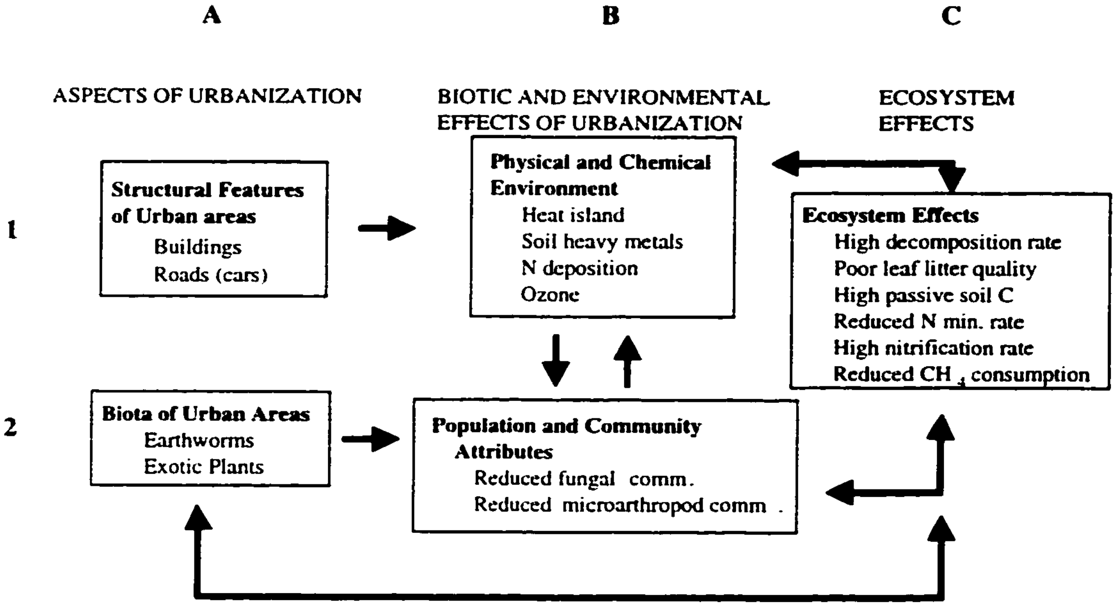


Figure 0-1. Diagram of relations between aspects of urbanization and ecosystem effects with examples from the New York gradient study (from McDonnell et al. 1997)

Although there have been many advances in the fields of urban ecology and remote sensing, few have combined these two discipline. In this dissertation I provide methods to assess satellite data to detect aspects of urbanization (column A in Figure 0-1), using biophysical land cover. I propose that land cover is a better indicator of urbanization and ecosystem change than many of the currently used measures.

In the first Chapter of this dissertation I outline the importance of urban-rural analysis and the implications of patterns that exist along the urban-rural gradient. Two case studies are presented that illustrate the difficulties of using satellite data to assess the interface between urban and rural regions. In Chapter 2 I introduce a technique of combining a spectral mixing model and the V-I-S model (vegetation, impervious, and soil) to quantify changes along the Seattle, Washington urban-rural gradient. In Chapter 2 the accuracy of the technique is tested and the results are compared to traditional urban-rural gradient analysis. Comparisons include thematic land use classifications, distance from city center, and population.

In Chapter 3 I utilize methods developed in Chapter 2 to illustrate how the spectral mixing model and V-I-S data can be used to perform landscape analysis. The techniques are compared with traditional landscape analysis methods, and a method of data smoothing is demonstrated to provide a means of determining the spatial context of a point in relationship to the urban-rural gradient.

One of the advantages of the V-I-S model is that it can be used to compare multiple locations. In Chapter 4 I use the techniques described in the earlier Chapters to make a comparison of 8 U.S. cities. These results are examples of the analysis that can be performed to compare different sites. Patterns in land cover are correlated with both city population and climatic variables.

Spectral mixing and V-I-S information are important tools to incorporate in any analysis of urban-rural gradients. The unique combination of techniques combined in this dissertation provide a tool to assess urban-rural gradients at a single city or to compare multiple cities. The questions that can be generated when provided with V-I-S data are of interest to planners, ecologists, and modelers. The steps involved in creating the V-I-S data are relatively inexpensive and provide a wealth of information. These data are useful for both current city assessments or to aid in the design of future studies.

CHAPTER 1: ANALYZING THE URBAN - WILDLAND INTERFACE WITH GIS: TWO CASE STUDIES.

Abstract

In this Chapter I discuss the characteristics of the urban-rural interface and two methods of quantifying the landscape gradient from the urban center to the surrounding rural areas. It is demonstrated through the use of geographic information system (GIS) technology how measures of urbanization can be compared with landscape patterns from a satellite image. The results of these methods provide information on vegetation cover, heterogeneity, edges, and unique regions in the gradient that can be incorporated into land management and land use policies.

Introduction

The concern over forest health is well established in forest management, and currently manifests itself in debates over the most appropriate methods of managing forests in the Pacific Northwest. How vegetation management objectives affect forest structure and function is of primary importance (Thomas 1994). Where human settlement occurs in forested environments, forest managers concern focuses on the character and condition of the residual forest stand (Bradley 1984). At the landscape scale the arrangement of forests and other vegetation can be used to infer ecological processes (Turner 1989). In this Chapter I provide a brief discussion of human settlement in rural environments. I then present methods that have been used to identify patterns in forest structure and their implications along urban-rural gradients. The application of geographic information system (GIS) and remote sensing technology is central to this discussion.

Human Settlement

Every human settlement, however large or small, was initially carved from a wildland environment. Grasslands, forest-lands, and wetlands were "domesticated" to produce a combination of commodities and amenities. The extent to which domesticated vegetation approximated initial settlement conditions varied according to the intensity and scale of resource production activities (Morrill 1984). However, in the United States, managed forest-lands and farmlands, regardless of intensity, continued to provide "green" landscapes.

Over time, the population shifted from its initial dispersion over the agrarian landscape to being centralized in the industrialized cities (Kivell 1993). Now the trend has reversed, and populations are spilling over the urban fringe into suburban and rural landscapes. In fact, for the first time in the twentieth century, most people in the United States now reside outside urban centers (Grubler 1994). The driving forces of migration and the resulting settlement patterns are largely due to a combination of regulation and the economics of land use. These factors include the cost of land, available transportation and infrastructure (such as sewer, water, and power), and other services, including schools, police, and fire protection. People tend to settle in affordable areas that offer the maximum combination of services and amenities. Sometimes they find this combination in the city, but for the most part, as reflected in current settlement patterns, areas bordering existing cities are preferred.

Landscape Change

When human settlement moves away from cities, it generally locates on lands that have long been used for forestry and farming. In fact, although a "resettlement" is occurring, people perceive that we are encroaching on these "wildlands" for the first time. The result is a landscape in transition, an area of change where forest or pasture is replaced by urban structures, leaving only a fraction of the original forest or farm. This period of transition is significant for two reasons. First, because of uncertainty about the future condition of the landscape, people have many concerns, including fears about the effects of conflicting land uses, potential loss of amenities, and inefficiency in how services are provided. Second, concerns are expressed as to our ability to define and maintain desired remnants of forest and pasture land through an assortment of land-use programs such as economic incentives, acquisition or regulation. These landscapes are clearly turbulent environments, and until "resettled", remain the center of land-use controversies, debates, and legal challenges.

Important Issues

Three primary issues at the center of land use debates are property rights, the optimal use of land, and the future condition of the natural environment. In the case of forests, the structure and function of the residual forest stand is of concern. While both property rights and economic efficiency are very important, and not unrelated to the disposition of the residual forest stand, the focus in this Chapter is the extent to which the residual stand may serve future land uses in a safe and effective manner. This of course requires a forest that is healthy. For the purpose of this discussion, the notion of forest health is the idea that the residual stand, or vegetation structure can produce a flow of benefits from throughout its system for those who reside close to the forest and society in general, over an established length of time (Flores 1996).

Forest Health

With regard to forest health, productivity, safety, and viability are the benefits that are of interest. The production of both commodities and amenities is often desired from residual forest stands. Commodities may include harvesting for commercial timber, or for firewood, even though possibly not at the level of intensity under prior management conditions. Other commodities may include special forest resources such as ferns, salal, berries, and mushrooms. The production of amenities such as scenery, wildlife, and special landscape features significantly contribute to the value of a region's settlements.

Managing a residual forest stand for safety includes facing problems of fire hazards and unstable stands containing trees susceptible to blowdown. Both problems are legendary for causing damage to both individual houses and large subdivisions. Finally, viability of the residual forest is linked to the structure and extensiveness of the forest and its ability to provide habitat for a variety of plant and animal species. Central to viability are questions of patch size, shape, and composition, as well as other aspects of patch dynamics (Greenberg 1996). Consequently the urban-rural interface, that area where human settlement encroaches on forest, farm, and grasslands, presents many challenges and opportunities for foresters, planners, and policy makers.

An Approach

One of the more important challenges is the process of detecting change in the landscape, identifying the nature of the change, and determining its significance. This requires both a method of vegetation analysis and the technology to employ that method. In this article I present two approaches to analyzing the urban-rural interface. The first is a transect method that uses distance from an urban center as the dependent variable. The second approach is to select some variables that represent the degree of urbanization of a location, and to use these as the dependent variables. Both approaches are variations of the gradient analysis technique, a method that helps reveal patterns that are found in the landscape as one moves along an urban-rural gradient. For example, is there a slow transition in vegetation cover or is there a distinct edge region? If there is a distinct region of landscape change, is the location of the change define the urban-rural interface?

Gradients

Gradient theory holds that along a single environmental gradient in a landscape, plant communities will change together, creating an “ecosystemic gradient” or “ecocline” (Whittaker 1967). Ecologists have found the gradient method of analysis is a useful tool in understanding vegetation changes along a continuum of environmental variables. Gradient studies in the Northwest have shown the relation of vegetation patterns to changes in moisture and temperature (Beals 1969; Agee and Kertis 1987; del Moral 1978). Although traditional discussions on gradients have focused on so called natural patterns, these same transitions are found in urban landscapes as well as between urban and rural regions (Bradley 1984). Previous researchers have proposed the application of gradient analysis to urban studies as a method of revealing the human impacts on landscapes (McDonnell and Pickett 1990). Recently, gradient analysis has been used to study urban-rural patterns in soil chemistry (Pouyat et al. 1995), forest structure (Medley et al. 1995), bird populations (Blair 1996), and microclimate (McPherson et al. 1994). In these studies the experimental design was based on correlations associated with human development, and used a distance measure from the city center as the variable to approximate the degree of human impact.

Methods

I have been working on methods of applying these techniques to large regions around urban centers by incorporating satellite data to help measure the effects of human development. Remote sensing imagery has the advantage of covering large spatial scales, with relatively frequent temporal intervals, and at a cost far cheaper than on-the-ground field collection. Another advantage to using satellite data is that standard methods can be adopted to apply studies to multiple urban-rural sites to compare patterns and trends at even larger scales.

Study 1: Seattle, Washington.

The first study was done in Washington State, extending from the urban downtown area of Seattle to the Cascade Mountains to the east. In place of using distance from urban center as a measure of human impact, the gradient variables selected were population density and road density. Data for both of these variables were readily available from the U.S. Census Tiger files. Landsat Thematic Mapper data were used to calculate amount of vegetation using a Normalized Difference Vegetation Index (NDVI), one of the most widely used methods for vegetation detection (Quattrochi and Pelletier 1990). NDVI is a ratio of infra-red and red reflectance (Tucker 1979) that can measure vegetation cover due to properties of chlorophyll that absorb red light and reflect infra-red light (Lillesand and Kiefer 1994).

To compare changes in the selected variables, I selected six sites with different land use characteristics. Although many gradient studies use a transect method to collect data along an environmental gradient, analysis of the gradient does not require that the data be spatially continuous (Austin 1985), so the sites I selected were chosen to provide a range of values for the dependent variables. Bordered by Puget Sound and Lake Washington, Seattle has grown in a water-constricted manner, producing a non-radiant pattern of development, as predicted in early models of urbanization. The study sites include a downtown business region, an international district shopping region, an in-city residential region, a newer business and residential area, a planned subdivision, and a state-managed forest (Figure 1-1).

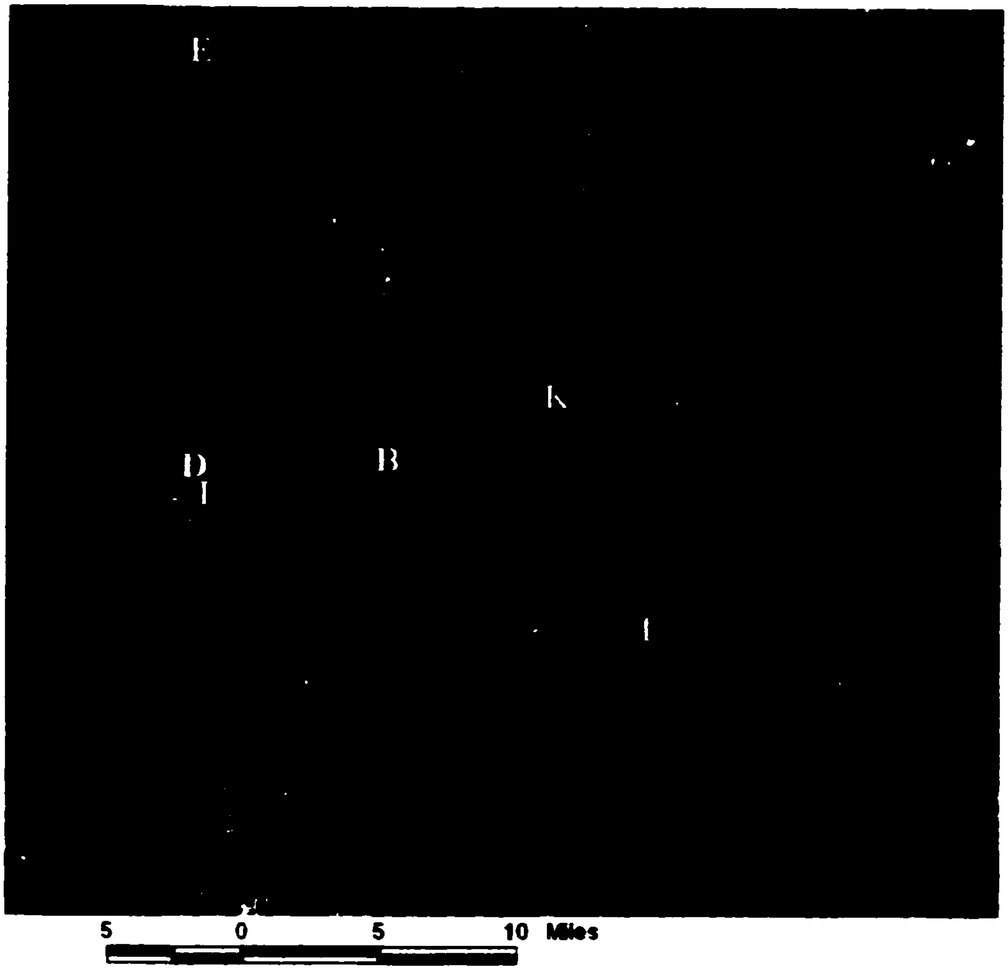


Figure 1-1. 1991 Landsat thematic mapper image of Seattle displaying bands 4,3, and 2. Vegetation appears as red. Study sites are show in boxes; D= downtown, I= International district, E= in-city residential, B= new business and residential, K= planned subdivision, T= state managed forest. In each of these regions, random points were selected and values for both the human development level (population density, road density) and the response variable (NDVI) were recorded.

The measures of human development covaried at all but one of the selected sites (Figure 1-2). The international district was the exception, apparently due to the low number of residents in the area, even though it is a built environment and has a high density of roads. The vegetation measure (NDVI) showed increasing amounts of vegetation cover as population density and road density decreased.

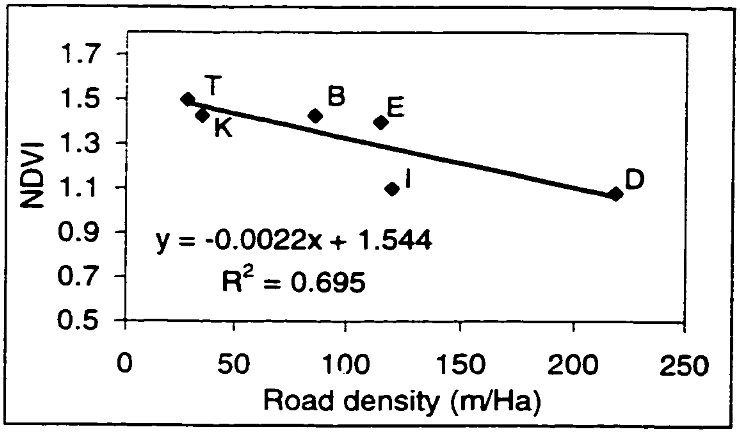


Figure 1-2. Comparison of road density and NDVI vegetation index at the six study sites.

As expected, vegetation cover increased with a decrease in human disturbance. This relationship is not necessarily causal, since vegetation cover also increased with increased elevation, which is not a measure of human disturbance. These multiple relationships illustrate the complex relationship that exists between human development, landscape patterns, and the physical environment. There is no single factor that explains the relationships of the measured variables, but in terms of the urban-rural interface, this method can determine where a particular neighborhood or region is located in the gradient.

Study 2: Eugene, Oregon.

The second study focused on Eugene, Oregon. In this case I chose the traditional transect method for gradient analysis, and therefore relied on a distance measure for human impacts, rather than using population density and road density variables. I employed a method of satellite data interpretation called the spectral mixing model (Adams et al. 1989; Sabol Jr. 1992), which uses a simultaneous equation approach to determine the composition of elements that create the spectral reflectance pattern of each pixel. What is appealing about this method is that it does not require the data to be classified into land cover types or use indices with confusing metrics. Instead, the results indicate the proportion of compositional elements found in each pixel. In theory these values are comparable across regions, biomes, and even continents.

The compositional elements I chose were vegetation, soils, and shade. Along the urban-rural gradient I predicted that values would increase for vegetation cover and decrease for soil cover. This pattern could occur due to human disturbances and modifications of the landscape, which remove vegetation and create built surfaces such as roads and buildings. An additional analysis was made to view the arrangement of the pixels around the observed point on the transect. For example, a heterogeneous landscape will have surrounding pixels with high variance, while a homogeneous landscape will have little variation in the surrounding pixels. A moving window analysis was conducted that calculated the standard deviation of the pixels in a 15 by 15 meter pixel region around the central pixel. I also calculated the slope or degree of change in pixel values in a 3 by 3 meter moving window. Areas where there is a large difference between neighboring cells will have high slope values. This type of analysis is a simplified method to detect edges in a landscape (Fortin 1994;Haining 1990). Both of these methods assess some of the spatial patterns that change along the gradient and imply changes in the structure and function of the forest systems.

Similar to the study in the Seattle area, in the Eugene study I used a Landsat Thematic Mapper image with a 30 meter cell size that was spectrally "unmixed" using software generated by the remote sensing laboratory at the University of Washington, Geology Department (Adams et al. 1995). Values were recorded along a linear path spanning the agricultural area north of Eugene to the city center, and then rotating to the east toward the Cascades, covering agricultural, urban, and rural regions (Figure 1-3). These values were then charted as distances along a single transect (Figure 1-4), although the transect could be considered two transects since it changes trajectories at the city center. To simplify analysis and presentation the transect was considered to be continuous.

Vegetation increased and soils decreased at the edge between the agricultural zone and the urban zone of Eugene. The transition from urban to rural is less noticeable in vegetation measurements, but there is a decrease in impervious cover and a slight decrease in average soil levels. The slope or “edge” measure has lower values in the agricultural zone and higher values in the urban and rural zone (Figure 1-5). This indicates fewer spectral edges in the agricultural areas than in either the urban or rural zones.

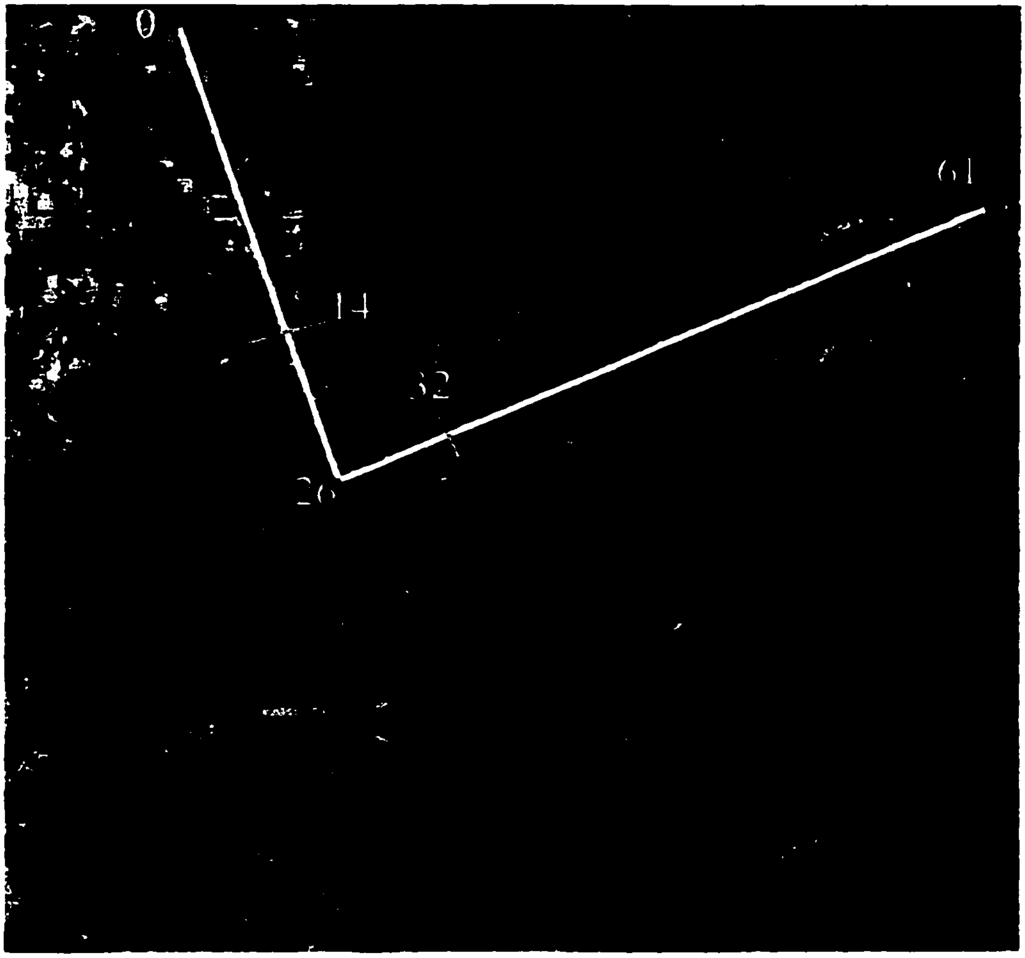


Figure 1-3. Landsat color composite of bands 5,4,3 for the Eugene Oregon area. Transect used to sample cover data derived from the satellite is shown in white, starting at "0", extending south to Eugene at 26 km, and then heading out to the east to a total of 61 transect kilometers. Break points for general changes in land cover are shown as orange hash marks at 14 km, and 32 km

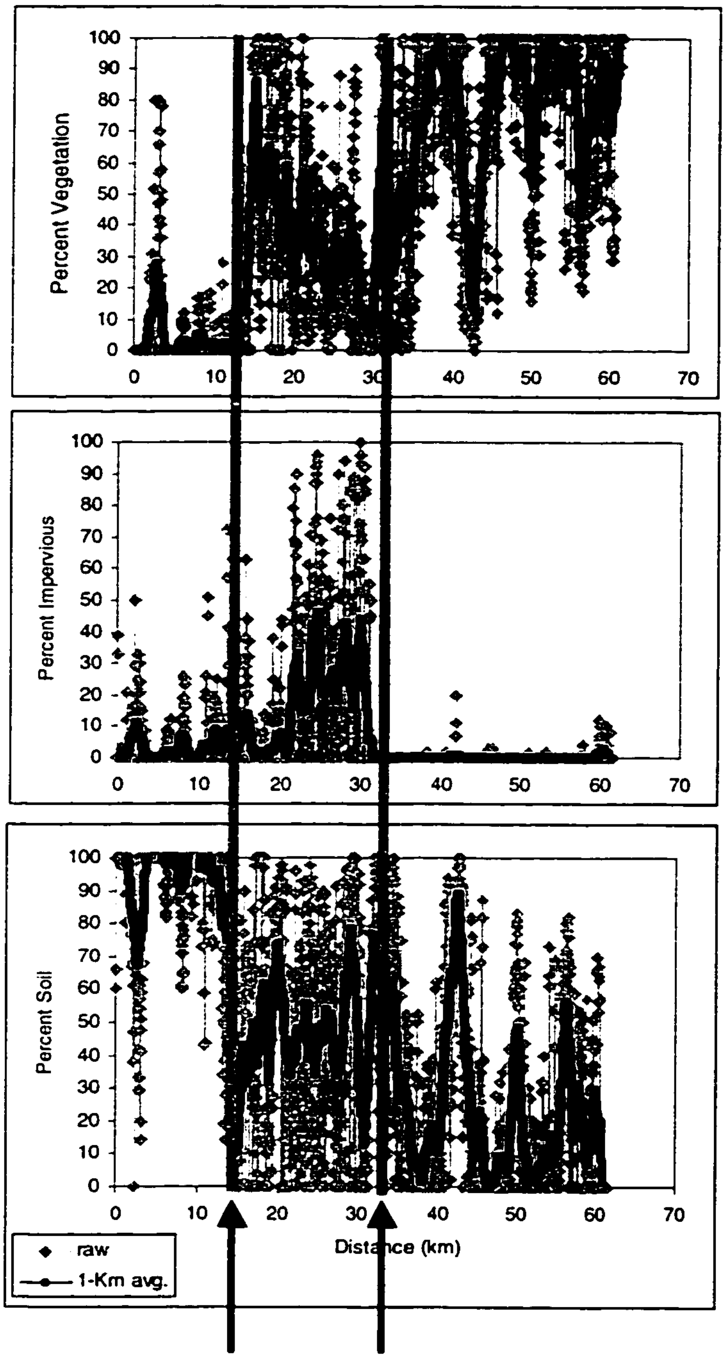


Figure 1-4. Values along an urban-to-rural transect in Eugene, Oregon. Grey lines are raw cover values, black lines are 1-kilometer averages along the transect for cover types (a) vegetation, (b)impervious, and (c) soil. Black arrows point to the 14 km and 32 km distances where land use changes.

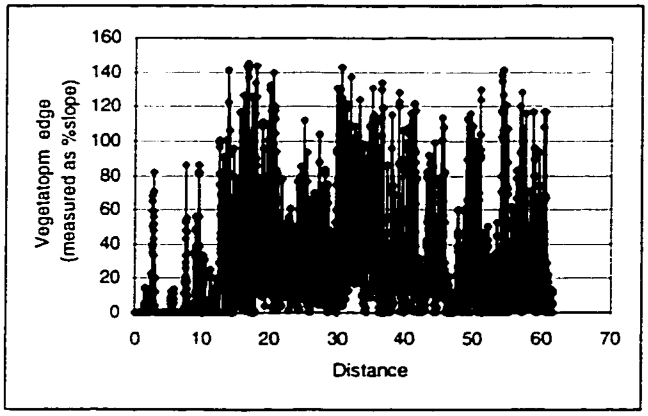


Figure 1-5. Vegetation edges along the transect. Edge is measured as the average slope of a 3x3 pixel moving window.

The standard deviation is lower in the agricultural zone, increases in the urban zone, and then decreases slightly in the rural zone (Figure 1-6). Although this type of spatial analysis is sensitive to changes in scale (Turner et al. 1989a), at this particular spatial scale there is a homogeneous agricultural zone, a heterogeneous urban zone, and a rural zone that lies somewhere in between. The transition between these zones is distinct using this method and could be described as a discrete interface between land-use regions.

This analysis was done on only one transect and at one spatial and temporal scale. More intense analysis can be made by changing the location of the transect, the size of the cells, and time periods during which the satellite image is taken. I offer these results only as an example of methods and the output that can be expected.

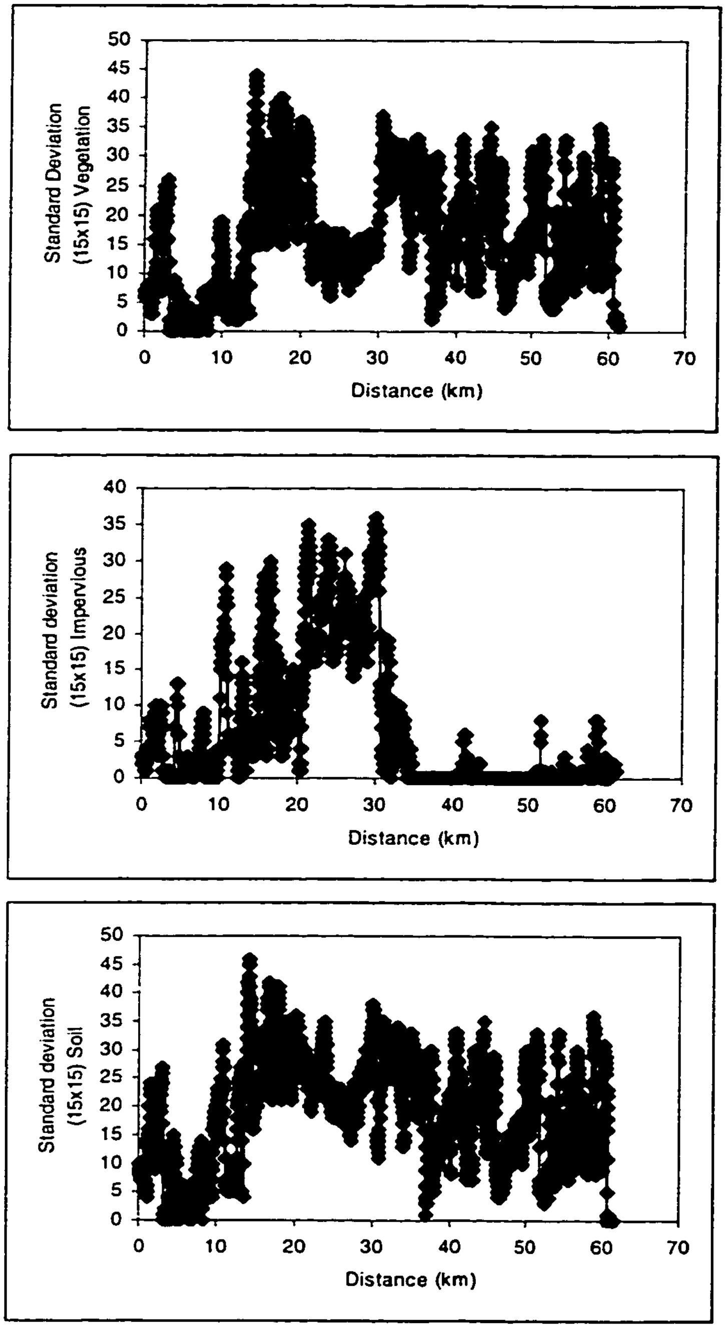


Figure 1-6. Land cover heterogeneity along the transect. Heterogeneity is measured as the standard deviation of the cover in a 15 by 15 pixel moving window. Land covers are (a) vegetation, (b) impervious, and (c) soil.

Discussion

I have identified two methods useful in assessing the urban-rural interface. These methods provide information about the patterns of vegetation on the landscape at a regional scale encompassing both an urban region and the surrounding rural areas. In addition, the output of these methods furnishes information on vegetation cover, heterogeneity, and edges. In other studies vegetation cover measurements have been correlated to a leaf area index (LAI) (Spanner et al. 1994; Wulder 1998), and to levels of productivity (Bonan 1993; Nowak 1996), although the exact relationship may vary from site to site.

The results of these studies are useful for examining trends that occur in landscape as one moves from a built environment to rural area. The trends can be both spatial, as shown with measures of edge and heterogeneity, and temporal, such as fragmentation and change. I used images from only one time period, and therefore was limited in the number of temporal patterns I could detect.

The spatial patterns I observed were at three different scales. The first is the pixel size of the satellite image. I measured the trends of the individual pixels in relation to a gradient variable: either distance from the urban core or population density. At any one location the average amount of vegetation for a 30 meter location was known.

The second spatial scale I assessed was the surrounding cells, in either a 3 by 3 or 15 by 15 meter grid. This analysis provides information on variation in vegetation cover in a small region around a central cell. I can extrapolate from this information to determine the level of heterogeneity and amount of vegetation edge for an area.

The third spatial scale I observed was the entire region. At this scale I looked for general trends and any sharp changes in the overall patterns. In the Seattle study the International district was detected as an outlier from the other regions sampled. In the Eugene analysis, I found a sharp distinction between the agricultural, urban, and forested regions. This distinction was detected by the trend of the fine scale cover analysis between the regions. In a simplified view one of two patterns might be expected: a gradual change or a stair step pattern. Both of the expected patterns were present depending on the methods that were used.

The results of the NDVI and mixing model analyses are interesting in themselves, but the practical applications are likely to be of interest to land-use planners and policy makers. The models help determine vegetation characteristics including edge, vegetation cover, diversity, and leaf area production. These in turn, and especially if examined over multiple time periods, provide information about the relation between human settlement and vegetation presence or absence and reveal trends in vegetation cover in the urban-rural interface. Trends of interest may include the proximity of vegetation to development, the size and location of remnant vegetation patches, the connectivity of the patches, and the relationship between vegetation masses and sensitive areas such as riparian zones, steep slopes, and wetlands.

This descriptive information is useful when considering the many issues associated with human settlement in the urban-rural interface. The location, extent, and fragmented nature of vegetation have important implications for controlling wildfire and its spread to structures. The relation between vegetation and development is important in addressing surface water management issues as well as the maintenance of viable habitat for a host of plant and animal species. Also, the relation between vegetation masses and development patterns is very important to the maintenance of open space, urban separators, and the scenic character of rural landscapes.

For the land-use planner and policy maker, this type of comprehensive information can help develop programs that link policy more closely to desired results on the landscape. Programs of interest include land-use ordinances concerning the location and extent of development in relation to vegetation, and regulations regarding buffers along sensitive landscapes. The NDVI and mixing model output may also provide useful information for land acquisition programs directed toward public open space, and scenic or conservation easements. Finally, in areas where settlement has negatively effected vegetation, information from the analysis may guide possible mitigation and restoration efforts.

GIS technology and the application of information generated by its use are becoming essential in forest management, land-use planning, and policy making, especially in the urban-rural interface where landscapes are undergoing rapid change. This change requires an understanding of how best to maintain the health and viability of the forest while providing for the safety and amenity demands of new residents. The methods described in this Chapter provide information that is essential in planning, managing, and comprehending the urban-rural gradient.

CHAPTER 2: THE USE OF SATELLITE IMAGERY TO MEASURE BIOPHYSICAL LAND COVER ALONG AN URBAN-RURAL GRADIENT.

Abstract

Ecologists have recently been urged to investigate the impacts of urbanization on the environment. Some researchers have used gradient analysis techniques to meet this challenge. Humans impact the environment through a complex combination of alterations in land cover, emissions, and resource use. In most cases, gradient analysis studies have used distance to city center as an indicator of the level of human impact. This approach assumes both a concentric ring pattern of development around cities, and homogenous patterns of development at a given distance. Other studies have used population density and land use to serve as a proxy measure for degree of human impact. I propose that land surface cover is a better measure to assess the degree of human impact since it can be more closely associated to ecological processes. In this study a method of satellite data interpretation is used to measure land cover values following a V-I-S (vegetation, impervious, soils) model. At large scales there is a general trend of increasing vegetation cover and decreasing impervious cover with greater distances from the city center, but the pattern varies with direction from city center. Comparisons of techniques demonstrate that distance measures, population density, and land use vary greatly in land surface cover values in the Seattle, Washington metropolitan region. These findings suggest that an urban to rural landscape might be better stratified in an ecosystem context based on biophysical land cover as an indicator of human impact.

Introduction

There is a growing interest in the effects of urbanization on the environment. Current trends indicate that U.S. populations are rapidly moving towards the rural fringes of cities (Berry 1990). Calculations using U.S. Census data show that the total area covered by regions classified as metropolitan have increased at approximately 8 million acres per year over the past 22 years (U.S. Bureau of the Census 1994). The urbanization of land is a concern for planners, land managers, and ecologists (Greenberg and Bradley 1997). In this chapter, I introduce a method of measuring biophysical land cover using satellite data. Biophysical measures are useful in estimating ecological processes (Ridd 1995) and are applied here to an urban-rural gradient around the city of Seattle, Washington. The results are compared with measures more commonly used to estimate urban impacts on the environment to demonstrate advantages of the biophysical land cover approach.

Gradient analysis

McDonnell and Pickett (1990) suggested that urban impacts on the environment could be assessed using the techniques of gradient analysis first developed by community plant ecologists (Austin 1985). With the gradient approach, the environmental variables used to determine plant communities are replaced with a proxy for human influence. Gradient analysis uses the variations in urban intensity found in and around cities as an experimental design to study the relationship between urbanization and ecosystem alterations. For example, studies that have used the urban-rural gradient approach have measured impacts on soils (Pouyat and McDonnell 1991; Pouyat et al. 1995), species diversity (Blair 1996; Guntenspergen and Levenson 1997), forest structure (Medley et al. 1995), and land use (Wear et al. 1998).

Although the concept of an urban-rural gradient has existed for several years (Bradley 1984), the actual definition of what is measured by the gradient variable has been unclear. The term 'urban' means "of the city" (American Heritage Dictionary 1992) and is used to describe the forms of settlement similar to those of a city (Rugg 1972). This definition does not provide a quantitative measure of urban.

The U.S. census defines urban as areas with a population density over 620 people/ km^2 (U.S. Bureau of the Census 1994). This density-based definition of urban areas is a binary approach in that an area is either urban or non-urban. A binary approach is not conducive to measuring alterations to an ecosystem on a continuum as needed in gradient analysis.

Urban areas impact the environment through a complex mix of land alteration, emissions, and resource extraction (Figure 2-1). Together, these impacts create a degree of urbanization that is theoretically the gradient along which changes to ecosystems. It is impractical to directly measure all these impacts and combine them together to determine the degree of urbanization.

To estimate the degree of urbanization scientists have used a measure of distance to urban center as the primary indicator of "human influence" (McDonnell et al. 1997). Another approach is to measure land-use (Wear et al. 1998) or population density (Kerr and Currie 1995). These variables are much cheaper, more quantitative, and easier to gather than measuring all of the individual factors that contribute to urbanization. There are, however, drawbacks to each of these estimates, and there are several reasons to consider using biophysical measures of land cover in addition to the traditional measures.

Overview of measures used to estimate urbanization

The measure of distance to urban center is based on the early geographic models of urban pattern being determined by optimal locations. These models stem from Von Thunen's work on agricultural land in 1826, but were modified to urban environments by Hurd in 1903 (Kivell 1993). The models predict a concentric ring pattern of diminishing human influence on the landscape based on diminishing opportunities for market access. These simplified models have been hotly debated in the disciplines of economics and geography. The existing development patterns around cities can vary from these models for a large number of reasons such as transportation corridors, topography, water, and planning policy. All these factors influence the patterns of development around a city and therefore affect the amount of human influence at a given distance from the city center.

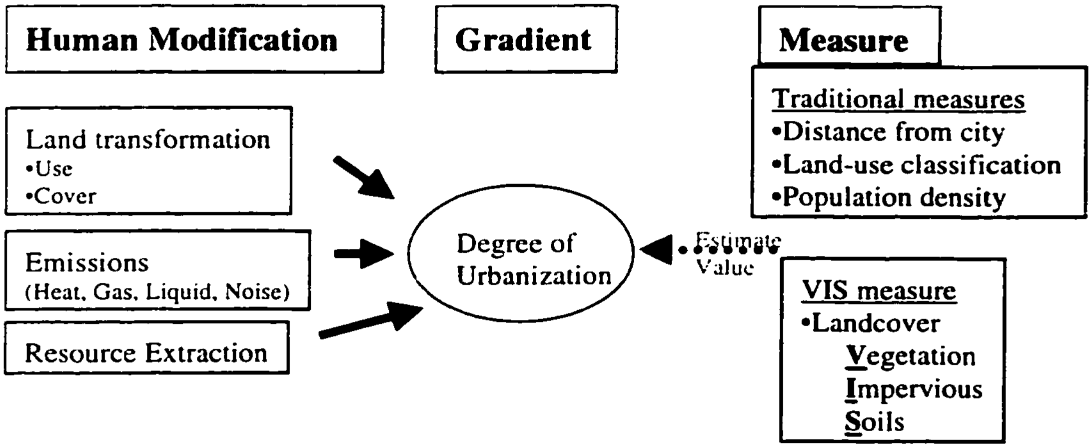


Figure 2-1. Conceptual diagram showing the factors that contribute to the degree of urbanization and factors used to estimate the degree; traditional estimates are shown in the upper box, while the VIS model (biophysical land cover) and its components are shown in the lower box.

Distance may serve as a reasonable proxy for human influence, but it should not be the only measure used. In fact, due to the high degree of heterogeneity found in urban environments, the variability in land cover along a distance gradient can be significant enough to mask the human impact found in the urban-rural gradient (Greenberg and Bradley 1997). For example, a large park in close proximity to the urban center may mitigate some of the human influences on the ecosystem in a gradient study. Conversely, a development at the urban fringe could increase local human influences.

The distance measure assumes that a concentric ring pattern of development exists around cities, and that homogenous patterns of development occur at a given distance. In this study, these assumptions are tested using biophysical land cover values. Using these tests, I illustrate difficulties that can occur in gradient analysis with traditional measures of urbanization, and I provide a method of using satellite data that may avoid many of the assumptions of previous methods.

In this dissertation, there is an important difference between land use and biophysical land cover classifications. Land use refers to thematic classifications such as the Anderson classification (Anderson et al. 1976). In the Anderson classification areas are grouped into thematic units such as "suburban development", "light industrial", or "forested". Biophysical land cover however refers to continuous measures of the biophysical material that covers the surface of the earth. Land cover is represented as a continuous percent cover of vegetation, impervious material, and soil. There is certainly a correlation between the land use classes and the biophysical land cover, but by comparing the two I show that there are also some large differences that should be considered in ecosystem analysis.

Since human population density is used in many urban definitions, I also look at biophysical land cover and population densities as a function of distance from city center. Since population is a measure of where people live, researchers have shown that population density does not necessarily measure the degree of land cover alteration (Greenberg and Bradley 1997).

Land cover approach

In this chapter I provide a complementary approach to the more traditional measures of degree of urbanization used to assess urban to rural changes. I use biophysical land cover measures as variables to assess the degree of urbanization, and provide a quantitative alternative to defining an urban-rural gradient. I test for a biophysical distance gradient and examine if the gradient is similar in all directions. Second, I compare biophysical land cover measures with traditional land-use classes often used to stratify a landscape. Finally, I compare population density with land cover values. These approaches illustrate the complexities in land cover patterns around urban regions and the care that should be made when conducting gradient research on urban-rural areas.

Using satellite data to measure land cover

Satellite data have the advantage of frequently capturing a large image area at a low cost (Lillesand and Kiefer 1994). Remote sensing is often used to determine the morphology of urban environments (Bowden et al. 1975; Jensen 1979; Paulsson 1992; Treitz et al. 1992; Barnsley and Barr 1996). Few urban-rural gradient studies have taken advantage of the wealth of information found in satellite data.

Classifying satellite data of urban areas is difficult because urban regions have high spectral variability (Elvidge et al. 1997), and fine scale spatial heterogeneity (Barnsley and Barr 1996). Traditional classifications using land use categories can involve complicated steps to achieve reasonable levels of accuracy (Jensen 1979; Gong and Howarth 1990; Treitz et al. 1992; Weber 1994). The land use classification scheme is difficult for urban-rural gradient analysis because land use classes are thematic, subjective, discontinuous measure, and difficult to interpret from satellite data. To illustrate these points, Figure 2-2 shows a region classified using an Anderson classification scheme.

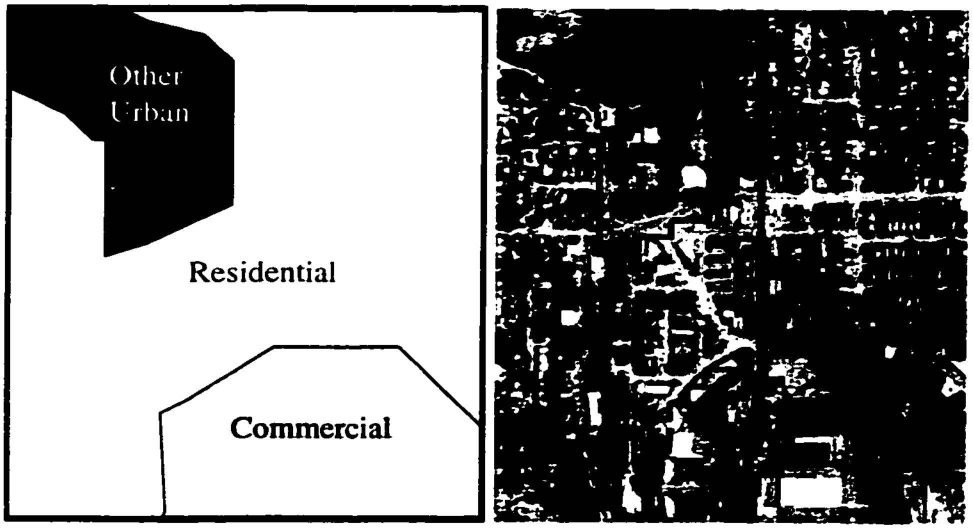


Figure 2-2. Example of traditional land-use classification with three USGS classes: other urban, residential, and commercial. Image on right is a Digital Orthophotographs Quarter-Quadrangles (DOQ).

Defining the exact location of a line between the classes is difficult and does not lend itself well to continuous measures. For example, at what point does "residential" become "other urban"? In this case other urban refers to a park. Visually it is difficult to determine how a small park differs in cover from a backyard with large trees. Second, satellite data measure ground reflectance, and not the land use; Anderson thematic classifications assume that the "use" classification results in a visual change to the land. Lastly, the land use classes have large variability in cover types, meaning they will vary in ecological processes. This variability can be seen in the park class (other urban) that has open grassland, forests, and play fields. All of these factors make land use classes difficult to use for ecosystem analysis.

Ridd (1995) has outlined a land classification approach called the V-I-S (vegetation-impervious-soil) model to assess urban ecosystems. This model uses biophysical land cover compositional elements to investigate urban patterns and morphology (Figure 2-3). The V-I-S approach overcomes many of the problems associated with land use classifications in urban ecosystem research.

Although land use is certainly a useful classification for many types of analyses, biophysical land cover measures are directly detectable using remotely sensed data, less subjective, and related to ecological processes (Figure 2-4). The V-I-S model is similar to the use of vegetation indices such as Normalized Difference Vegetation Index (NDVI), which researchers have suggested are related to ecosystem processes (Bohlman 1994; Gamon et al. 1995; Ramsey et al. 1995; Carlson and Ripley 1997; Stoms and Hargrove 2000).

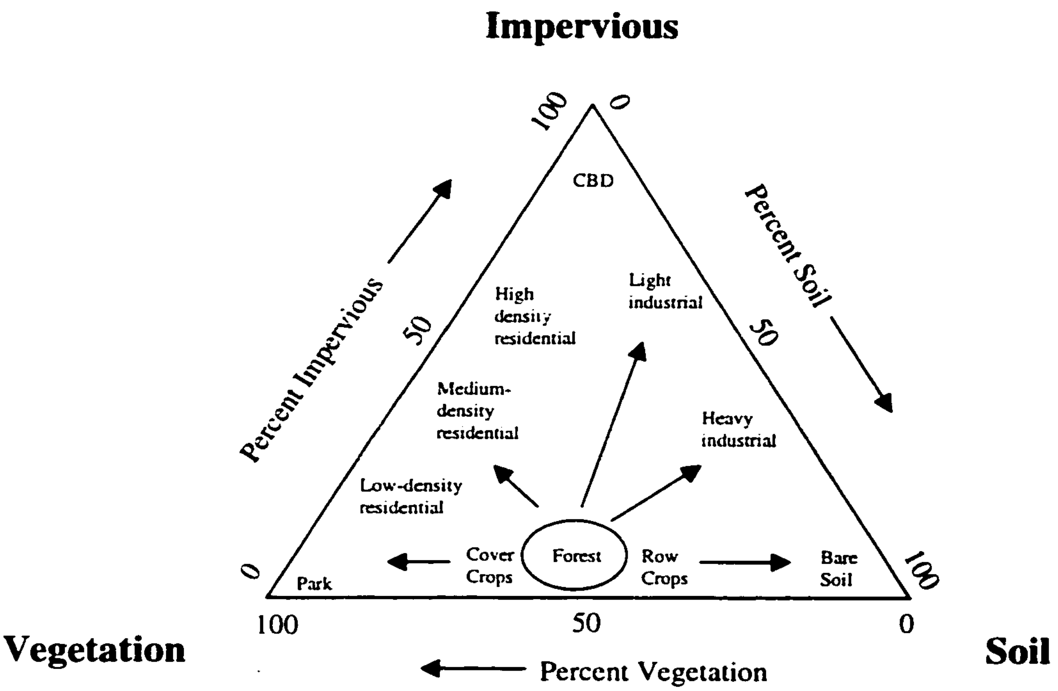


Figure 2-3. V-I-S model proposed by Ridd (1995), illustrating land cover for a pixel as the percent of three land cover compositions: vegetation, impervious, and soil. Within this conceptual ternary diagram are Ridd's predicted location of different land use categories (CBD = central business district), and the assumed change in land cover from a forested to an urbanized landscape.

However, the impervious and soil cover types used in the V-I-S model provide additional information that can help researchers assess processes such as heat islands and hydrologic flows. Vegetation, impervious surfaces, and soil cover have inherent processes associated with them that occur both in urban and rural environments. Some examples of processes that change with land cover are provided in Table 2-1, but many more could be added to this list.

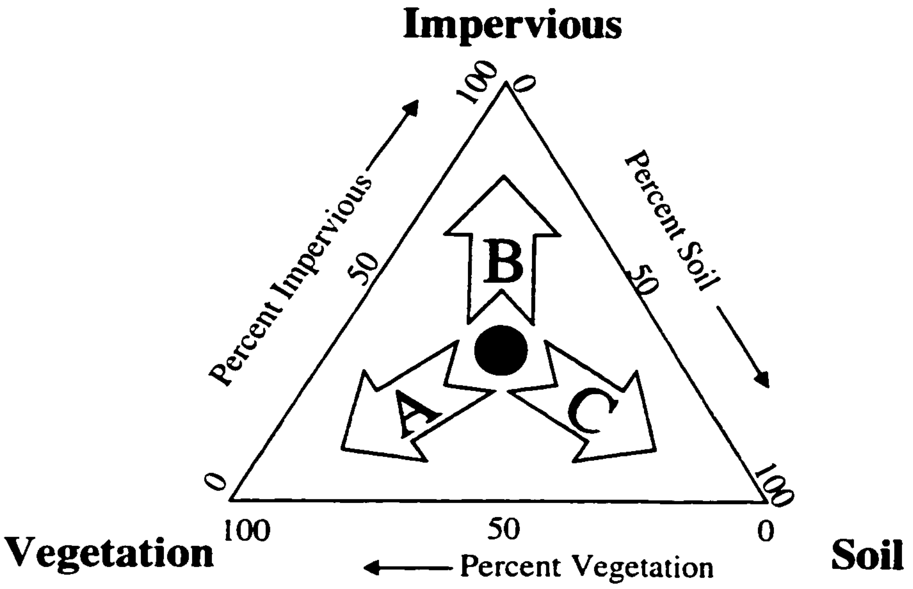


Figure 2-4. V-I-S ternary diagram illustrating the change in land cover (A, B, C) associated with changes in processes listed in Table 2-1.

Table 2-1. Changes in location of V-I-S model from Figure 2-4, and predicted change in processes with changes in land cover.

A - Increased Vegetation Cover	B - Increased Impervious Cover	C - Increased Soil Cover
↑ Photosynthesis	↑ Albedo	↑ Siltation of water
↑ Transpiration	↑ Surface temperatures	↑ Annual cover variation
↑ Carbon Sequestration	↑ Overland water flow	
↑ Productivity	↓ Below ground productivity	

Although land cover in a city may function differently from land cover in an undisturbed area, there are some generalizations that can be made about processes, especially with diverse cover types. For example, urban vegetation is more similar in process to rural vegetation than any amount of impervious cover.

Determining V-I-S values

The V-I-S model provides a method of representing land cover, but it does not include the method of gathering the data. The spectral mixing model is an approach to satellite data classification that allows the determination of biophysical land cover composition of remotely sensed data. The spectral mixing model decomposes multi-spectral image data and provides sub-pixel estimates of the surface composition (Adams et al. 1989; Adams et al. 1995; Sabol Jr. et al. 1992). The results of the model provide the cover composition of a landscape based on the spectral mixing of a few surface elements that are spectrally distinct (endmembers) such as vegetation, soil, non-photosynthetic vegetation, and shade. An algorithm that solves a series of simultaneous equations gives the percent of each endmember detected within a pixel.

Biophysical measures are continuous (0-100%) and can be used at multiple sites and over multiple time periods. Output from the spectral mixing model is typically viewed using the same ternary diagrams that Ridd (1995) used in his V-I-S model. By using the transition from rural land cover to human modified land cover, the spectral mixing model results can be used to examine biophysical changes due to urbanization.

In this paper I illustrate how the spectral mixing and V-I-S models are used to assess the urban-rural gradient around Seattle, Washington. I demonstrate that there is a biophysical gradient in Seattle, but the assumptions of the distance gradient measure do not hold true in all directions. Finally, I compare biophysical land cover with land use classifications and population density.

Methods

Study Site

The city of Seattle is located on the edge of the Puget Sound in Western Washington (Figure 2-5).

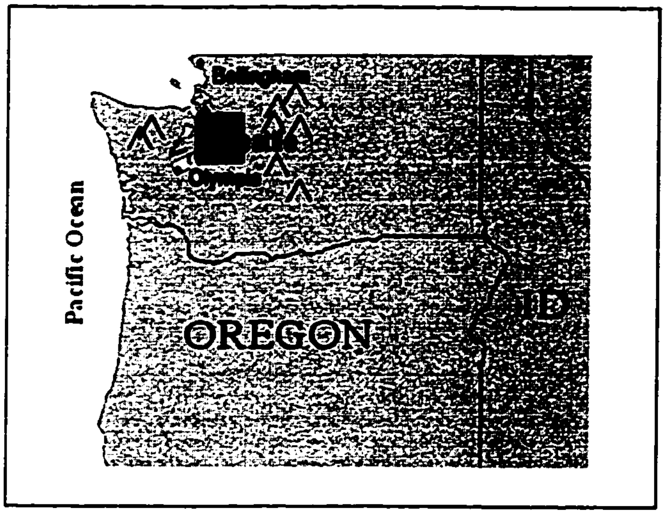


Figure 2-5. Location of study site in Washington state. The dot location marks the city center for Seattle, and the shaded box delineates the extent of the image used for regional analysis.

The region was heavily forested before white settlers entered the area in the mid-19th century. The metropolitan population of Seattle is over 2.5 million and the rate of growth for the region has been close to 40,000 people per year between 1998 and 2000. Due to constraints of water to the west and mountains to the east, much of the development has occurred in a north-south corridor. These constraints have resulted in a city with an abrupt urban-rural boundary to the east, which creates an excellent opportunity to apply gradient techniques to quantify changes in ecosystems from downtown Seattle to the Cascade Range.

Image Analysis

A Landsat TM image for the Seattle region acquired on August 28, 1999 was used for this study. This image was georeferenced to digital orthographic quads (DOQs) in UTM projection. The extent of the image was clipped to cover all of King county including the city of Seattle and the main drainage areas within the county. The image covers an area roughly 100 kilometers wide, with a resolution of 28.5 meter pixels.

I used only one image in this analysis to capture reflectance at a single point in time. Annual variation in land cover can make it difficult to classify and make predictions that assume land cover is static. By using a late August image, much of the natural vegetation in the region will be dry and appear as soil in the V-I-S model. Arguments could be made both in favor and against this approach. I felt an important factor in this choice is the ability to see differences between irrigated and non-irrigated vegetation. Seasonal and annual variations are also interesting aspects that could be observed with the V-I-S approach but were not incorporated in this study.

A simple dark image correction was made by shifting band values so that the band histograms start with a zero value. Topographic normalization analysis was used to identify areas that are too dark for image assessment based on sun angle, satellite angle, topographic slope, and aspect calculated using a 30 meter digital elevation model (DEM). All shadow areas were excluded from analysis, even in cases where additional efforts may have detected land cover. Water cover is not used in the V-I-S model and open water bodies were identified using unsupervised and supervised classification techniques and masked out of all subsequent analysis. Although the image was relatively cloud free, small clouds were also masked from analysis.

The satellite image was analyzed using the Impact software developed by the University of Washington Geology Remote Sensing lab. This software performs a simple linear spectral mixing using the equation:

$$DN_b = \sum_{i=1}^{N} F_i DN_{i,b} + E_b \qquad \text{And} \qquad \sum_{i=1}^{N} F_i = 1 \quad , \qquad\qquad (2\text{-}1)$$

where DN_b is the relative uncalibrated radiance in band *b* of an image pixel; F_i is the fraction endmember of *i*; DNi,b is the relative radiance of endmember I in band *b*; *N* is the number of endmembers; and E_b is the error for band *b* of the fit of *N* spectral endmembers (Adams et al. 1989).

I selected endmembers spectra to represent the three surface covers used by Ridd (1995) in the V-I-S model including a shade spectrum to account for structural and topographical shading.

In this dissertation the terms vegetation, impervious, and soil refer to specific cover types but are categorized based on spectral uniqueness. The definitions of the endmember cover types are as follows:

Vegetation: Green vegetation at time image was acquired. Does not include vegetation that is dead or not green. Actually is related to the chlorophyll in the vegetation (Myneni 1994). The typical spectra found for vegetation is low red and high infra-red reflectance.

Impervious: This is a process, but spectrally is connected to surface types that are impermeable to water. Materials are typically cement, and asphalt, but natural rock is counted also. It is important to note that satellites do not directly measure a process and materials that generally are impermeable may spectrally appear as soils. In most cases impermeable materials are bright in the visible spectrum and lower than soils in the near infra-red.

Soil: This cover includes dirt and gravel as well as non-photosynthetic vegetation (NPV). NPV materials include tree bark, dead grasses and exposed wood. Typically *soil* varies from *impervious* cover by lower reflectance in the visible spectrum and higher values in the near and mid infra-red.

Spectra were selected from the image using areas that had 100 percent cover for each surface material. Spectra from a spectral library could have also been used, but the image would require correction for atmospheric influences so that lab measured spectra would more accurately match the image spectra. By using spectra values from the image, there is less need to correct for atmospheric distortion because the distortion is included in the spectra. The difficulty of selecting areas from the image is that the success of the model is based on the point(s) selected, and on the ability to find a pixel that represents 100 percent of the selected cover type.

After the image was unmixed, I performed a shade normalization to correct for shading in the image. Due to model error, some values were less than zero or more than 100 and were reset to either equal zero or 100. The resulting image consisted of pixels containing the percent of vegetation, impervious, and soil cover in a combination equaling 100 percent.

I assessed data accuracy during the spring of 1999. Ground observations were made at 30 sites to select a diversity of land cover between sites, homogeneity within site, and at various locations in the region. The V-I-S values were estimated at each site using visual estimates of cover, and each site was georeferenced using a Trimble GPS unit. I estimated ground conditions using best approximations of each V-I-S cover as viewed from the ground and without the aid of satellite images. A comparison of these observed values with those determined from the spectral model was made using a simple linear regression.

Data Analysis

The following types of analysis were performed using the V-I-S land cover data: comparisons of distance to city, direction from city, land use, and population density. The V-I-S land cover values along the urban-rural gradient were assessed using mean values in one kilometer distance rings from the city. This distance was selected based on autocorrelation assessment of the land cover values using the equation:

$$c = \sum_{k}^{n} C_{ij} / \left(\sqrt{\sum_{k}^{n} (Z_i - Z_m)^2} * \sqrt{\sum_{k}^{n} (Z_j - Z_m)^2} \right) \qquad (2\text{-}2)$$

where n is the total number of cells in the image, i is any cell on the input image, j is any cell that is offset from the i location by a specified distance, Zi is the value of the attribute cell i, Zj is the value of the attribute cell j, Cij is the similarity of i's and j's attributes: (Zi - Zm)*(Zj - Zm). Results indicated spatial independence around one kilometer distance (Figure 2-6). Within each one kilometer ring, I calculated the mean land cover for the V-

I-S data. Mean land cover was also calculated for direction from the city center in 8 compass directions (45° angle) within each one kilometer ring.

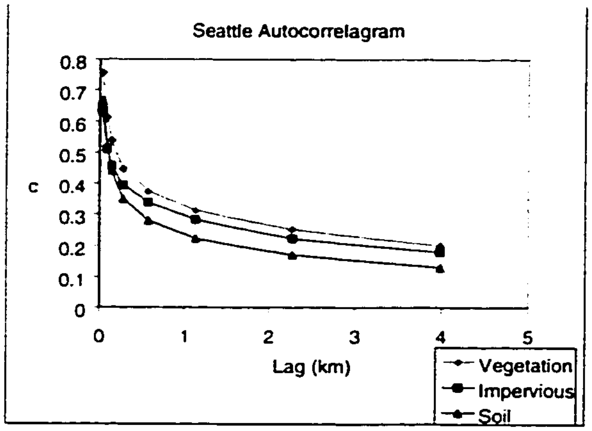


Figure 2-6. Autocorrelation ("c") at increasing lags for the three land cover types derived from the Seattle satellite data using equation (2-2).

Comparisons were made with traditional classification using the United Stated Geological Survey (USGS.) 1:250,000 land use/land cover (LU/LC) dataset. Ten points were selected randomly in 19 of the USGS classes and compared with the V-I-S cover. Since any point may be an outlier of a class, a three by three cell focal neighborhood was created around each random point and the mean of the total of 9 points was used in the analysis. This allows for a better comparison with the scale at which the USGS data is classified.

To evaluate the total land cover (VIS) variation within USGS land use classes, I sampled all pixels in four of the USGS classes and compared the results with V-I-S data. The mean and standard deviation of *vegetation*, *impervious* and *soil* cover within the four USGS classes was calculated. The classes used were residential, industrial, deciduous forest, and barren lands.

I compared population density along the urban-rural gradient with V-I-S values. Population density was determined using the U.S. census "TIGER" data at the block group level. For each block group the population density was calculated using the polygon area for the block group provided in the Arc/Info coverage. These polygons were then converted into grids to create a spatially continuous data set at the same pixel size as the V-I-S data. The Analyses included both block group boundaries and one kilometer distance intervals.

Results

Image analysis

Spectra for the spectral mixing model were selected from the image at four points (Figure 2-7).

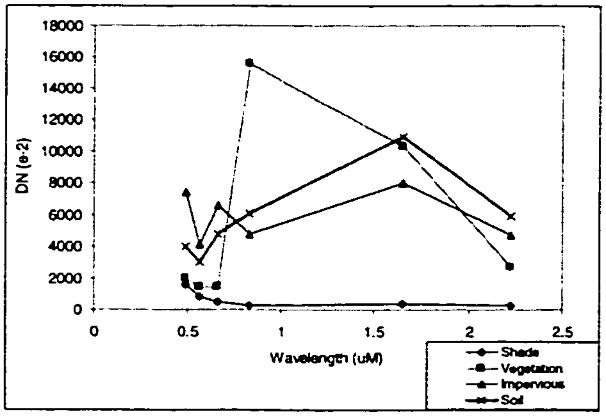


Figure 2-7. Satellite digital number (DN) values selected as endmembers for the three V-I-S model covers types, and a fourth shade endmember.

Soil spectra were selected that also included dead vegetation (NPV- non-photosynthetic vegetation). Visual assessment of the spectral mixing results indicate that the model captured the general patterns known to exist in the city (Figure 2-8). The downtown

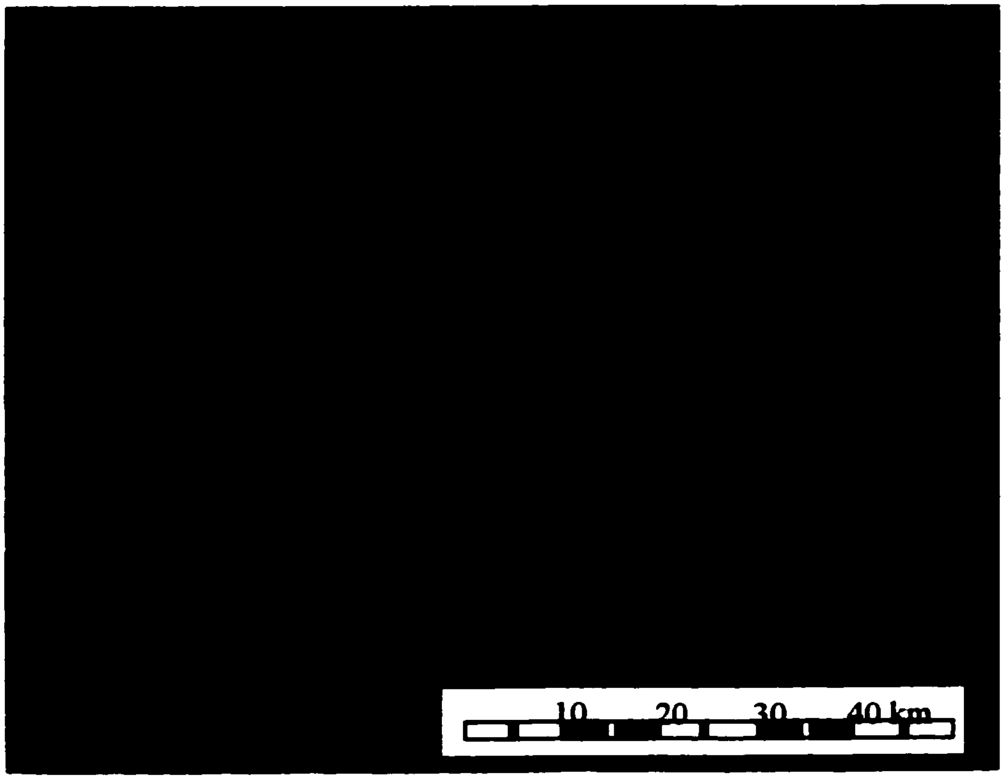


Figure 2-8. Classified image from spectral mixing model with shade correction, and water mask. Classes are continuous data from 0 to 100 percent and shown as vegetation (green), impervious (red), and soil (blue).

region has high values of *impervious* cover as does the upper elevation mountains that have non-vegetated rocky outcrops. As expected, *vegetation* is high in the parks and forested regions outside the city. *Soil* cover is high in agricultural areas, recent forest harvest patches, and areas with senesced vegetation from lack of irrigation.

The observed land cover values from the ground truth site varied in composition and included samples that represent most regions of the V-I-S diagram (Figure 2-9)

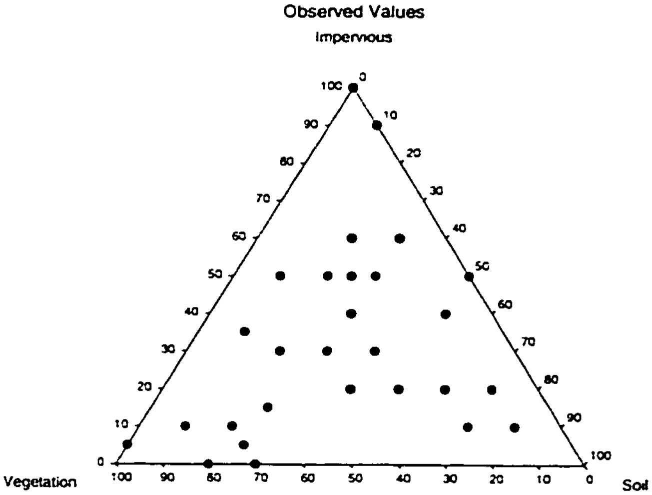
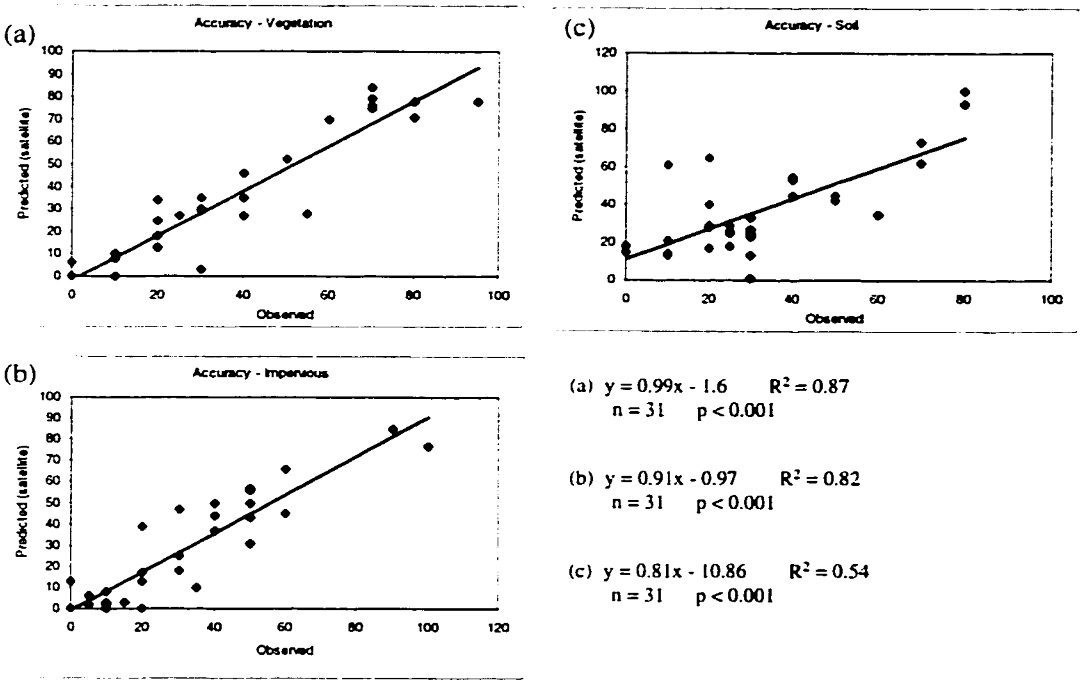


Figure 2-9. Ternary diagram of observed land cover at accuracy assessment sites. Each point represents the land cover as determined by an on the ground observation.

An accuracy assessment of the spectral mixing model with ground-based cover observations indicates satellite determined V-I-S surface cover values are accurate ($P < 0.005$). Correlation coefficients are R^2 of 0.87 for *vegetation* and R^2 of 0.82 for *impervious* with nearly a one to one relationship: *Vegetation* $y = 0.99x - 1.6$ and *Impervious* $y=0.91x-0.97$ (Figure 2-10). *Soil* was less accurate with an R^2 of 0.54 and regression line of $y= 0.81x + 10.86$, but still significant at the $P < 0.005$ level.



(a) $y = 0.99x - 1.6$ $R^2 = 0.87$
$n = 31$ $p < 0.001$

(b) $y = 0.91x - 0.97$ $R^2 = 0.82$
$n = 31$ $p < 0.001$

(c) $y = 0.81x - 10.86$ $R^2 = 0.54$
$n = 31$ $p < 0.001$

Figure 2-10. Observed versus predicted percent cover values using satellite a spectral mixing model for (a) *vegetation*, (b) *impervious*, and (c) *soil*.

Distance V-I-S analysis

Analysis of the mean cover type in relation to distance from city center demonstrates that there is a gradient for vegetation and impervious land cover with distance from city center (Figure 2-11). *Impervious* cover is 60 percent at the city center and drops sharply too less than 10 percent at 30 kilometers from the city center. *Vegetation* cover starts at 8 percent in the city and increases to 60 percent at about 30 kilometers from the city center. *Soil* increases to a maximum of 47 percent at 9 kilometers from the city center, but does not show a linear relation to distance from city center.

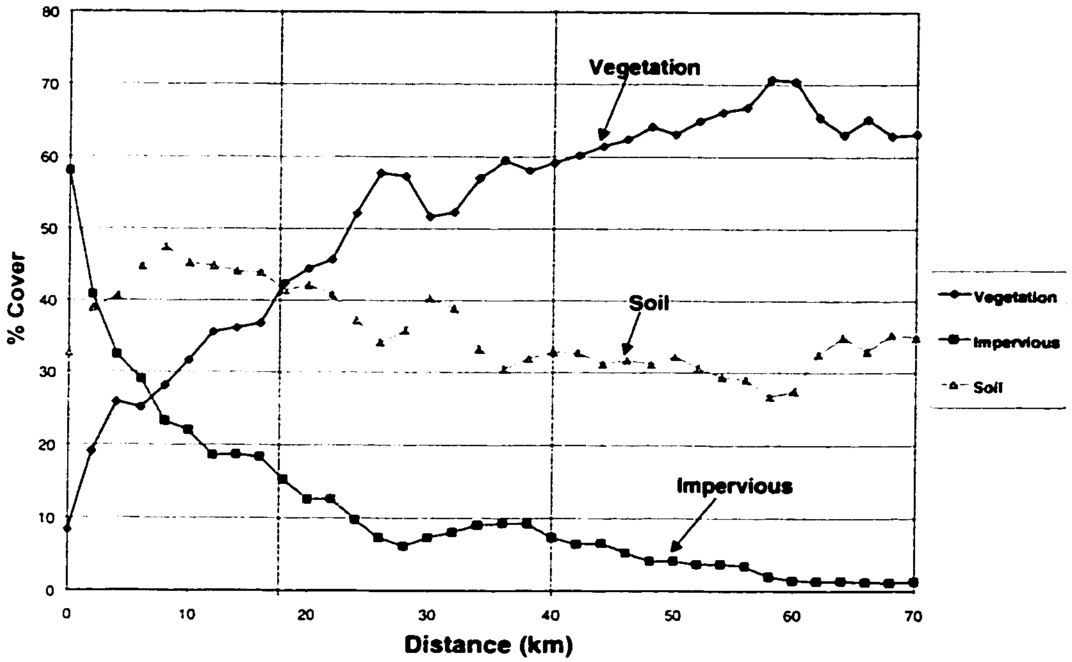


Figure 2-11. Mean percent cover for one kilometer rings centered on downtown Seattle and moving outward in all directions.

Variability around these mean values is high; maximum and minimum values at most distance intervals range from 0 to 100 percent. Comparisons of distance with a ternary diagram show that Seattle follows predicted changes from city center to rural areas (Figure 2-12). Again, variation around these mean values is high, but trends indicate a transition from the urban to a forest environment as predicted by Ridd's diagram previously described (Figure 2-3).

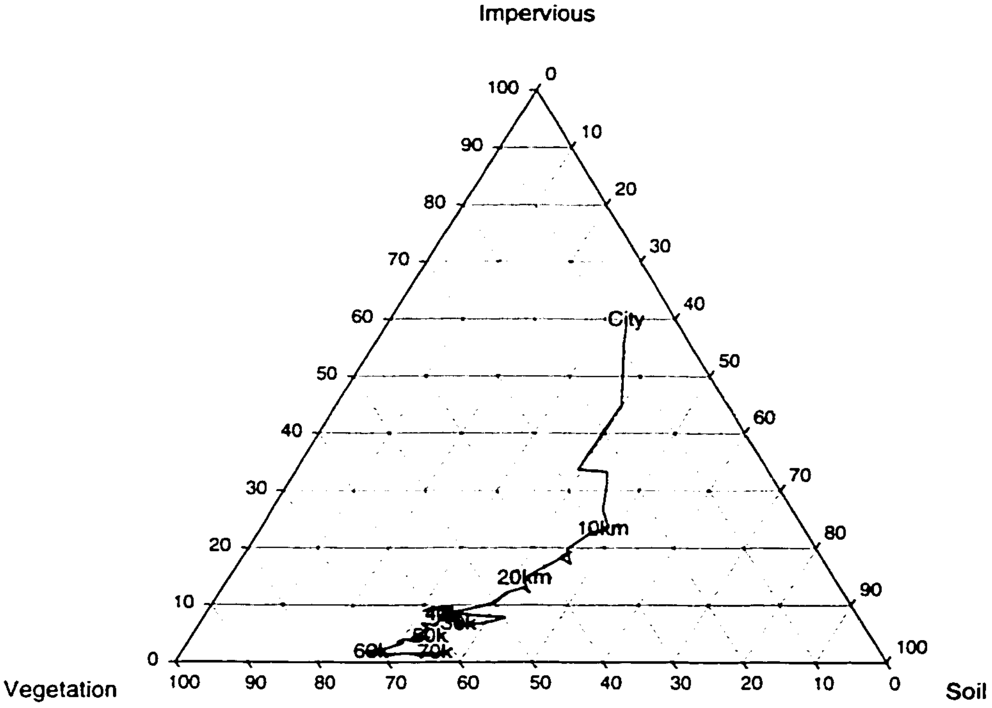


Figure 2-12. Ternary diagram of mean land cover in one kilometer distance rings from city center (City) to 70 kilometers from city.

Direction V-I-S analysis

Adding the direction from city center to the distance analysis, results indicate changes in cover are different in all directions (Figure 2-13). There is a north-south trend for high *impervious* values and east-west trend for high *vegetation* cover.

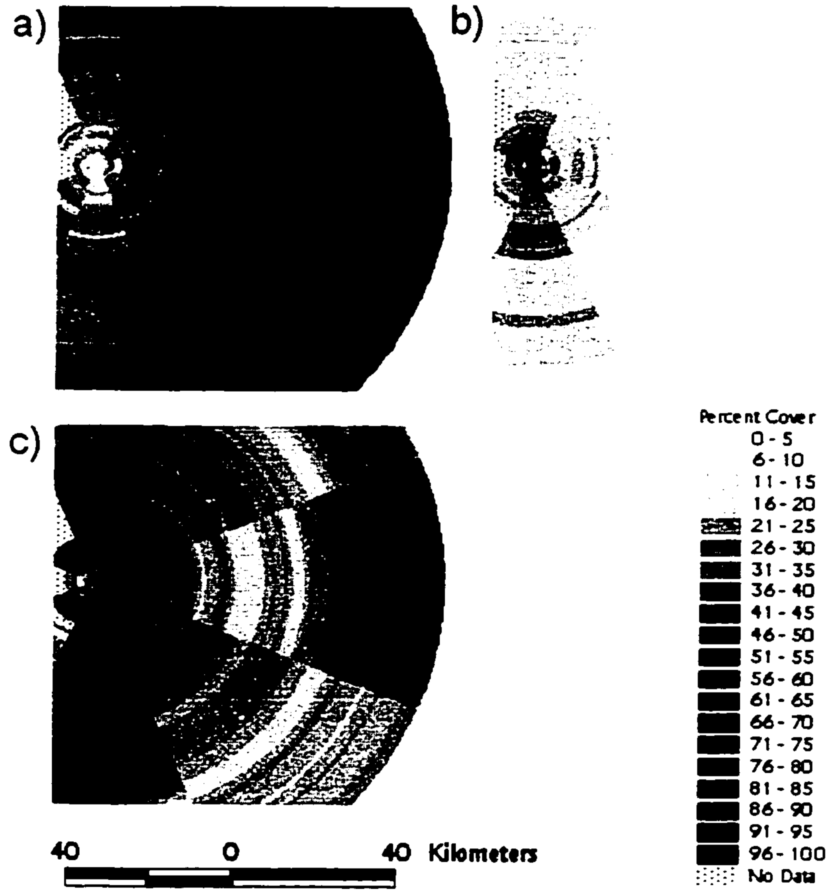


Figure 2-13. Mean percent cover calculated for distance from city center (1 km width) and direction (45°) for (a) *Vegetation*, (b) *Impervious*, and (c) *Soil*.

Thematic comparison to V-I-S

Comparisons of USGS land use maps and the satellite-interpreted land cover maps reveal large ranges in cover for each class. Values ranged greatly (from 0 to 100 percent) in *vegetation*, *impervious*, and *soil* for all of the land use classes. Mean values for each land use class, however, fell into the predicted locations (Figure 2-14). The variability of the four U.S.G.S. classes is shown in Figure 2-15. The mean and one standard deviation of V-I-S values are shown in the four ternary diagrams.

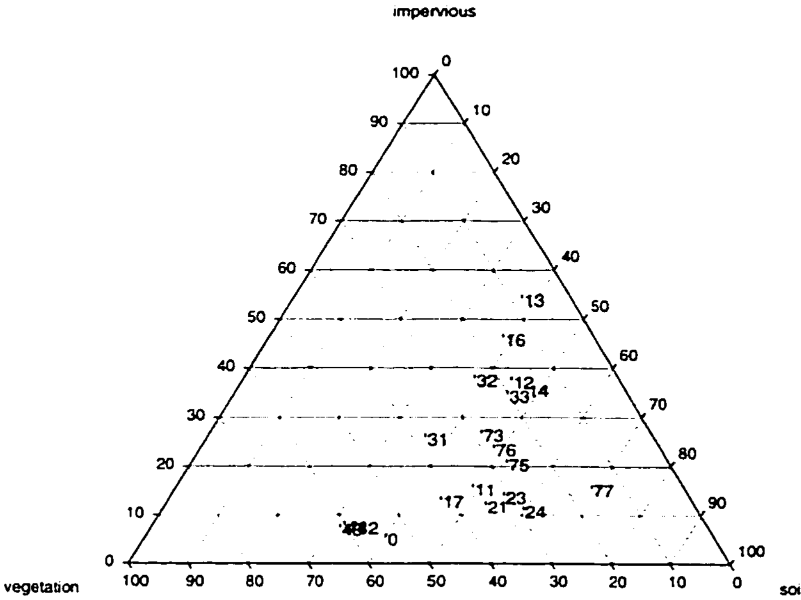


Figure 2-14. Ternary diagram of mean cover values for selected USGS land use classes of the study area. 11 = Residential, 12 = Commercial, 13 = Industrial, 14 = Transportation, 16 = Mixed urban, 17 = Other urban, 21 = Crop and pasture, 23 = Confined feed operations, 24 = Other agriculture, 31 = Herb rangeland, 32 = Shrub, 33 = Mixed range, 41 = Deciduous forest, 42 = Evergreen forest, 43 = Mixed forest, 73 = sandy areas, 75 = Strip mines, 76 = Transitional areas, 77 = Mixed barren lands.

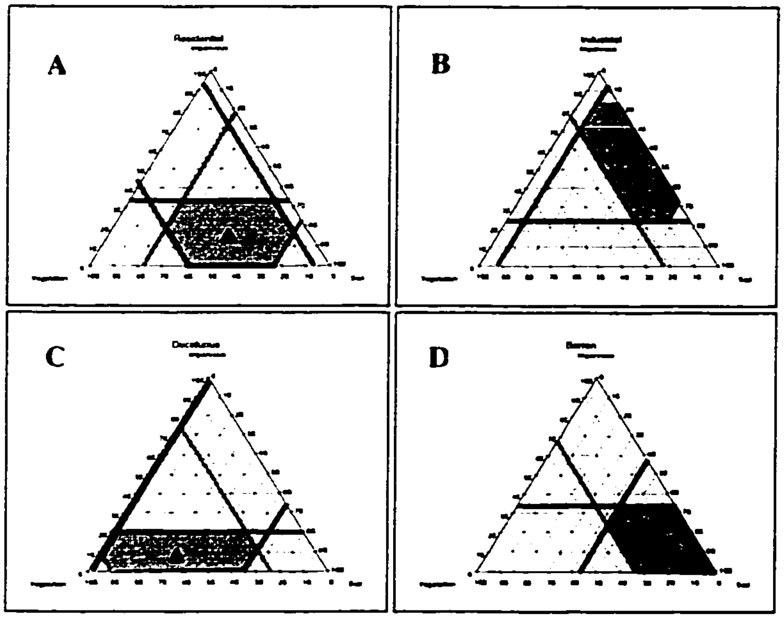


Figure 2-15. Ternary plots of V-I-S cover for USGS land use classification types based on satellite spectral mixing. Black triangles show class mean, shaded areas represent ± one standard deviation from the mean. Classes are: (A) residential (B) industrial (C) deciduous forest (D) barren lands.

Population density decreases with distance from city center starting at 27 people per hectare in the city and diminishing to zero people per hectare at 40 kilometers away from the city (Figure 2-16a). The density decay can be described using a natural logarithm of population density (Figure 2-16b), with a correlation coefficient of $R^2 = 0.93$, $n = 61$, and $p < 0.05$.

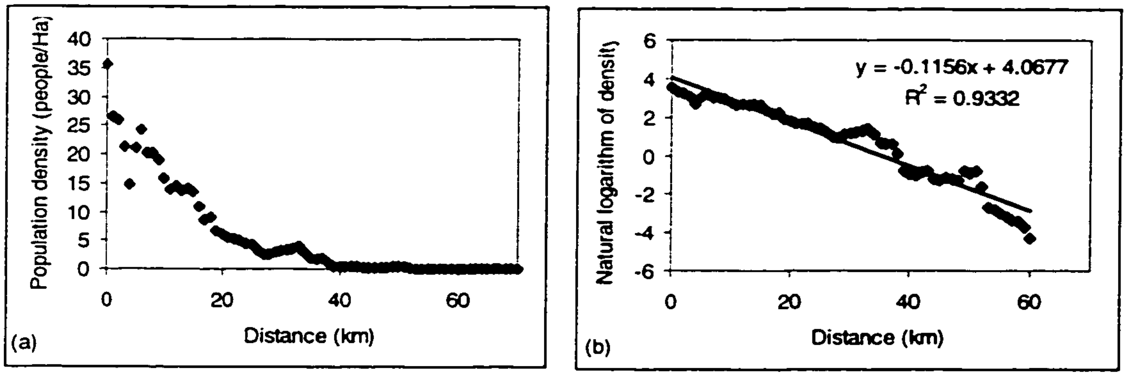


Figure 2-16. Population density calculated as mean value per one kilometer distance bands where (a) shows mean value at each distance, and (b) shows natural logarithm of population density at each distance interval, with best fit line and equation.

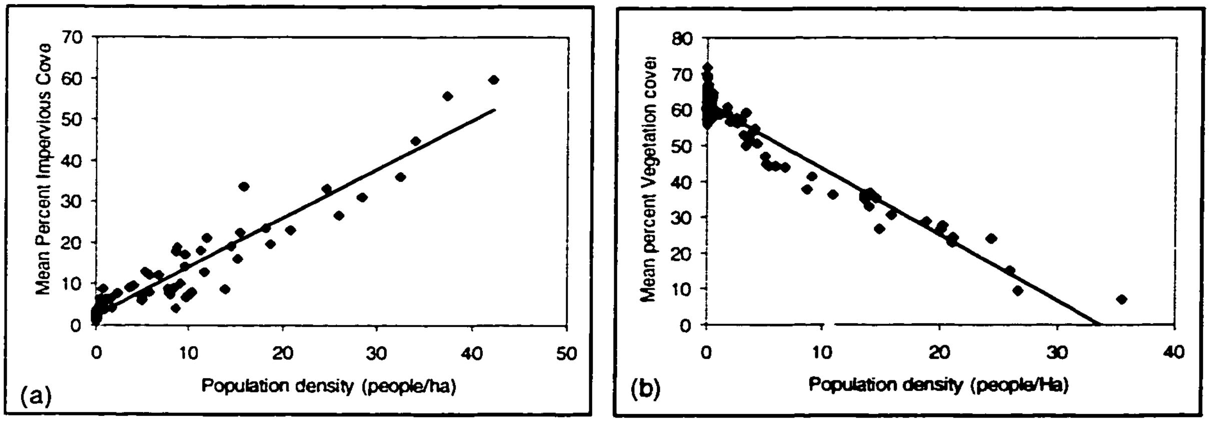


Figure 2-17. Mean population density and mean cover type in one kilometer distance bands. (a) impervious: $y = 1.19x + 2.3919$, $R^2 = 0.9095$, $n = 85$, $p << 0.05$ (b) vegetation: $y = -1.84x + 61.90$, $R^2 = 0.9294$, $n = 85$, $p << 0.05$.

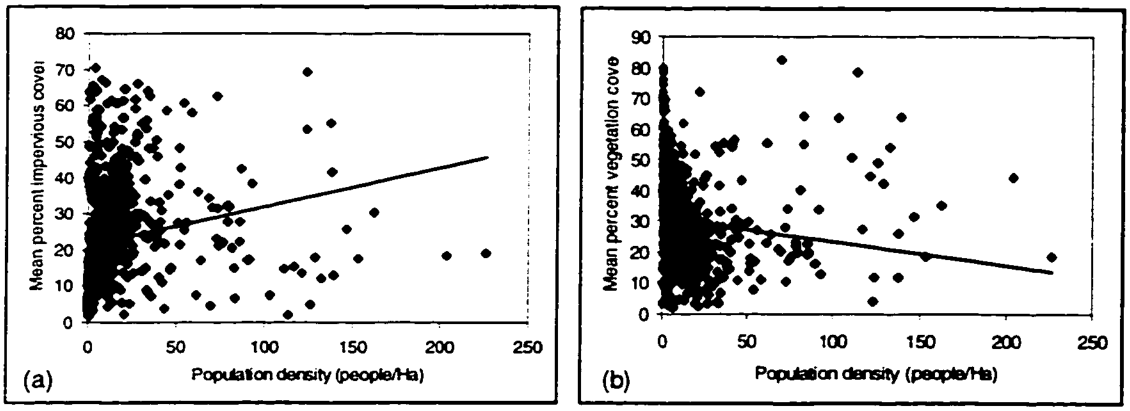


Figure 2-18 Mean population density and mean cover type in block groups. (a) impervious: y = 0.1084, $R^2 = 0.03$, $n = 1032$, $p < 0.05$ (b) vegetation: $y = -0.077x + 31.123$, $R^2 = 0.015$, $n = 1032$, $p < 0.05$

For each distance band, I compare the mean percent of *impervious* and *vegetation* cover to the mean population density. *Impervious* cover has a significantly positive relationship with population density (Figure 2-16a); *vegetation* has a significantly negative relationship (Figure 2-16b). When using the resolution of the population data (block group delineation), the relationship between population density and surface cover is not correlated. The R^2 values drop to less than 0.1 for both *impervious* and *vegetation* cover. Areas that have high residuals from the regression (Figure 2-18) indicate regions where population density does not accurately predict *impervious* cover. Examples of these regions are shown in Figure 2-19. In the industrial region of Seattle there is higher than expected *impervious* cover for the population density, while the small parks have less than expected *impervious* cover.

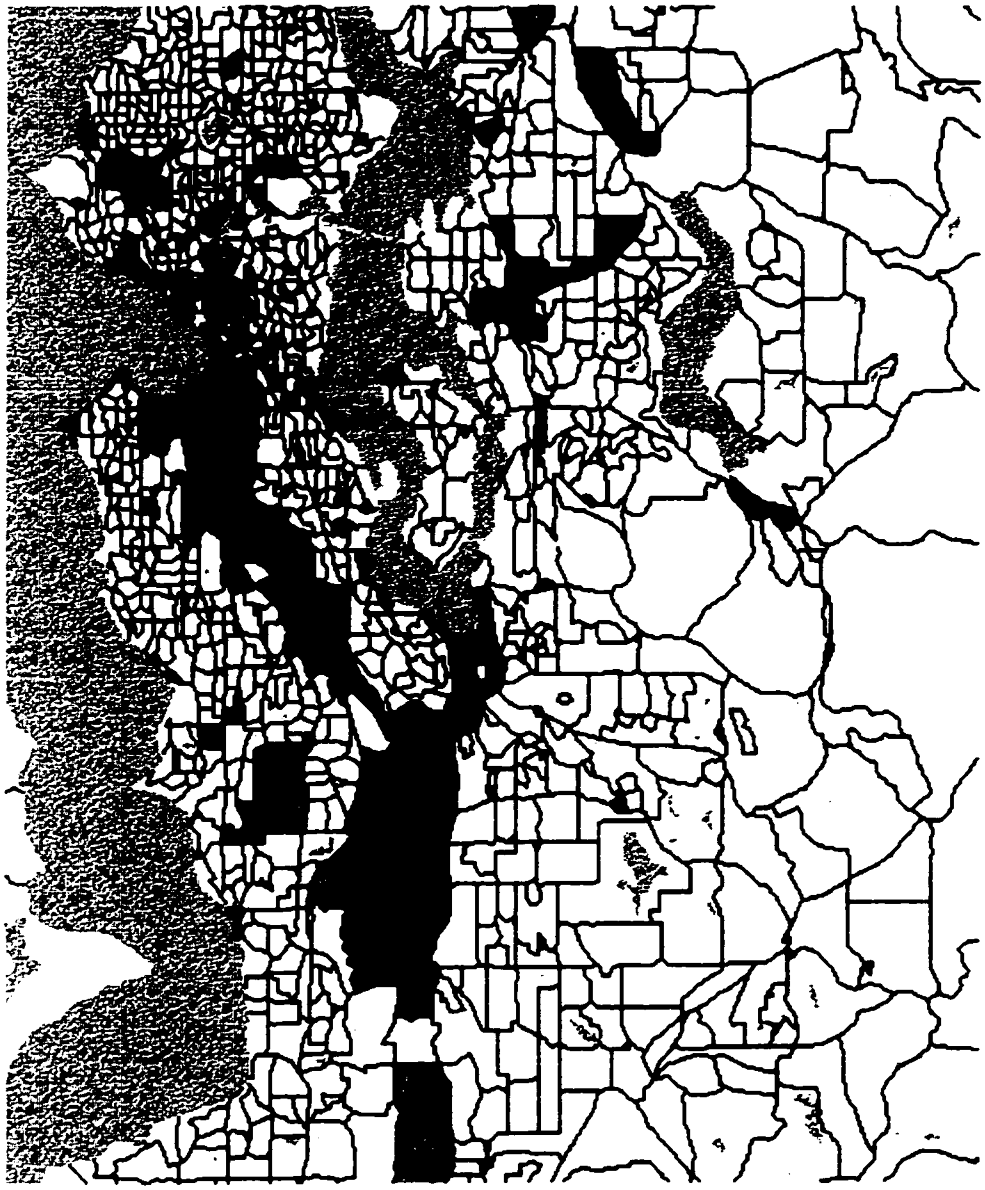


Figure 2-19. Difference in predicted versus observed impervious cover based on population density regression from Figure 2-16. Areas shaded in red have higher than expected impervious cover based on population density. Areas in blue have less impervious cover than expected.

Discussion

Satellite data were classified acceptably using the spectral mixing model. Predicted surface cover was close to observed values with high correlation coefficients for *impervious* and *vegetation* surface covers. *Soil* cover estimates were less accurate, but still had a significant positive correlation. Variations between observed values on the ground and satellite measures could be due to observer bias or changes with time; i.e. satellite image capture date was not the same as the field observations.

Several factors make it difficult to field test the spectral mixing model results for the V-I-S model. The most important challenge is determining the actual land cover values for a location, since it is difficult for an observer to aggregate to a 90 square meter region. Soil between blades of grass, leaves, and branches on a tree all aggregate and contribute to the final V-I-S value, yet all these surfaces are hard to measure when standing at a site.

A second difficulty in working with the V-I-S model parameters is that "impervious" is a process not a surface material. The term *Impervious* relates to a surface that is impenetrable to water, but this surface can be composed of a variety of materials. Although most impenetrable surfaces in and around urban areas are paved material, spectral surfaces vary depending on whether the material is cement or asphalt.

A third difficulty is that all cover materials are actually forced into four cover types: *vegetation*, *impervious*, *soil*, and shade which is later removed from analysis. Clearly some cover types do not fit this classification well, such as dry grass and dead wood. Many of these "stray" surface types were grouped into the soil classification. Since it is difficult to account for the stray materials during field testing, the error for the *soil* class is higher than for the *vegetation* and *impervious* cover types.

A final difficulty in the accuracy assessment is the evaluation of areas with standing water mixed with other cover types, i.e. a wetland or shoreline along a lake. These areas were not masked as water since they do not have pixels that are pure water However since shade and water are so similar, water was normalized out, increasing other land cover values in the cell. This results in high values of the cover type that is mixed with water. In the case of a cobble area along a stream, the rocks were assessed as *impervious* cover occupying 80 percent of the cell when actual values were 40 percent, with water occupying 50 percent. This problem occurs in a very small portion of the region and did not alter the results. Care should be taken to evaluate water covered areas differently when the spectral mixing model is used to evaluate lands with partial water cover.

Overall, the spectral mixing model did well considering the challenges of this type of analysis. Urban areas are inherently difficult to classify using satellite data, and the spectral mixing model seems to provide results that are more accurate than previous attempts to determine V-I-S values with Landsat images (Card 1993; Hung 1996). Improvements could be made on the spectral signature selection, atmospheric correction, and water identification. Seasonal variation is a factor that I did not included in the analysis but could improve land cover assessment. The results of the accuracy assessment and the visual inspection of the resulting maps suggests that the measurements are close enough to "truth" that they can be used for analysis.

The land cover values indicate that a biophysical gradient follows Ridd's predicted path of urbanization from industrial to forested land use types. The change from city center to rural is generally a gradual change in V-I-S cover. There is a transition zone at 20 to 30 kilometers from the city when averaging land cover for all directions. This transition correlated with distance where population density decreases. These patterns are likely due to human development. The results of converting land from forest to human settlement changes the observed surface cover, and the transition between these rural and urban regions is observed to be a gradual change over one kilometer distance rings.

Although a distance can be measured at which the general land cover changes at the edge of a city, the boundary is a part of a gradient. Often in mapping, lines are viewed as a sharp transition between classified regions. The departure from this concept has evolved into fuzzy classifications (Hung 1996) and emphasizes the importance of scale in classification. The use of gradient analysis assumes a continuum of urban impacts exist in urban environments; however, few studies have tested the assumption. In the urban-rural gradient context, land cover exhibits a continuum of change.

Direction

As expected, land cover varied along gradients in different directions. The north-south orientation of development in the Seattle region was noticeable in both *vegetation* and *impervious* values. *Impervious* cover has a steeper gradient to the east than to the north and south. When performing a gradient analysis, anisotropy (changes in values that are not equal in all directions) in land cover requires careful selection of variables in addition to distance to serve as a proxy for human impact. A distance measure is a poor indicator of ecosystem impact by urbanization when comparing distances in different directions from the city center. Based on V-I-S cover values, the rural environment is reached in 25 kilometers from the city to the east, but this distance doubles to the north.

Land use vs. land cover

Although the USGS land use data used in this comparison were intended to identify the land "use" and not the surface cover, these data are often used to estimate many ecological processes that are a function of cover. The mean land cover values for a USGS land use category fall within those suggested by Ridd. However at the 30 meter cell size, there is considerable variability in land cover values for each land use class. Even with one standard deviation from the mean, there is overlap in land cover values for a specific land use category (Figure 2-15).

Land cover is usually altered with urbanization and these results suggest that a land cover rather than land use classification is a better way to stratify and model the landscape. Many ecosystem models (hydrology, microclimate) interpret average surface cover based on assumptions that land use classifications describe homogeneous cover. This analysis shows that in urban environments and at fine resolutions these assumptions do not hold true. More accurate information for models can be achieved by directly detecting land cover. For large-scale models, land use might serve as a general indicator of land surface cover, although surface cover variability around the mean should be considered even in these models.

This recommendation does not discount the usefulness of a land use classification. Land use classifications provide information that is important to understanding ecological processes, particularly aspects of urban impacts that can not be detected by surface cover alone (Figure 2-1). The best method for urban analysis would incorporate both land use and land cover. In cases where an accurate land use map can not be created, predicting V-I-S values using the outlined techniques is a quick and inexpensive alternative method.

Population densities

Overall, population decreases with distance from city center in a non-linear fashion (Figure 2-16b) as predicted by many population models (Berry et al. 1974). Much of the Seattle population is at lower elevations, and since elevation increases with distance from city center, it is impossible to attribute population density solely as a function of distance. The distance at which the population density reaches 0 is close to the distance at which *impervious* cover reaches the background value. Even though population density is very closely correlated with *impervious* and *vegetation* cover at the one kilometer scale, the variation around the regression is high for the finer scaled analysis (Figure 2-17). This finding indicates that population density alone may not be a good indicator of human alteration of land cover at a given site. The errors are most apparent in areas that do not have a high population density, but do have a large change in surface cover. Industrial areas to the south of Seattle illustrate this error, where there is more impervious cover than predicted, as do parks where there is less impervious cover.

Conclusion

Researchers continue to study the influence of land cover on ecosystem processes in human dominated systems, but investigators can take advantage of information about land cover variability in studies on urban-rural gradients. Estimates of urbanization that use distance, land use, or population density may be satisfactory for large-scale approximations, but fine-scale predictions are inaccurate. The analysis of the Seattle region shows that there is a V-I-S gradient, with low *vegetation* and high *impervious* cover in the city. When averaging in all directions, these values change gradually to low *impervious* cover and high *vegetation* in the rural areas.

I have provided a method of measuring land surface cover using satellite data that is relatively inexpensive, accurate, and rapidly obtained. These measures are comparable over time and space and could be used to study surface cover changes over time or compare the surface cover of different cities. These results could be used to answer important questions about urban change in specific cities. With a better understanding of urban impacts on the environment, planners can more effectively mitigate these impacts in existing and new urban developments.

CHAPTER 3: LANDSCAPE ANALYSIS OF THE SEATTLE WASHINGTON URBAN-RURAL GRADIENT

Abstract

Investigators are increasingly using gradient analysis techniques to assess human impacts on ecosystems. Few studies however, have incorporated landscape patterns to help measure the degree of human impact along an urban-rural gradient. Current thematic land-use classification methods make it difficult to evaluate landscape patterns across urban and rural areas since they are treated as separate and distinct regions. Methods that are developed for landscape level analysis in and around urban areas must use well-defined variables that have meaning across diverse regions. A spectral mixing model was used to classify satellite data into biophysical measures of land cover. These measures are based on a percent cover for each pixel in the image. Following the V-I-S model developed by Ridd (1995), I classed land cover as the percent cover of vegetation, impervious, and soil in a pixel. In addition, a more traditional supervised classification method was used to identify forested areas and evaluate landscape changes of forest patches along the Seattle, Washington urban-rural gradient. These combined techniques allow for comparisons of land cover and landscape pattern. My objectives in this paper are to illustrate methods for analyzing a landscape using V-I-S data and to compare the results with landscape analysis using thematic land use data. Results from analysis of thematic data supported V-I-S analysis, but are problematic to apply in an urban-rural gradient context. The V-I-S techniques used to assess landscapes show promise for future urban-rural gradient studies examining ecological processes.

Introduction

Recently ecologists have been urged to investigate urbanization impacts on the environment (McDonnell and Pickett 1990; McDonnell et al. 1993; Bradley 1995; Rowntree 1995; Pickett et al. 1997). The processes being studied are complex because their relationships in space and time are confounded by the ecological mechanics of diverse ecosystems, perturbation, and natural resource extraction. Both environmental and urban scientists are emphasizing the study of the transition from urban to rural regions using gradient analysis to study human impacts on natural processes (McDonnell and Pickett 1990; Pickett et al. 1997). Studies that have used the urban-rural gradient approach have measured impacts on: soils (Pouyat and McDonnell 1991; Pouyat et al. 1995), species diversity (Blair 1996; Guntenspergen and Levenson 1997), forest structure (Medley et al. 1995), and land cover (Wear et al. 1998). Landscape ecology is the study of pattern on process, and little work has been done to look at land cover patterns along urban-rural gradients.

My objectives in this chapter are to illustrate how satellite data can be processed to provide biophysical land cover information that can then be used to assess landscape patterns. These results will be compared with other techniques traditionally used for landscape analysis. Landscape level studies along the urban-rural gradient pose interesting challenges. The techniques and results presented in this chapter are explorations of some additional forms of analysis to provide knowledge about complex urbanized regions.

Review - Landscape approaches to urbanization

Landscape ecology is the science investigating the link between ecological patterns and ecological processes (Gustafson 1998). The field of landscape ecology provides the techniques needed to assess landscape patterns (Turner 1989; Cullinan and Thomas 1992). By comparing urban patterns with rural patterns, investigators can better understand the importance of landscape pattern in urban areas.

Sharpe et al. (1986) conducted a study in Wisconsin looking at the change in patterns as land was converted from field and forest patches to suburban developments. They found that there was a trend toward removal of native vegetation from the rural regions, but that there was no overall change in vegetation cover. The creation of small parks, fence-rows, and street and yard vegetation in suburban settings was enough to balance the amount of native vegetation removed from the rural areas. This illustrates how urbanization can alter vegetation patterns without altering the amount of vegetation.

This point is also illustrated in a study by Medley et al. (1995). In examining a transect that extended 140 km out of New York city, the investigators found that forest patches increased in size and urban patches decreased in size in a non-linear relationship with distance from the city center. The greatest change in values was in the suburban regions, also known as the urban-rural interface (Bradley 1984).

A study conducted in southern Ontario by Ouellet and Snuffling (1992) documented a gradual fragmentation or "nibbling away" of sensitive areas by housing developments. The authors attributed this change to the desire of residents to live outside the city in a rural setting but still close enough to commute to the city. Homes were built in the woods to provide a natural setting. Although this development pattern did not alter the shape of the forest patch, it did alter patch condition. These examples illustrate possible effects of a decentralizing population, changing both the pattern and condition of a landscape.

Investigators have also measured landscape patterns generated by natural resource extraction. An analysis of a northern Wisconsin forested region by Mladenoff et al. (1993) showed that human-disturbed areas had smaller patches with simpler shapes than older unmanaged areas. This pattern was also found in a study of forest to cropland conversion in Louisiana (Krummel et al. 1987). In a study of managed forest lands in western Oregon researchers found a similar transition to smaller patches, but the smaller patches became more irregular in shape (Ripple et al. 1991). The irregularity was attributed to an effort to maximize timber production and harvest to all naturally imposed boundaries, such as riparian areas. Amount of patch edge increased with human disturbance in all three of the above cases.

Classification methods in landscape analysis

All of the studies mentioned above included landscape analysis using thematic classifications and indices measuring the classification patterns. Numerous indices have been created that describe properties of landscape pattern such as connectivity, diversity, or fragmentation (Turner 1990; Cullinan and Thomas 1992; Gustafson 1998). These measures require investigators to classify the landscape into thematic units before assessment. A classification is the simplification of information found on the earth's surface by grouping features together (Aronoff 1989; Lillesand and Kiefer 1994). In many examples the classification used will determine the patterns observed as suggested by Bradshaw and Garman:

> "Two landscape patterns may vary in terms of their composition, spatial arrangement of units and variability through time. Thus it is often insufficient to classify a given landscape with a single statistic. In fact the identification and definition of components composing a landscape pattern in itself will determine what form the pattern will take and therefore distinguish it from other patterns."
>
> p538 (Bradshaw, 1994)

If landscape patterns are sensitive to classification methods and, as discussed in Chapter 2, many land-use classes vary dramatically in biophysical land-cover composition, then of what use are landscape pattern measurements? The problem stems from the subjectivity of many classification methods. While most landscape pattern techniques have used thematic data to describe ecological functions, use of continuous data is often the best method of recording some environmental and ecological conditions (Gustafson 1998).

An alternative approach to using a thematic land-use classification system is to focus on continuous biophysical land cover measures. Ridd (1995) presents a V-I-S model that uses vegetation, impervious, and soil land cover to analyze urban environments (Figure 3-1). In Chapter 2 I demonstrated the usefulness of this model in assessing an urban-rural gradient and some advantages over traditional measures of urbanization.

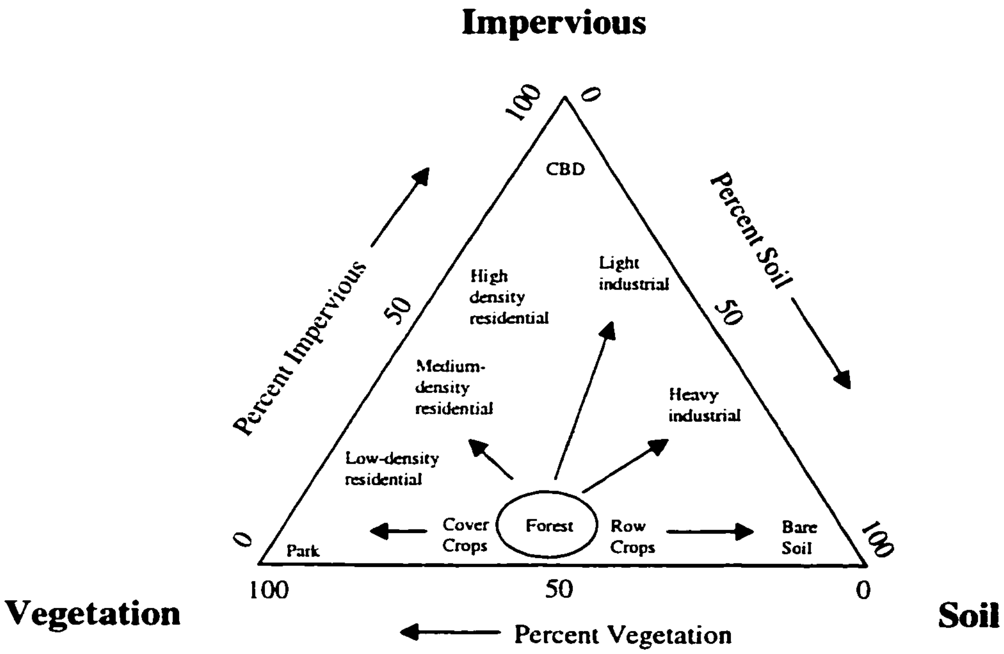


Figure 3-1. V-I-S model proposed by Ridd (1995), illustrating land cover for a point as the percent of three land cover compositions; vegetation, impervious, and soil. Within this conceptual ternary diagram are different land use categories, and the prediction of change in land cover from a forested to subsequent urbanized landscape.

The V-I-S measures can be beneficial in models that assess biophysical and human systems. Since percent cover of vegetation, impervious, and soil surfaces is a continuous and quantitative measure, the values determined at one location can be compared to other sites, both in the same satellite image and at different cities. Traditional land use classes can often be vague and difficult to determine. Housing density in a desert community may be very different in biophysical cover from a similar housing class in a moist temperate community. The V-I-S approach can help standardize land-cover measures across diverse regions such as those found along urban-rural gradients. Definitions for the cover types are as follows:

Vegetation: Green vegetation at time image was acquired. Does not include vegetation that is dead or not green. Actually is related to the chlorophyll in the vegetation (Myneni 1994). The typical spectra found for vegetation is low red and high infra-red reflectance.

Impervious: This is a process, but spectrally is connected to surface types that are impermeable to water. Materials are typically cement, and asphalt, but natural rock is counted also. It is important to note that satellites do not directly measure a process and materials that generally are impermeable may spectrally appear as soils. In most cases impermeable materials are bright in the visible spectrum and lower than soils in the near infra-red.

Soil: This cover includes dirt and gravel as well as non-photosynthetic vegetation (NPV). NPV materials include tree bark, dead grasses and exposed wood. Typically *soil* varies from *impervious* cover by lower reflectance in the visible spectrum and higher values in the near and mid infra-red.

To gather land cover data for the V-I-S model, I used a spectral mixing model to classify satellite data. Details of this method are described in Chapter 2. The final product from the mixing model is the percent cover in a pixel. Cover can be *vegetation*, *impervious*, and *soil*. The combination of these three elements must add to 100 percent, and I assume that all surface materials can be described using these three variables. Pixels that are not assessed include areas with cloud cover, water, and topographic shadow.

I used land cover (V-I-S) in place of land use (e.g. Anderson classification), to evaluate landscape patterns along a gradient. Landscape ecology traditionally evaluates patterns in a single image, or using polygon classes that are within the image. Continuous data such as percent vegetation does not allow calculation of the polygon shapes. Since a gradient is being evaluated (as shown in Chapter 2), a statistic for the entire image can be misleading. An example of a landscape analysis using continuous data is a study by Riera et al. (1998) evaluating heterogeneity of vegetation indices for several regions and correlating with land use and topography. The continuous data used in the study was calculated using a vegetation index. They measured pattern as the standard deviation of vegetation values within a moving window.

Other studies have looked at heterogeneity and spatial autocorrelation within images by using semi-variograms (Woodcock et al. 1988; Cohen et al. 1990), fractals (Milne 1991; With 1994; Pastor and Broschart 1990; Krummel et al. 1987), and wavelets (Greenberg et al. 1997; Jones 1996; Jawerth and Sweldens 1995). Although these techniques use continuous data, variogram and fractal analysis are total image analysis tools that are sensitive to both change in size and position of the image extent. Small changes in the analysis region can have very large changes in the values produced (Cullinan and Thomas 1992; Turner et al. 1989b). In addition, these methods assume isopotry, or lack of spatial trends, which does not apply in a gradient analysis. Wavelet analysis uses moving windows and multiple scales to decompose an image (Jones 1996). Although this technique shows much promise for landscape analysis (Greenberg et al. 1997), the algorithms are not found in many remote sensing software packages. The software that does exist to calculate wavelets is limited to smaller image sizes than needed for urban-rural gradient analysis. In addition, the results of wavelet analysis vary depending on the "mother wavelet" and are difficult to link to real processes that exist on the ground.

The objectives of this chapter are to illustrate landscape analysis methods using V-I-S data, and to compare these results with thematic land use data analysis.

Methods

The Seattle image was unmixed as described in Chapter 2. Output from the model produced three different images with values ranging from 0 to 100 percent cover. The cover values of vegetation, impervious, and soil sum to100. I created a mask to restrict analysis of regions covered by clouds, water, or shadow from topography. All subsequent calculations did not include these areas.

In this study I assess the landscape using both the continuous data from the mixing model, and thematic data determined using supervised satellite image classification. For both of these data sets, landscape measures are calculated (Figure 3-2). For the V-I-S data I used different measures of pattern in moving windows to calculate heterogeneity. In addition, a smoothing analysis is used to demonstrate how the landscape context of a point can be examined using continuous data. I focus the thematic classification on forest classes by delimiting forest patches and determining patch size and amount of edge.

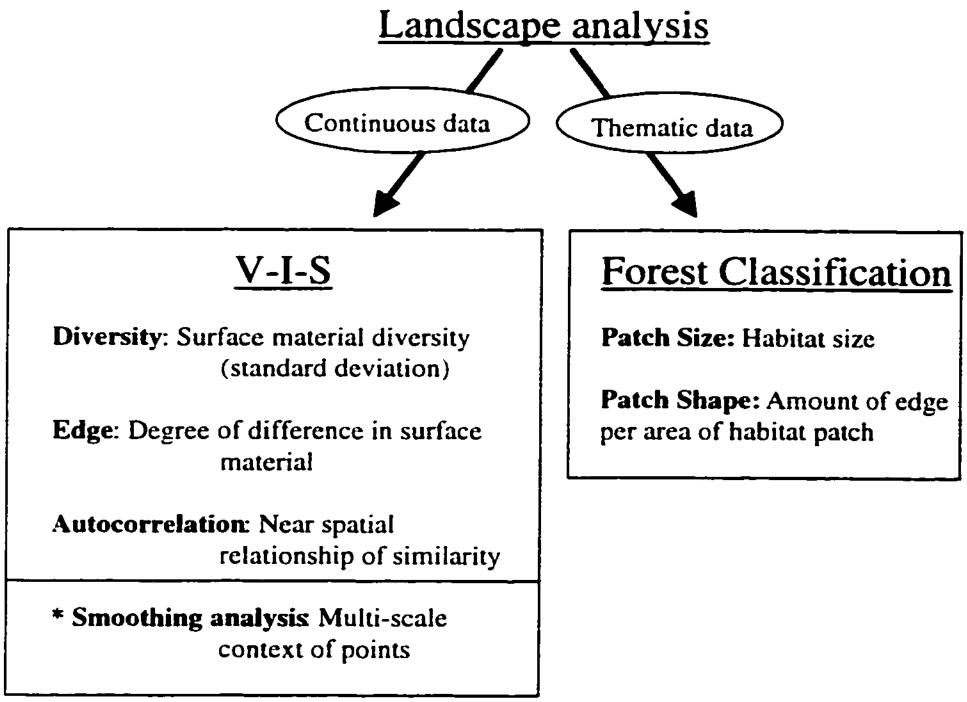


Figure 3-2. Overview of measures made with V-I-S continuous data and with thematic data.

Landscape analysis with continuous data

Heterogeneity is the uneven and non-random distribution of objects in space (Forman 1995). The measure of heterogeneity is critical to comprehending most ecological processes (Farina 1998). Heterogeneity can be calculated in a number of ways (Li and Reynolds 1995). This analysis will use three common measures of heterogeneity; diversity, edge, and autocorrelation.

Diversity

I calculated diversity as the standard deviation of cover values (Riera et al. 1998) for a moving window that is three by three pixels in size. The standard deviation of the window is recorded for each central cell, and by moving the window over the entire image, every cell is given a value. When the mask covers any of the cells, the window is skipped, as are windows where there is not enough data to fill all 9 cells of the window. For quantitative analysis I averaged the standard deviations for every one kilometer-wide band from the city center. High diversity values (standard deviation) for a cover indicate high variability in cover values. If the amount of cover is similar within the analysis window, the diversity values will be low.

Edge detection

Edges are important in landscape ecology for their habitat and the boundaries they create between the two adjacent homogenous patches. Edge regions are often associated with environment change, natural disturbance, or human disturbance (Forman 1995). Edges can be detected either as the region between two homogenous patches, or as boundaries created by areas that have high spatial change (Fortin and Drapeau 1995). When using continuous data from the V-I-S model, the spatial change method is more robust. Spatial change was measured as the "slope" of the land cover values. Slope was calculated using the average change in the x and y directions of a three by three cell window and recorded as percent slope for vegetation and impervious cover. This technique identifies an edge region where cover changes greatly in a small area. Edges were defined as the threshold of slope values that are greater than two standard deviations from the mean image values. All cells greater than two standard deviations were classed as edge, and cells with values lower were classed as background. I classed both *vegetation* and *impervious* cover using this method.

Autocorrelation

Autocorrelation is useful to determine the scale at which processes operate (Legendre and Fortin 1990) and important in the selection of study sites (Fortin et al. 1989; Jeffers 1988). Spatial autocorrelation was calculated using the Moran's I statistic within 2 kilometer distance zones and 8 compass directions for each of the land cover types. Moran's I is a measure of the similarity of neighboring cell values. Cells with similar values that are near each other will be highly correlated, while those with different values are not spatially correlated. Autocorrelation is similar to the diversity measure but is made over a larger region. Values for Moran's I vary from +1.0 to -1.0 with +1.0 being highly correlated, zero indicating spatial independence, and -1.0 indicating segregation (Arc/Info v7.2; Fortin et al. 1989).

Forest thematic comparisons

Forest areas were identified using a combination of unsupervised and supervised classifications of the satellite image. I identified forest sites for the supervised classification using Digital Orthophotographs Quarter-Quadrangles (DOQs) taken between 1991 and 1992 and registered to the satellite data. Areas with estimated tree cover greater than 50 percent were selected as forest. An accuracy assessment was made on the forest classification using DOQs and stratified random sampling of 63 points (44 in non-forest, 19 in forest). Overall accuracy of the forest classification was 93.6 percent resulting in a Kappa statistic of 0.86. All errors were reviewed; using the raw satellite data, I identified these errors as recently cleared forest areas that were not captured in the DOQ images. With the omission of sites with recent change, the accuracy assessment was 100 percent. Forest stands were identified from the forest classification based on adjacency in all non-diagonal neighboring cells. Every cell was given the value corresponding to the size of the forest patch that surrounded the cell. These data were averaged over a one-kilometer distance from city bands to provide the mean forest patch size at a given distance.

To calculate forest patch shapes, I converted the forest thematic raster image to polygons. Forest patches were selected that did not intersect the image extent and were larger than 10 hectares. This eliminated many small forest patches that could not be assessed for patch shape since they were heavily influenced by the pixel shape. This also eliminated the largest patch in the image because it extended beyond the north and south edges of the image.

Shape index was calculated using the equation:

$$SI = \frac{2\sqrt{\pi \bullet a}}{p} \qquad (1)$$

where a is the area of a patch and p is the perimeter. This equation provides values ranging from 1 for a circle to 0 for increasingly complex shapes. SI is a measure of the relationship between area and perimeter of a patch. It is often intended to provide an estimate of the convolution of a patch. SI values are then related to both patch core habitat and amount of edge habitat (Forman 1995). This equation is not responsive to the size of the stand, meaning that a large square and a small square will both have the same SI value of 0.886. The SI was calculated for all selected forest polygons.

All forest polygons were also assessed for mean land cover using the spectral mixing results. I calculated the mean *vegetation*, *impervious*, and *soil* cover for each forest stand. To calculate the distance of a stand to the city center, a grid was made with the same 30 meter grain as the images. Each cell was a measure of the distance from the cell to the center of the city. This distance grid was then used to calculate the mean distance of each forest polygon to the city. This technique creates for every polygon an area-based mean distance from the city.

A smoothing method

Although the neighborhood analysis provides useful measures, I developed a multi-scale approach to view and assess the continuous V-I-S results. Usually when continuous data is resampled, the cell sizes are increased. This can create false boundaries on the edges of the cell that might not accurately describe the pattern at a point. In the smoothing approach, data were resampled but in order to maintain the spatial patterns, pixel sizes were kept constant. To do this a focal analysis was performed to calculate the mean cover type within a given radius of a point. While this method is computationally intensive and samples a point multiple times, it also allows regional cover values to be determined specific to any point in the image. Focal radii distances where selected at 1,3,10,20,40 and 80 pixels (28.5, 88.5, 285, 570, 1140, 2280 meters), providing a regional cover average up to 1,633 hectares around a point. These focal average images were stacked together to allow the software (Erdas -Imagine) to interpret the multiple focal scales as bands. In addition, an unsupervised classification was performed that groups regions together based on their multi-scale regional values. To illustrate the usefulness of this technique, I selected three contrasting forest patches. Location of the forest patches are shown in Figure 3-3. Forest patch 1 is a city park with large trees and high forest cover. Patch 2 is a forest immediately surrounded by development but located 25 kilometers from the city. Patch 3 is equally far from the city center, but lies in a large state-owned forest area. At each patch a point was sampled and compared at varying focal smoothing sizes. Using the classification data for all the focal sizes, similar forest (vegetation) stands were then displayed for the entire image.

Many studies use transect data in urban-rural gradient analysis. I compared results using the smoothed data from the maps and smoothing the data from a transect was made. The cover data and smoothing techniques were the same for both methods. The only difference in the approaches is that the map approach used all the data within a distance of a cell, while the transect approach only used the data along the transect. The selection of the transect will dramatically alter the data, but the trends seen should be similar. I selected two transects to illustrate this point; one directed to the east of the downtown and the other to the south (Figure 3-4).

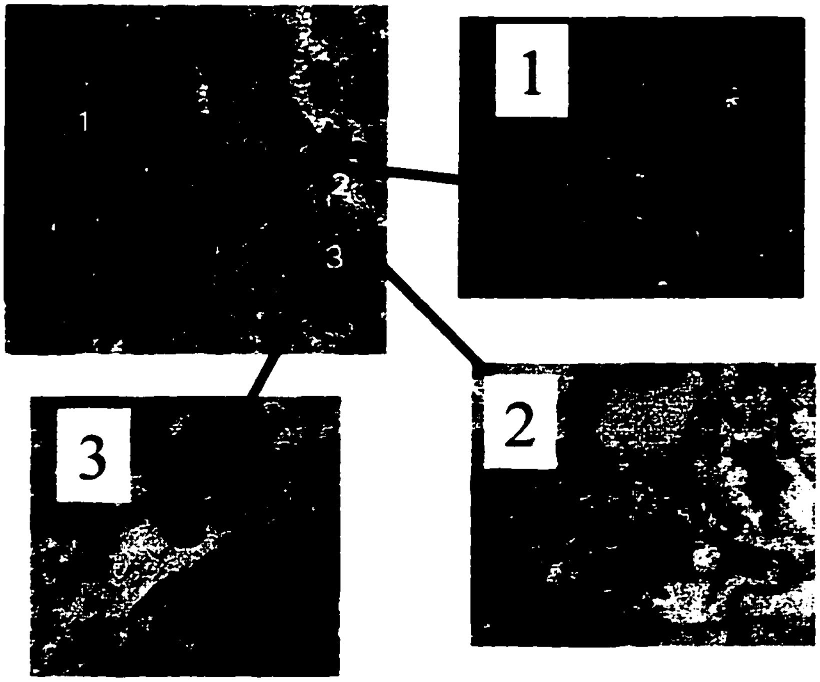


Figure 3-3. Location of forest patches used to illustrate rescaling technique. Site 1 is an urban park. Site 2 is small forest patch surrounded by some suburban development. Site 3 is a large state managed forest. Image is raw TM data, bands 5,4,3.

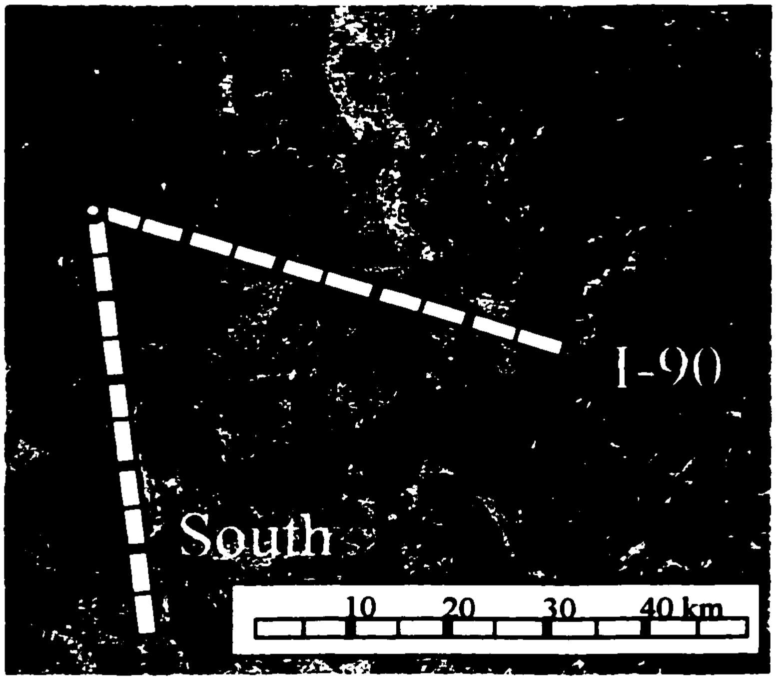


Figure 3-4. Location of transects used to illustrate differences in smoothing analysis between a transect and a map approach. Transects are "I-90" to the east along the highway corridor, and "South" along a development corridor. Image is raw TM data, bands 5,4,3.

Results

The spectral mixing model correctly captured biophysical cover properties based on the results of the analysis. High values of *impervious* cover occur in the downtown region and in the mountains in non-vegetated rocky outcrops. As expected, *vegetation* is high within city parks and forested regions outside the city. *Soils* are high in agricultural areas, recent forest harvest patches, and areas where vegetation seasonally dies. Chapter 2 includes the details of the accuracy assessment of the mixing model. Based on an accuracy assessment of the spectral classification model, predictions of V-I-S surface cover are correct ($p < 0.005$). Correlation coefficients of $R^2 = 0.87$ for *vegetation* and $R^2 = 0.83$ for *impervious* with near one-to-one relationships: *Vegetation* regression of $y = 0.9969x - 1.6$ and *impervious* $y = 0.91x-0.97$ were measured (Figure 2-10). *Soil* was less accurate with an $R^2 = 0.54$ and regression line of $y= 0.81x + 10.86$ but still significant at the $P < 0.005$ level.

Diversity results

Diversity of *vegetation* cover was low near the urban center with a standard deviation of 6, and highest at 20 kilometers from the city center with a standard deviation of 15 (Figure 3-3). Impervious diversity was highest in the urban center with a standard deviation of 22, and continuously decreased to zero at 60 kilometers.

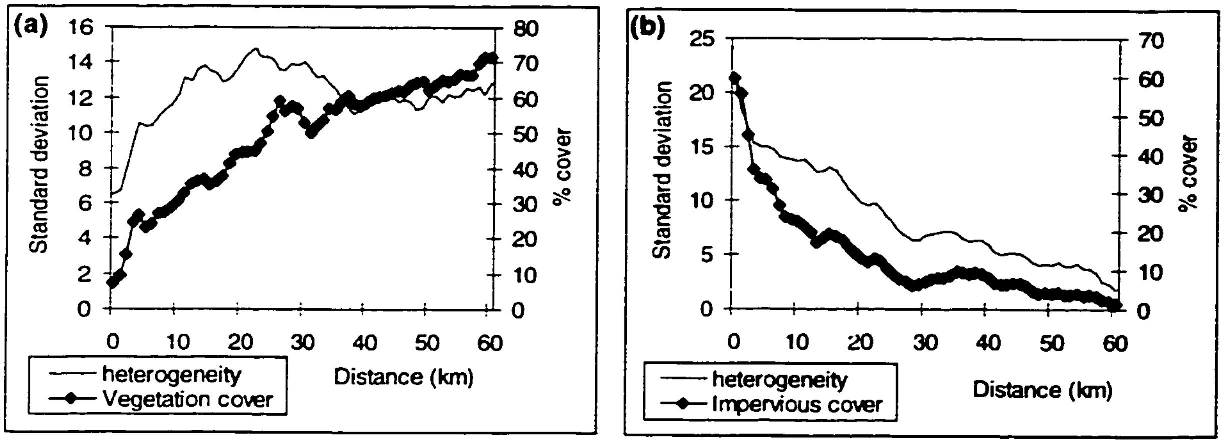


Figure 3-5. Comparison of heterogeneity and cover values for; (a) *vegetation*, and (b) *impervious* cover. Heterogeneity measured as the diversity of cover values in a 3 by 3 pixel window (standard deviation of the window).

In analyzing surface cover values, *impervious* values for diversity are similar to those for percent cover (Figure 3-5b), decreasing in value with increased distance from the city. *Vegetation* diversity, however, peaked at 20 kilometers and then decreased while *vegetation* cover continually increased with distance from city (Figure 3-5a).

Edge results

Edge measures followed trends similar to the diversity measures. There are more *impervious* cover edges within the city than in rural areas, and more *vegetation* edges outside of the city. Comparing amount of edge as a function of distance from city center (Figure 3-6) illustrates a decrease in *impervious* edges and an increase in *vegetation* edges.

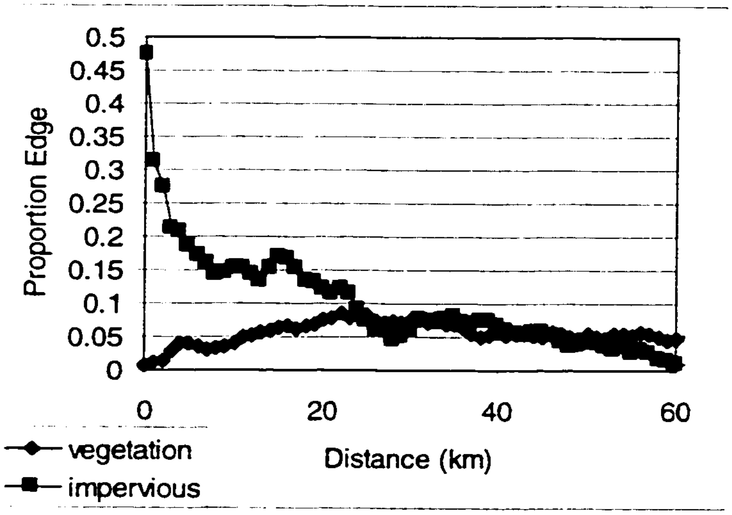


Figure 3-6. Proportion of area classed as edge for *vegetation* and *impervious* land cover in 1 kilometer distance bands from city center.

Analysis was also performed to assess if edges occur more frequently at different cover values (Figure 3-7). For example, are there higher slope values (steeper edges) with high cover values? *Impervious* cover changes more rapidly with higher amounts of *impervious* cover. This same trend was not evident with *vegetation*, for which edge steepness increases to about 20 percent *vegetation* cover, but then decreases with *vegetation* cover greater than 75 percent.

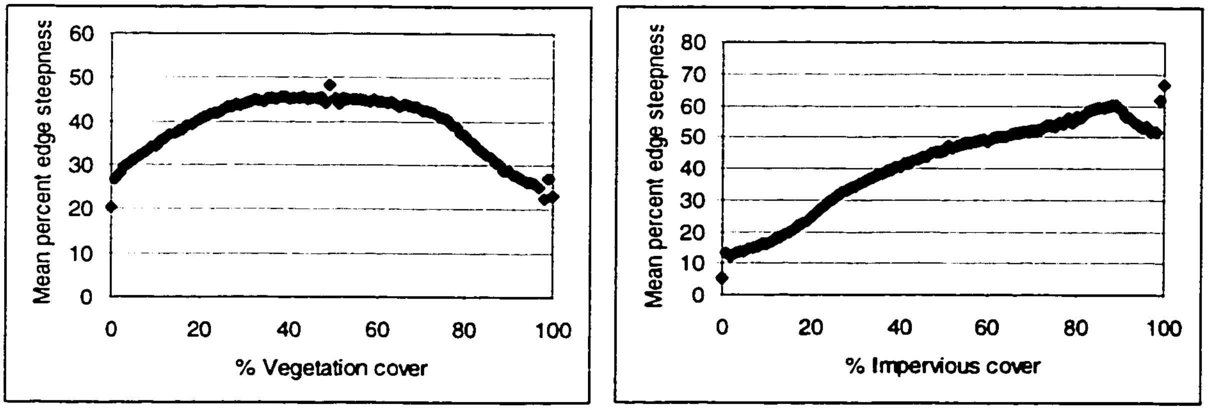


Figure 3-7. Slope values calculated as percent cover change (rise/run), and values of the cover surface used to calculate slope; (a) *impervious* (b) *vegetation.*

Autocorrelation

Spatial autocorrelation using the Moran's index produced values that ranged from 0.27 to 0.88 for *vegetation* and 0.13 to 0.83 for *impervious* cover. For both cover types, values varied but no pattern was detected based on distance or direction (Figure 3-8).

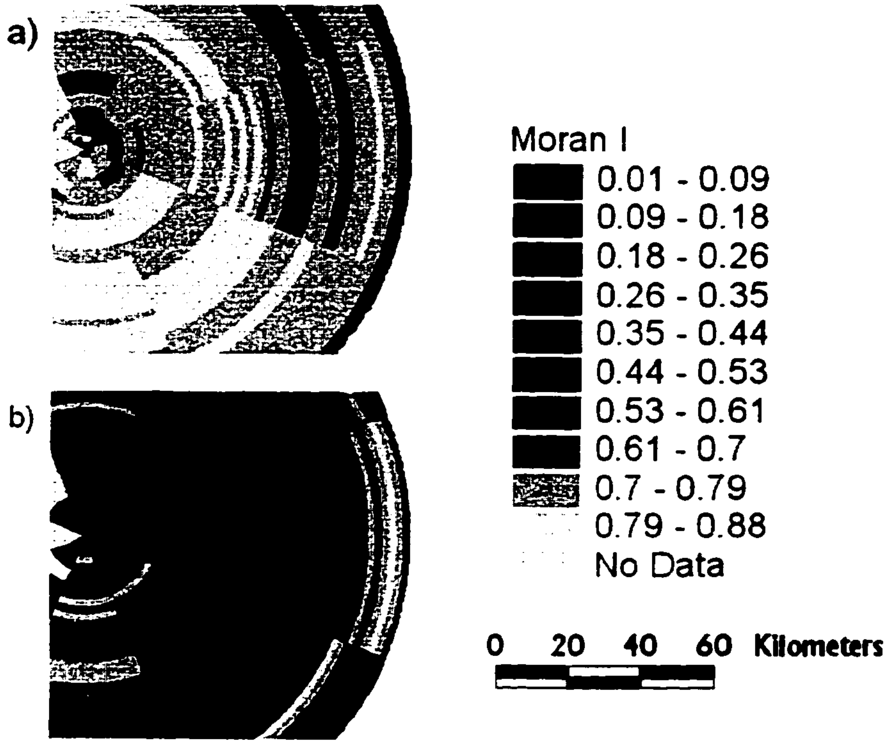


Figure 3-8. Moran's I calculated for distance (2km width) and Angle (45°) from city center. Cover types assessed are (a) *vegetation* and (b) *impervious*.

Forest thematic comparisons

Thematic classification of the forested regions provides an image of forest and non-forest regions (Figure 3-9). Before white settlers arrived to the Northwest, most of

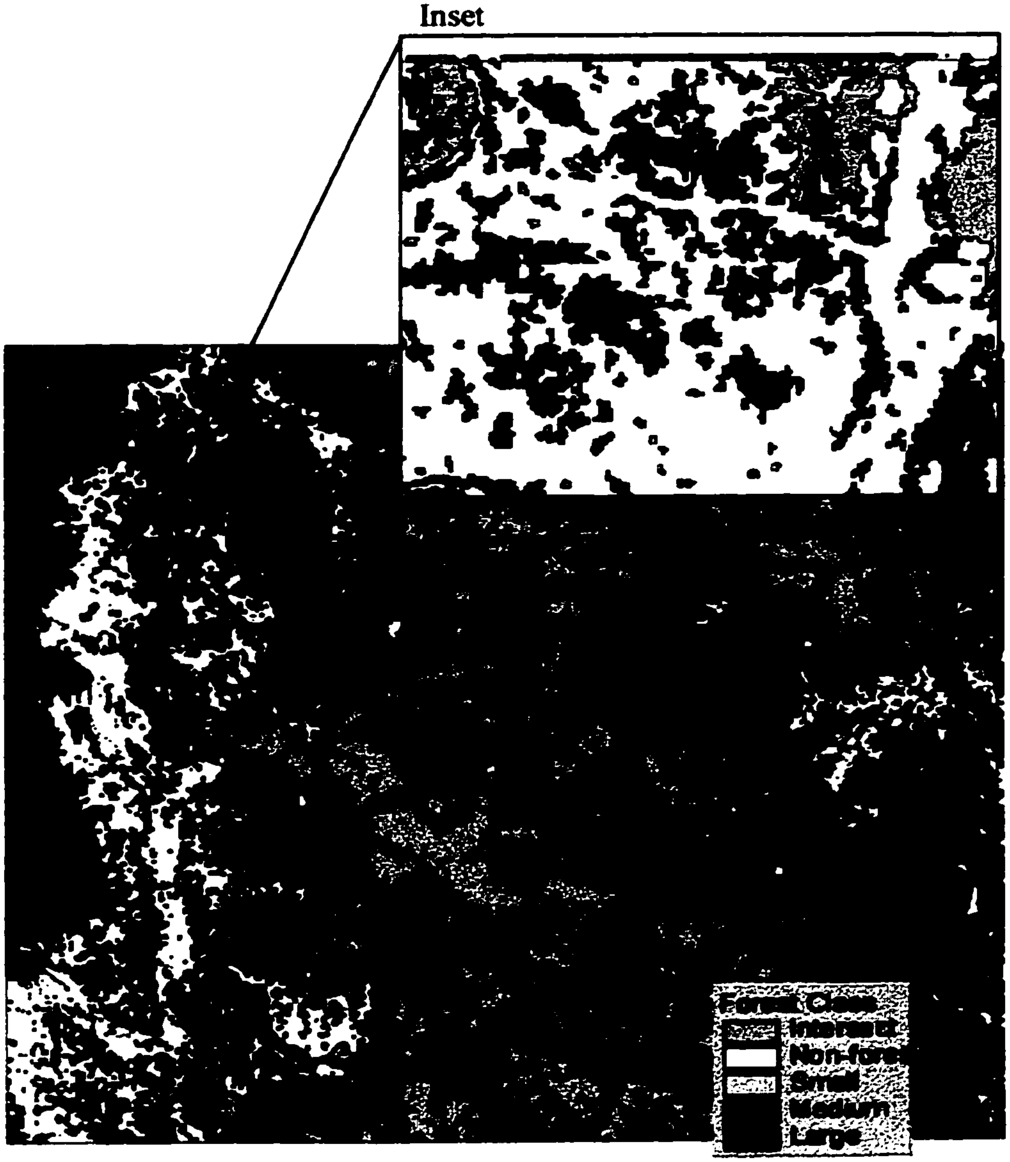


Figure 3-9. Areas classified as forest (small < 1 Ha, medium 1 - 10 Ha, large > 10 Ha). Inset provided to show details. The orange patches are forests that intersect the edge of the image. These forests were assessed for the mean forest patch analysis, but not the shape analysis. The orange forest patch to the east of Seattle is almost one large patch.

the region was covered in forests and vegetation (Van Pelt 1996). The majority of the deforestation is near coastal populated areas.

A comparison of forest patch size as a function of distance from city center shows small patch sizes near the city and an increase in size at 12 kilometers from the city center (Figure 3-10). Average patch size continues to increase up to 50 kilometers from the city center, and then stays constant at around 500,000 hectares.

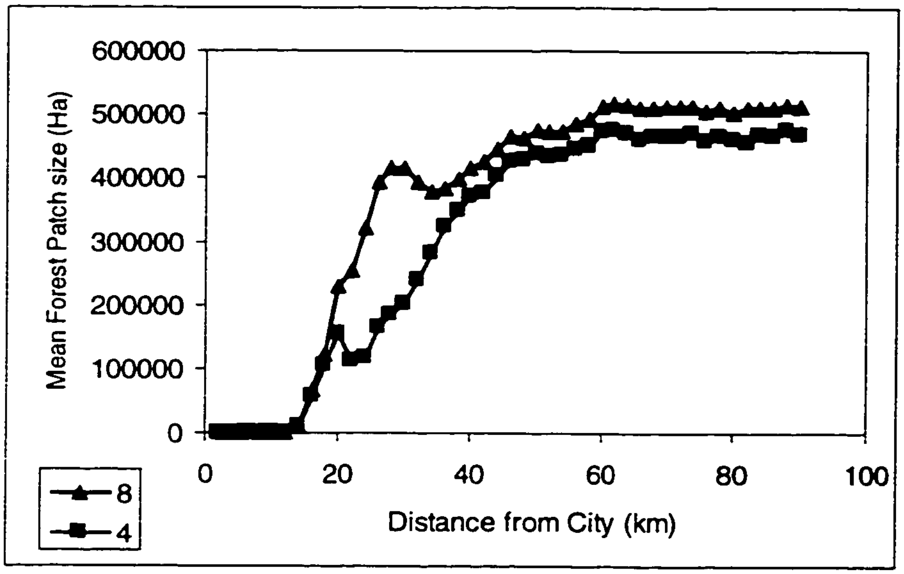


Figure 3-10. Mean forest patch size along a distance gradient, using 4 neighbor and 8 neighbor connected rules. This analysis was done using all forest patches.

This patch size pattern is similar for patches that were determined using four adjacent pixels and patches using the surrounding eight pixels. I used the four non-diagonal directions to determine patches for all subsequent analysis.

Mean forest patch size varies depending on direction from the city center (Figure 3-11). Large patch sizes are found closer to the city to the east than patches to the south or northeast.

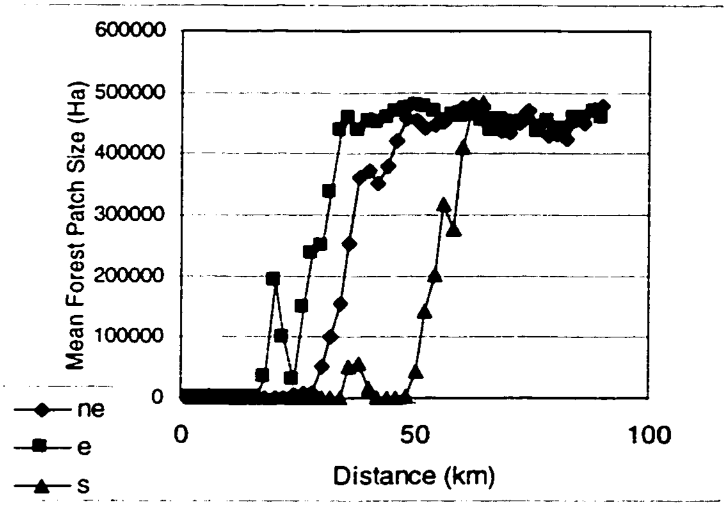


Figure 3-11. Comparison of mean forest patch size and city distance for three different directions from the city center.

When distance to city is analyzed for all directions using only the selected forest patches (10 to 10,000 Ha), there is no trend between distance and patch size, with a correlation coefficient $R^2 = 0.00$ (Figure 3-12).

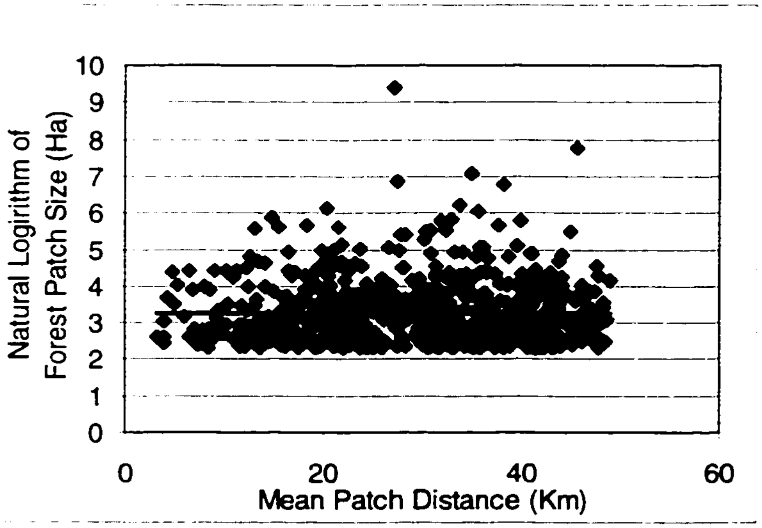


Figure 3-12. All forest stands larger than 10 Ha not intersecting the image extent. Relationship between size of stand and average patch distance from city center. Correlation coefficient is an R^2 of 0.00 and $p > 0.005$ with $n = 678$.

Likewise I found no trend relating forest patch shape and the mean patch distance from the city center (Figure 3-13).

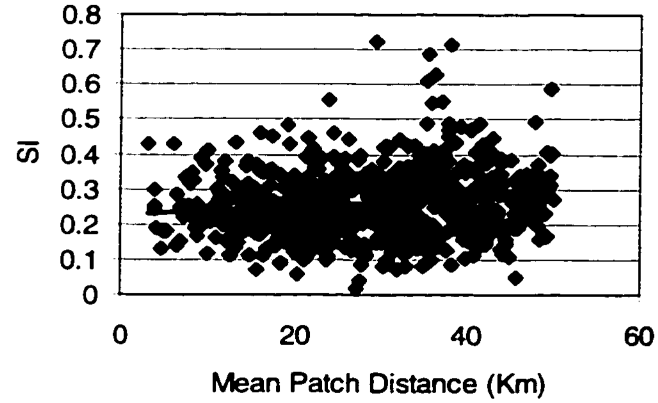


Figure 3-13. Shape Index of forest stands as a function of distance from city center. Correlation coefficient is an R2 of 0.018 and $p < 0.005$ with $n = 678$.

A comparison of thematic classed forest stands and the land cover using the V-I-S model (Figure 3-14) show that most forests are high in *vegetation*, although there is some land cover variability.

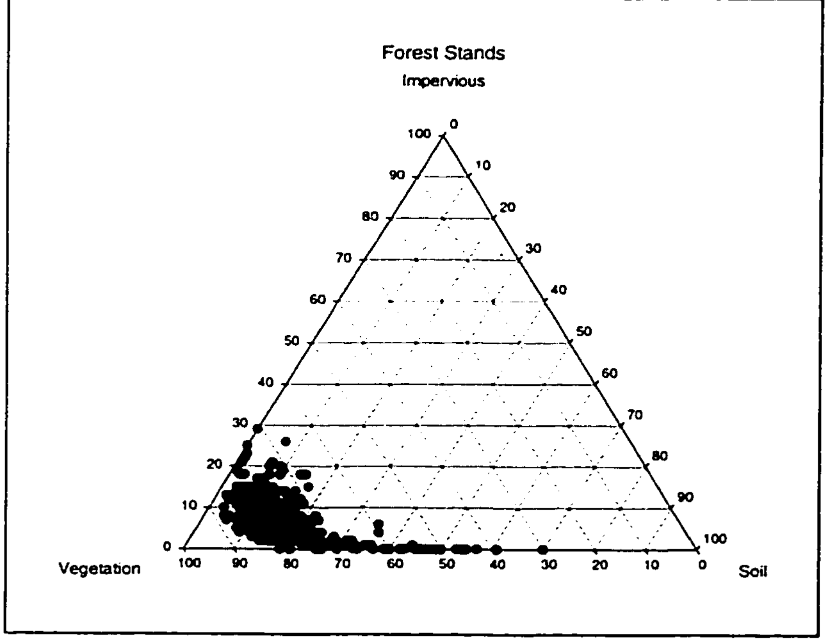


Figure 3-14. Ternary diagram of mean cover composition of forest stands between 10 and 10,000 Ha.

Smoothing

Urban-rural trends become more apparent as smoothing increases from 28.5 meters to 2,280 meters (Figure 3-15). Using smoothed data helps identify urban zones with the *impervious* cover data. Continuous forested zones are identified using smoothed *vegetation* cover data.

Smoothed data allows investigation of land cover information at a point as well as in the region. To illustrate this technique, I selected three different forest patches in the Seattle region.

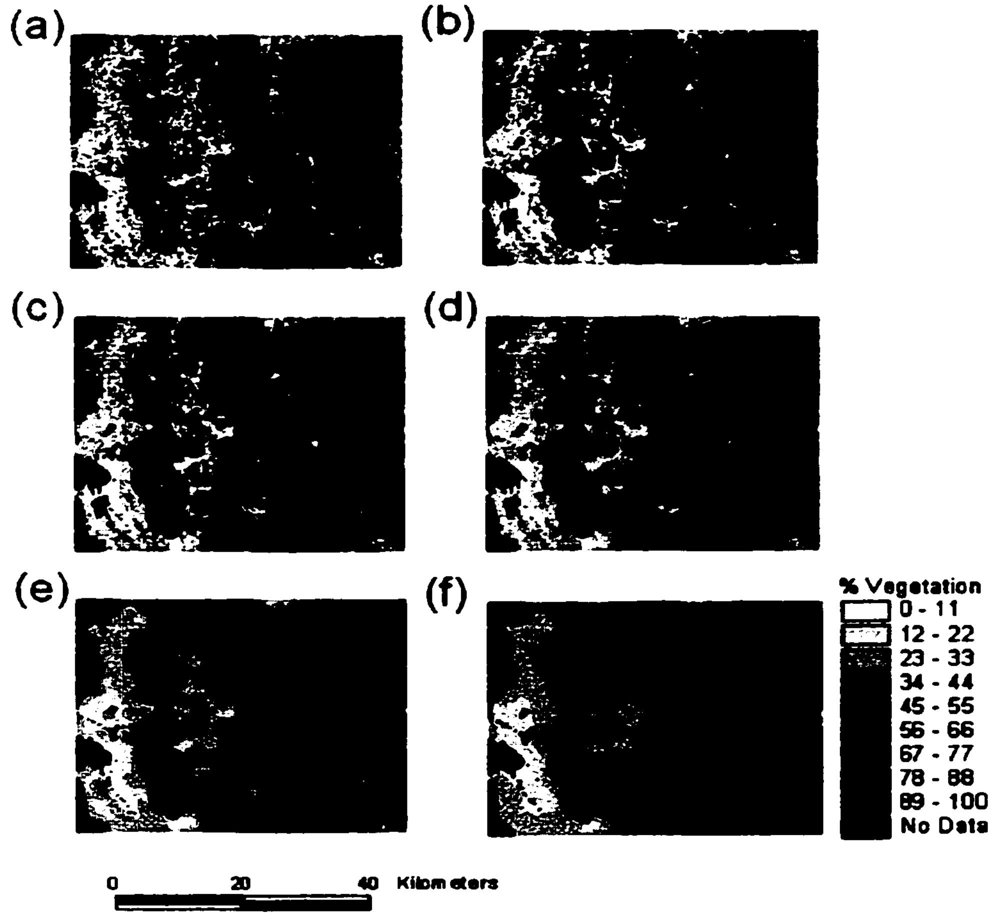


Figure 3-15. Rescaled vegetation cover, focal averages over a radius of: (a) 28.5 meters, (b) 88.5 m, (c) 285 m, (d) 570 m, (e) 1140 m, and (f) 2280 m.

The point data for these forests is very similar with values between 80 and 90 percent cover (Figure 3-16). However, if the context of the region is included in the analysis using the smoothed data, these three forests separate into distinct cover values.

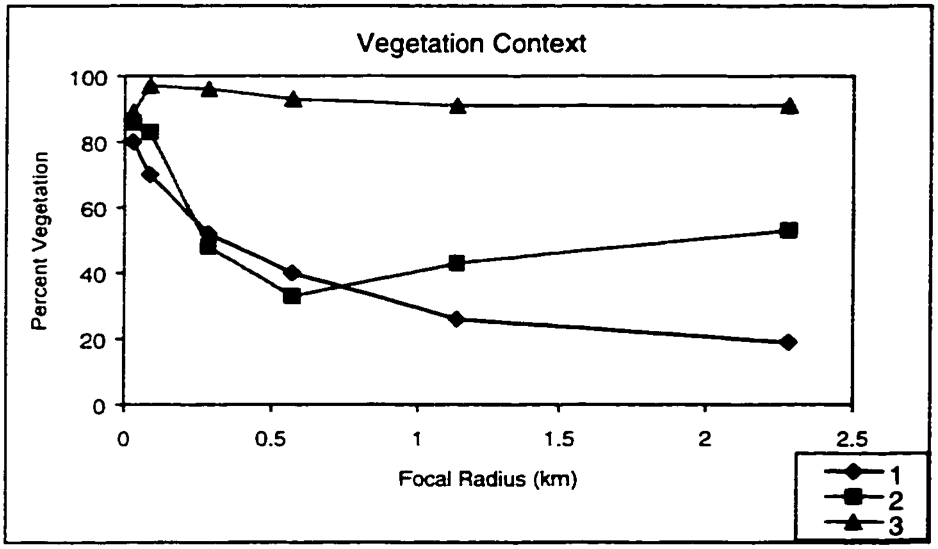


Figure 3-16. Percent *vegetation* cover changes for each of the three forest patches with increasing focal radius.

Using the V-I-S ternary diagram with the smoothed data (Figure 3-17) illustrates how the three patches vary in the regional context. Patch 1 continuously moves towards a more urbanized (*impervious* covered) location in the ternary space, patch 2 increases in *soil*, and patch 3 remains virtually unchanged with increasing the focal distance.

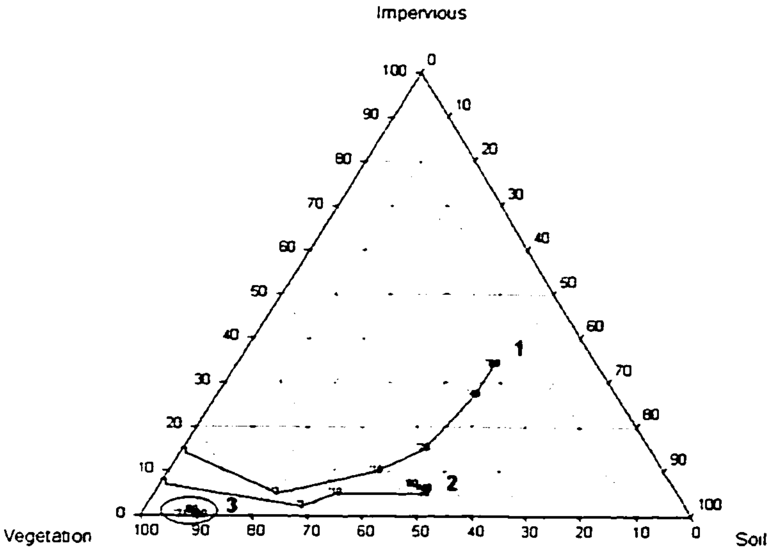


Figure 3-17. Ternary diagram using the V-I-S approach to represent cover of three forest patches with increasing focal radius from 1 pixel to 80 pixel radius distances.

I grouped the multiple-scaled data into 40 classes based on the cross-scale cover values. Signatures of these classes are based on the cover of the point and all the focal distance values for a single cover type. Using this classification, the signatures of the three forest patch classes are shown in Figure 3-18, and the location of all areas classed the same as these forest patches is shown in Figure 3-19. This method helps distinguish between a forest patch in the city, such as a park, and a forest patch outside of the city. Smoothed data provides classes that have similar point and regional vegetation characteristics. Smoothing could also be used to analyze *impervious* and *soil* land cover data.

Analysis using the smoothed data for a transect approach indicated that transect data had little to no visible trend at the original 28.5 meter scale. When the data was smoothed to 2.2 kilometers on the map (Figure 3-20), transect trends were more apparent (Figure 3-21).

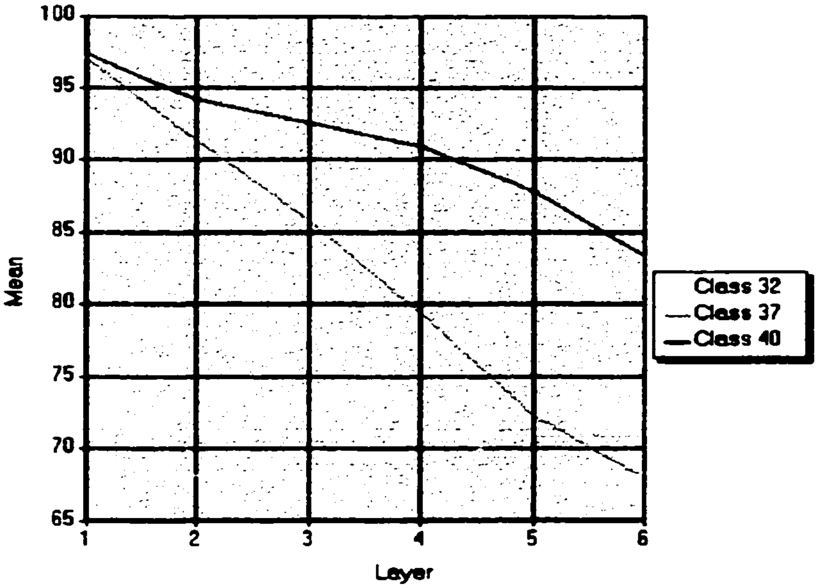


Figure 3-18. Mean signature values from multi-scale classification using unsupervised classification techniques and 40 classes. The signatures shown represent the class that covers the forest patches in Figure 3-3.

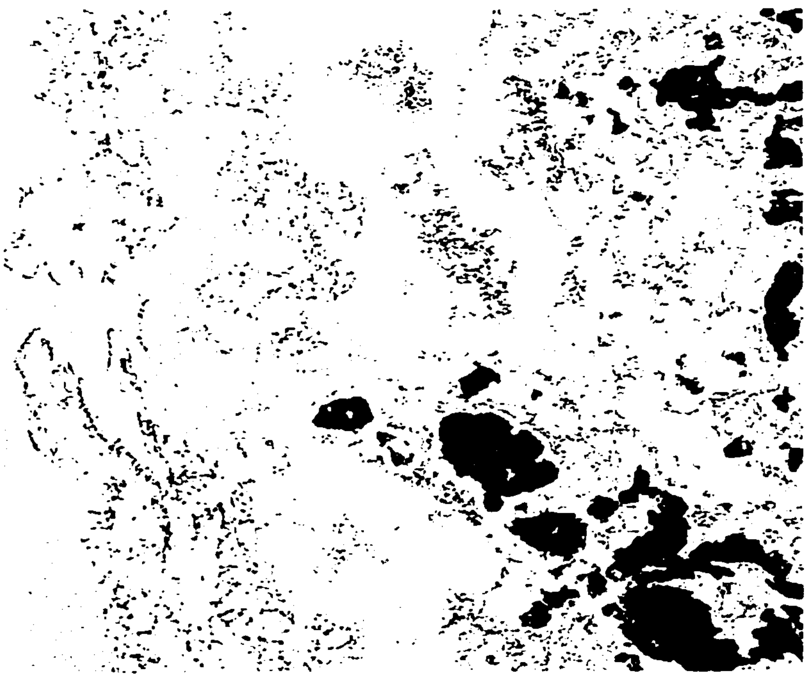


Figure 3-19. All areas that are similar to the three forest patches used to illustrate point and regional *vegetation* cover variation signatures are shown in Figure 3-17.

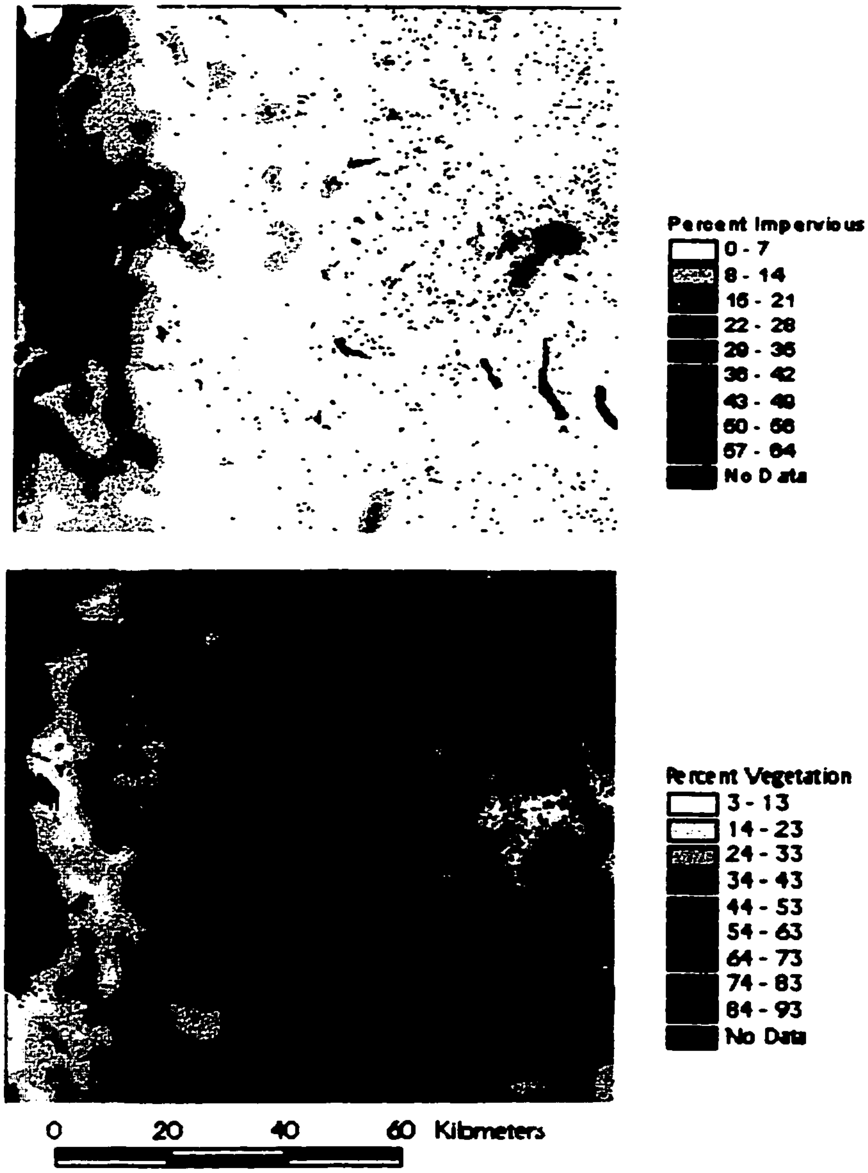
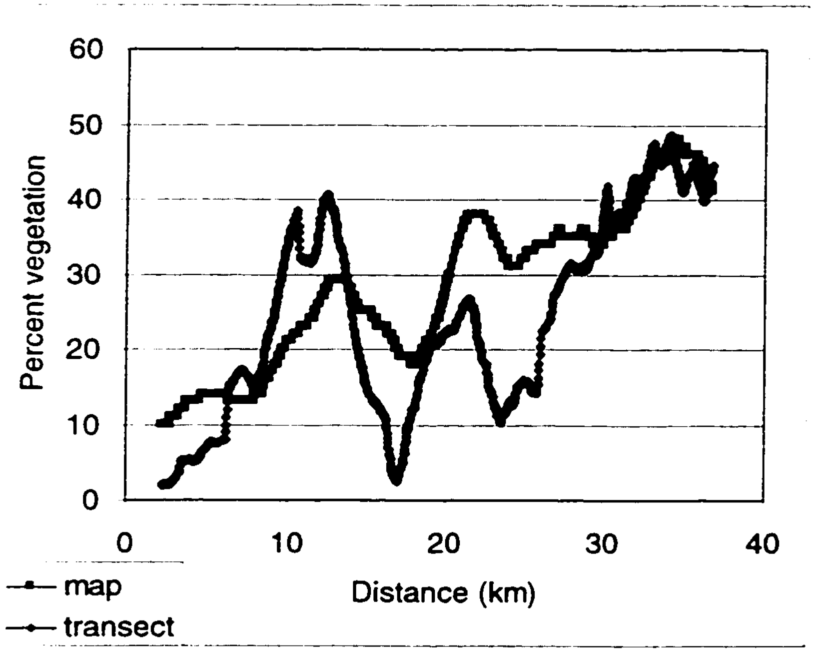


Figure 3-20. Data rescaled to 2.2 kilometer average for *impervious* and *vegetation* cover types. Smoothed data illustrate how cover does not increase in a linear pattern from the center of the city, but in a north-south oblong shape.

Surprisingly, the other approach of smoothing the data, using only the transect data, resulted in different patterns than the map data for both transects.



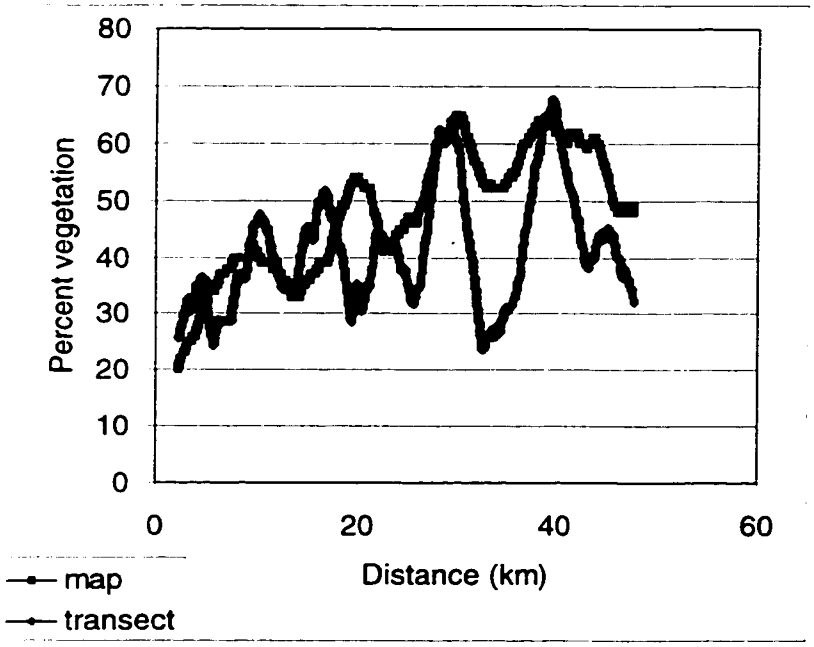


Figure 3-21. *Vegetation* cover data from transects made from city center. Data has been averaged using the mean of 2.2 km radius around a point on image (2.2km) and 4.4 kilometer mean along transect (expected). Transects are: (a) to the south; and (b) along the I-90 highway corridor.

The south transect started with 10 percent vegetation cover in the city and increased to 30 to 40 percent cover 35 kilometers from the city. Peaks in the data can be traced to suburban regions covered by the transect. The transect covers an urbanizing region between Seattle and Tacoma. The Interstate highway 90 transect starts at similar values, but reaches 60 percent vegetation cover in the mountains. In both cases the data smoothed from the transect alone had higher variability along the transect, and the gradient of change was more difficult to discern.

Discussion

In Chapter 2 I illustrated how measures of land cover can assess changes along the urban-rural gradient using point information. *Impervious* cover decreased to 28 kilometers, and *vegetation* increased steadily to the same distance but continued to increase to 60 kilometers. In this chapter the arrangement of the pixels in space was also included in the analysis. A few methods were used and many more additional techniques exist. Measures selected were chosen to capture the major focus of landscape analysis: diversity, edge, patch size, and spatial correlation.

Heterogeneity as measured in this study is greatly influenced by the overall amount of cover. If there is very little *vegetation*, such as seen in the city center, then the overall variability of *vegetation* would be low. Even at a particular point with high *vegetation* values such as a small park surrounded by roads, the overall values are expected to be low. As a result, general trends found for *vegetation* heterogeneity and *impervious* heterogeneity are as expected. *Impervious* surface cover alone is a good indicator of the amount of edge and *impervious* diversity. With increased amounts of *impervious* cover there is increased *impervious* heterogeneity and *impervious* edges. Extrapolating this relationship suggests that with increased development and creation of more *impervious* cover, there will be increased amounts of *impervious* edge and *impervious* diversity. Since *impervious* cover has some negative impacts on the environment (heat island, low water absorption, poor habitat), the impact of the increased *impervious* area may not only increase *impervious* cover but fragment the landscape as well.

In contrast to *impervious* cover, *vegetation* heterogeneity does not continue to increase with increased *vegetation* cover. At a point in between the urban and rural areas, also known as the urban-rural interface (Bradley 1984), diversity begins to decrease with increased distances from city center. A similar trend is also apparent in the edge analysis presented in Figure 3-7a. Therefore, rural areas with high levels of *vegetation* cover are more homogeneous than the transition zone of urban areas. *Vegetation* edges and heterogeneity are highest in the transition area, likely due to a high degree of landscape fragmentation from roads, houses on midsize lots, and lack of centralized development.

Autocorrelation varies within the urban-rural gradient and is only correlated with distance from the city at the city center where values are high. Moran values did not indicate trends with direction from the city. Although it is likely there is some underlying property of the land cover configuration that alters the Autocorrelation index, this property was not identified. Autocorrelation does change within the image from low Moran's values indicating un-correlated regions to high values indicating high degrees of correlation. The variation in Moran's values suggests that care should be taken when sampling the urban-rural gradient. Changes in process can alter the distance and scales at which processes operate, i.e. the distance between independent points will vary in urban and rural areas. Clearly some regions have processes that extend further in distance than other regions. These influences could be anything from microclimate around a small forest patch to pollution that affects square mile areas. Using V-I-S data, researchers can investigate the connection between spatial dependence and ecological processes.

Thematic forest classification

Logistical difficulties were encountered using the thematic forest to perform landscape analysis along the urban-rural gradient. Forests in the city are very different from forest outside of the city. Defining an urban forest involves decisions regarding the minimum tree density and patch size required for classification. Also, the large forest patches in rural areas often extended beyond the study area, making patch size and patch shape measures inaccurate. Comparisons with the V-I-S data, however, do show some similarities in the results.

The large increase in average forest patch size found between 12 and 28 kilometers is distinct. The single large rural forest patch has a strong influence on this analysis. As soon as any portion of the large forest patch is encountered in the distance band, the mean forest patch measurement is skewed higher. The fact that the forest patch size increases so sharply in the same region that *vegetation* heterogeneity is high suggests that patch size of forest stands has an impact on heterogeneity levels. Direction from the city affected the transition to larger forest patches. The edge of the largest forest patch can help determine the location of the urban-rural interface.

When the three largest patches are removed from the analysis (by selecting only those patches that do not intersect the image extent) I observed no trend in patch size and distance. Likewise, there was no correlation between forest patch shape and distance from city center. There is enough disturbance, through human or natural causes, to create a number of small forest patches outside the city, and these patches have the same shape index as those created within the city. In this particular urban-rural gradient, mid-sized forest patches do not exhibit any shape or size variations with proximity to the city center. This lack of variation contrasts with the study made along an urban-rural gradient in New York city, which did find a change in patch size (Medley et al. 1995).

Although the forest patch analysis did provide interesting information, the fact that the large rural patches are omitted due to being cut off by the image extent makes it difficult to make strong conclusions from the results. For example, the large forest patch is in fact larger, extending south to the Columbia River and north to Canada. Even if only one cell of the large patch were to extend near the city, the size of the patch will alter the statistics. Although I investigated other methods of patch calculation for this paper, the large patch problem persisted.

Smoothing approach

The smoothing approach provided an easy visualization of patterns found in land cover at multiple scales of resolution. The urban-rural gradient analysis is a concept that relies on hierarchy ideas (Lavorel et al. 1993; Klijn and Udo de Haes 1994). Any point along the gradient can have 100 percent *vegetation* cover, but the gradient concept works at larger scales of change. A park in the city may have high *vegetation* cover, but the gradient concept includes the urban context within which the park exists.

The assessment of the three forest patches illustrate that the smoothing method can classify patches along the urban-rural gradient. Most forest patches have a similar *vegetation* cover within the patch, but the regional context helps identify processes occurring outside the point that might influence the forest. This approach integrates the V-I-S, the thematic classes, and the landscape scale approaches in urban-rural gradient analysis.

The transect comparison is also interesting. Many gradient studies incorporate a transect method to sample variables. Results of the two sample transects varied depending on whether the analysis includes the entire region or just the transect. A gradient of change was more apparent when the entire image was smoothed as compared to smoothing the transect data alone. In Chapter 1, I attempted several rescaling techniques but these techniques did not help locate an urban-rural gradient change in the Eugenen Oregon region. This is an example of how the transect approach can make a gradient less apparent than a complete image smoothing approach.

Advantages to V-I-S approach

One advantage of using continuous data is that the results are comparable across both location and time. The method does not require subjective classification and allows results to be easily interpreted. This approach provides generalizations about areas because the data is ordinal and the mean can be calculated for regions of various sizes.

The V-I-S approach allows investigators to use a smoothing technique to examine landscape patterns at different scales. This technique can be used to look at both single points and surrounding regions using continuous data sources. Generalized patterns can be observed at a selected focal distance. Specific processes will have different zones of influence, and the choice of focal radius for site selection will depend on the process being studied. Clearly, there are some processes that will be influenced by land cover on a large scale, such as temperature. Other processes may be more influenced by small-scale changes such as absorption of water into the ground.

Conclusion

In this chapter I demonstrate several methods and advantages to using V-I-S data for landscape analysis. Cover heterogeneity, including measures of diversity, edge density, and autocorrelation distinguish patterns along the urban-rural gradient. Comparisons of this technique with traditional thematic classification techniques often provided similar results, but there are logistical problems with the thematic approach. The introduced smoothing approach allows a multi-scale perspective of cover patterns and can be used for contextual classifications. The smoothing approach also can reveal gradient trends that are not detected by using a transect approach alone. These tools provide additional analysis techniques and information about urban-rural gradient.

CHAPTER 4: THE USE OF SATELLITE DATA TO COMPARE THE LANDCOVER ALONG THE URBAN-RURAL GRADIENT OF MULTIPLE CITIES

Abstract

Urban-rural gradient analysis provides a useful approach to investigating urban impacts on ecosystems. Changes to the land surface structure can be evaluated by looking at changes in biophysical land cover. The V-I-S (vegetation, impervious, and soil cover) model provides a useful framework to conduct biophysical analysis of a gradient and can be applied to compare the gradients of multiple cities. In this study I compare the urban-rural gradient associated with 8 cities that vary in population, climate, and location within the United States. Within these eight cities the urban land cover is relatively similar, but the rural environments were diverse. Rural vegetation cover was correlated with precipitation, and changes in vegetation cover along the gradient were greater for wet environments than dry. Changes in impervious cover are closely correlated with population. This indicates that the extent of the built environment and the rate of change in impervious cover are connected to population size of a city. This chapter illustrates an approach that can successfully be used to compare the land cover of multiple cities with relatively low cost. These comparisons can be used to evaluate more cities, perform additional analysis, and evaluate changes over time.

Introduction

To better understand human impacts to the environment there is a need to view landscapes that include both urban and surrounding rural regions (McDonnell and Pickett 1990). Few studies have compared multiple urban-rural gradients for environmental changes using techniques that are standard across diverse regions. In Chapters 2 and 3 I demonstrated the techniques and utility of measuring biophysical land cover to investigate the urban-rural gradient of Seattle, Washington. The study presented in this chapter uses measures of biophysical land cover to compare multiple cities and relate regional changes in biophysical land cover to population and environmental conditions.

The ways in which urbanization alters the environment are complex. Land transformations, emissions, and resource extraction alter the microclimate, habitat, and hydrologic cycles (see Chapter 2). McDonnel and Pickett (1990) have suggested using the gradient analysis technique developed by plant ecologists to better understand human influences on ecological systems. The gradient technique attempts to relate the degree of urbanization to ecosystem changes. One approach to assess ecosystem change is to measure the biophysical land cover along the gradient.

In Chapter 2 I illustrated that land cover changes along the Seattle gradient are similar to those predicted by Ridd (1995) using a V-I-S model. The data from the V-I-S model is used to describe all land cover as being composed of three cover types; vegetation, impervious, and soil (Figure 4-1). Although land use is unarguably a useful classification, measures using biophysical land cover have the advantage of being detected directly with remotely sensed data, are less subjective then land use classes, and can be used in cross-site comparisons.

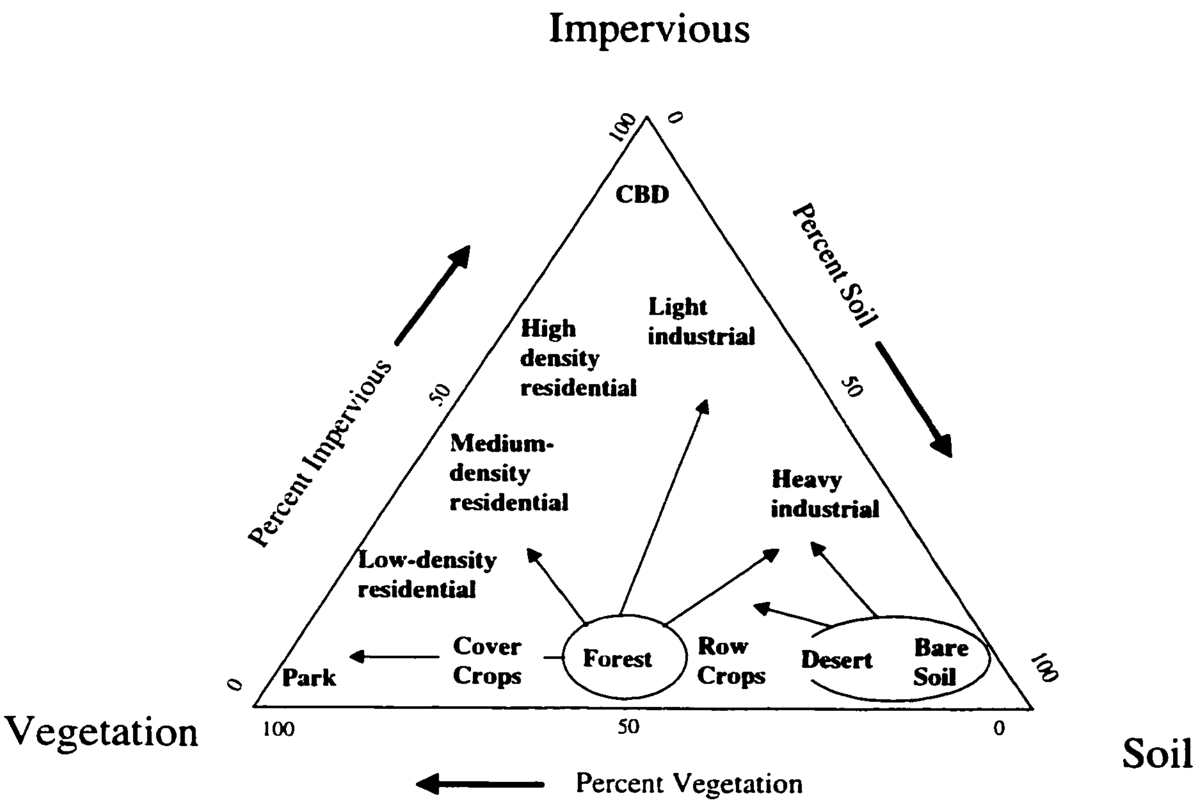


Figure 4-1. Ternary diagram of predicted land use and land cover classes in V-I-S composition, and anticipated changes from rural to urban environments for forested areas and desert areas (after Ridd 1995).

Additionally, Ridd predicted that changes in land cover by development can be characterized by changes from the original ("natural") land cover to developed ("urban") land cover. For example, a forested region would move from the region marked "forest" in Figure 4-1 to the developed regions. Similarly, a development in an arid environment would move from the "desert" and "bare soil" region to developed classes. This model has been tested using the gradient approach for Seattle, but has not been applied to other cities. The methods developed in Chapter 2 using satellite data to provide data for the V-I-S were successful for the Seattle analysis, and conceptually should be transferable to additional cities. Changes in biophysical land cover can also be related to changes in ecosystem processes such as rates of photosynthesis, albedo, and overland water flow (See Chapter 2, Figure 2-4). Comparison of biophysical land cover among multiple cities provides information on variations in ecosystem processes among diverse urban rural gradients.

There are few studies comparing biophysical land cover gradients in multiple cities. The analysis of the Seattle urban-rural gradient revealed a land cover gradient with low vegetation and high impervious cover within the city, and high vegetation with low impervious cover outside the city. These patterns are generalized in Figure 4-2.

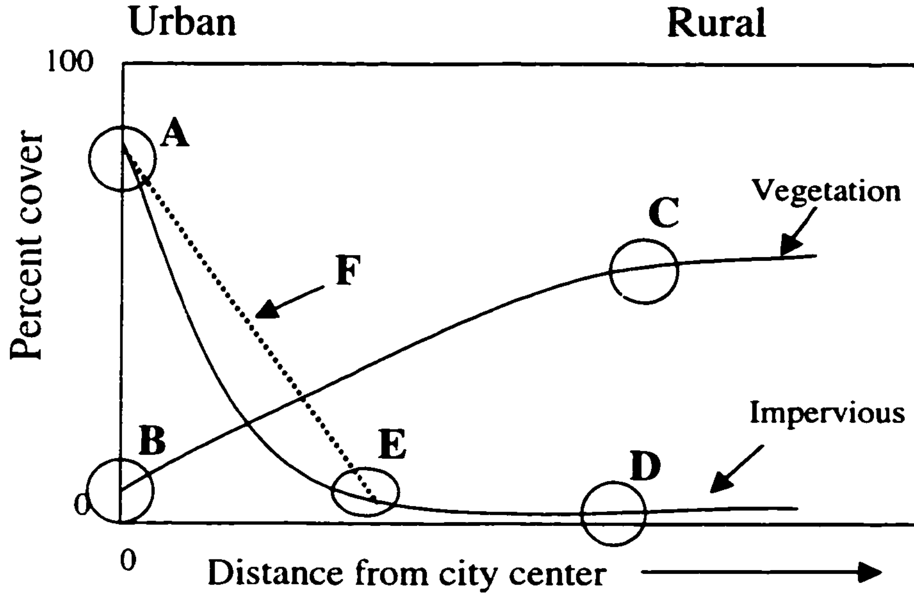


Figure 4-2. Generalized change in land cover along a distance gradient. Distance 0 is the city center. The urban region is considered a one kilometer ring around the city center (0.5 for smaller cities as described in the text). A is the percent impervious cover in the urban zone. B is the percent vegetation cover in the urban zone. The rural zone is determined as the point at which land cover does not change with increasing distance. C and D are the land cover values in the rural zone. E is the distance at which the impervious cover no longer continues to decrease. F is the slope of the gradient from the city center to point E.

In comparing the urban-rural gradient of other cities, I will address several questions: these questions are summarized in Table 4-1.

Table 4-1. Questions regarding the gradient of multiple cities.

Number	Question	Variables tested
1	Is there a biophysical gradient at multiple cities	Vegetation, Impervious vs. Distance
2	Does the rural biophysical cover depend on climate	Rural cover (vegetation, impervious) vs. Annual precipitation
3	Is urban cover influenced by rural cover	City cover (Vegetation, Impervious) vs. Rural cover
4	Does the extent of the built environment depend on city population.	Impervious extent ("E" in Figure 4-2) vs. City population
5	Does the degree of change in impervious from city to rural vary with population	Slope of impervious gradient Vs. City population

(#1) V-I-S Gradient test

Although the results from Chapter 2 suggest there is a gradient in land cover for Seattle, there is no guarantee that biophysical gradients exist in other cities. The existence of gradients can be determined in several cities by looking at amounts of V-I-S cover and comparing the values to distance from city center. There are two alternatives to a gradient pattern; one includes a pattern of very little change with distance, and another includes a sharp boundary at the urban-rural interface. Predicting little change in cover assumes that the city's land cover is similar in composition to the rural area. Alternatively, a sharp boundary in cover values indicates that there are factors such as policy regulations that influence the land cover at the urban-rural interface.

(#2) Rural V-I-S comparison with climate

The natural biotic environment is greatly affected by moisture (Agee and Kertis 1987; Moral 1978; Prentice et al. 1992). Ridd (1995) predicts that the "natural" V-I-S values for a region will determine the path of change from the rural to the urban region. My second objective was to analyze the relationship between climate and land cover values of rural regions (points "C" and "D" in Figure 4-2). In this study, I compared annual precipitation as the environmental climatic variable with levels of vegetation and impervious cover in the rural area.

(#3) Rural cover relation with urban cover

A city that is located in a wet environment with high vegetation cover is expected to have high vegetation cover in the urban environment. This vegetation may be remnant vegetation from the pre-built landscape (Sharpe 1986), or simply exist because it takes less water to maintain vegetation in wet regions. In dry environments, efforts to conserve resources might involve xeric landscaping, which mimics the rural land cover. The relationship between cover values at points A and D or B and C in Figure 4-2 illustrate the relationship between rural vegetation cover and the cover found in the urban environment. For example, a high rural cover value (C) might be a predictor for a higher percent cover value in the urban region (B).

(#4 & #5) Population relation with impervious cover

Another factor that needs to be included when assessing the urban-rural gradient is the population of the city (Weber 1994; Emmanuel 1997). A review of population and distance from city studies made by Berry et al. (1974) concluded that in most cities population shows a natural logarithmic decrease with distance from city center. In the population analysis of Chapter 2, large-scale population trends were closely related to impervious cover. Although population and land cover do not always correlate at fine scales as shown in Chapters 1 and 2, regional population patterns are expected to be well correlated with impervious cover at multiple cities.

In this study I measured change in impervious cover in two ways. I considered the point at which impervious cover stops decreasing (point "E" in Figure 4-2) the distance to rural impervious cover levels and assumed to be the extent of the built environment. This point is different than the gradients in vegetation and soil, which might be altered beyond the built environment. Impervious cover is assumed to be a land cover that is part of the built environment (although natural rock outcrops are also classed as impervious cover in the VIS model). Examples of structures in the built environment are roads, parking lots, and roof tops. Urban alterations outside the built environment primarily include removal of trees, dispersed development and agricultural activities, which typically do not significantly increase natural impervious cover values. Therefore, the population of the city should be correlated with the extent of the built environment.

The second measure of impervious cover along the gradient is the rate of change in impervious cover from the city center to the edge of the built environment (slope "F" in Figure 4-2). This is a measure of the rate of change in impervious cover along the gradient and should be greater (steeper slope) for larger cities as measured by population.

Methods

Study site selection

I selected 8 cities for this analysis. Data sources for analysis came from the Long Term Ecological Research (LTER) data archive. Images were selected that covered a city and its surroundings and did not have significant cloud cover in the region. Image data for two cities were purchased outright based on their proximity to where the research was performed (Seattle and Spokane). Information on the cities selected is displayed in Table 4-2 and geographic locations are shown in Figure 4-3.

Table 4-2. Selected cities.

# reference on map	City	Image date	Path/Row	Abbreviation
1	Seattle, WA.	10/27/98	46/27	SEA
2	Spokane, WA.	07/31/96	43/27	SPO
3	Eugene, OR.	8/19/95	46/29	EUG
4	Fairbanks, AK.	6/22/91	69/500	FAI
5	Phoenix, AZ.	9/8/99	37/37	PHO
6	Albuquerque, NM.	7/7/95	33/36	ALB
7	Kalamazoo, MI.	6/6/91	21/31	KAL
8	Baltimore, MD.	7/28/99	15/33	BAL

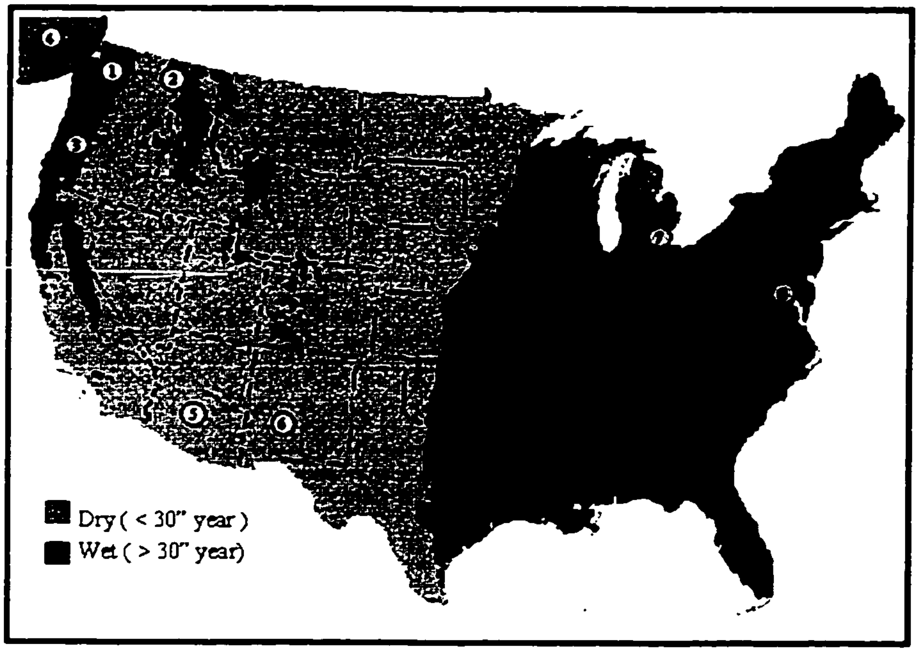


Figure 4-3. Location of study sites, with precipitation cutoff of 30" of annual rain. Less than 30" precipitation shown in light gray (dry) and greater shown in dark gray (wet). Sites are (1) Seattle, WA., (2) Spokane, WA., (3) Eugene, OR., (4) Fairbanks AK., (5) Phoenix AZ., (6) Albuquerque, NM., (7) Kalamazoo, MI., and (8) Baltimore MD.

Whenever possible, images were used that were taken in the early summer because the V-I-S model is sensitive to annual changes since dry vegetation is considered "soil".

Climate

The cities vary in mean annual precipitation (Figure 4-4), with Eugene, Oregon being the wettest and Phoenix, Arizona the driest. Annual precipitation is only one climatic measure. Precipitation can occur at different times of the year and with various influences from temperature and physical land form. Although these additional factors are important, the only variable I used was annual precipitation. Mean annual temperature was also considered, but the cities were not evenly spread across temperature ranges. Phoenix has a very high annual temperature, while Fairbanks has a low value, so regressions were high if they included these endpoints.

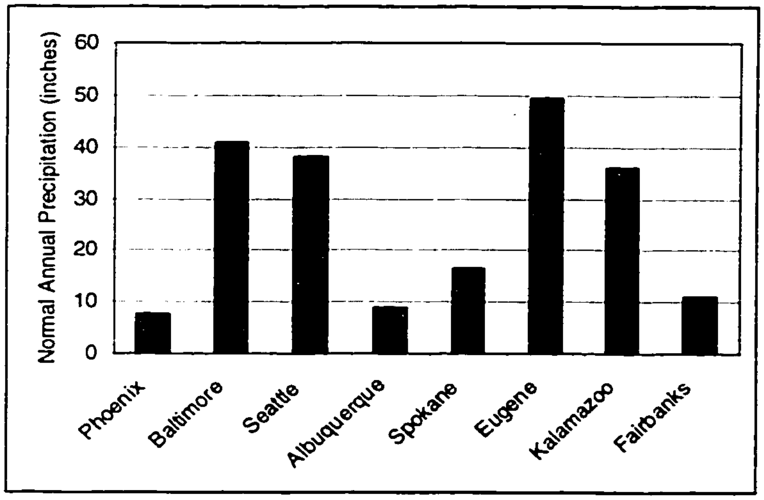


Figure 4-4. Normal annual precipitation at study sites. Data from the National Climate Data Center (NCDC 1999).

The 8 cities vary in population (Figure 4-5) from Phoenix with a 1990 population of almost one million, to Fairbanks with a population of 30,000.

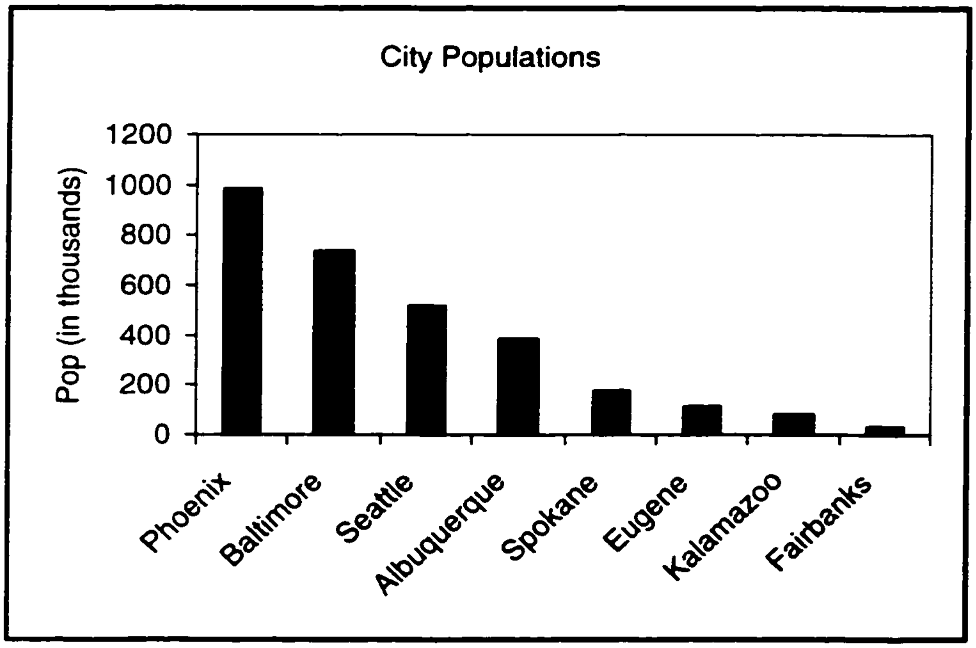


Figure 4-5. City populations (based on city limits) in thousands. Data 1990 U.S. census.

Image analysis

I used the same methods to analyze the satellite data as described in Chapter 2. Landsat TM images were dark corrected (minimum band values set to zero) to help standardize for atmospheric differences, and then unmixed using standard endmembers found in the Seattle image. With more information and ground truthing for each city, new endmember spectra could have been selected for each city. I used a standard set of spectra to standardize the image classification. Each image was then shade corrected and masked for shadows, water, and clouds by using a combination of unsupervised and supervised classifications.

Comparisons were based on distance to city center at one kilometer intervals. Small cities required an initial half-kilometer radius to represent the central city environment since a one kilometer radius went beyond the city extent. Average cover values were made for each one kilometer distance band from the city center. The rural environment was identified for each city based on the distance at which the V-I-S variables remained constant with increasing distance. Additionally, the extent of the built environment was measured at the distance from the city center where impervious cover stopped decreasing with increased distance. I calculated the rate of impervious decrease from city center by dividing the difference in impervious cover (urban to rural) by the distance to the extent of the built environment.

Results

All city images were visually inspected for accuracy. For basic visual assessment I observed V-I-S values at known features such as roads, forests, and golf courses and compared the values with ground truthing performed on the Seattle image (Chapter 2). Additional ground truthing was preformed for Spokane following the methods used in Seattle (Chapter 2). Results of the accuracy assessment are shown in Table 4-2 and are comparable to the results for the Seattle image.

Table 4-3. Accuracy assessment of the spectral classification (unmixing) for the Spokane, Washington image.

Vegetation	$y = 0.920x - 0.68$	
$R2 = 0.77$	$P < 0.005$	n=27
Impervious	$y = 0.993x - 0.64$	
$R2 = 0.81$	$P < 0.005$	n=27
Soil	$y = 0.805x + 9.69$	
$R2 = 0.62$	$P < 0.005$	n=27

Overall, the unmixing of the Spokane site was acceptable. Some of the errors found in the analysis were similar to those described in Chapter 2 (variations in time, vegetation seasonally drying, errors in ground estimation). I determined that image analysis for the additional city images was acceptable based on my visual assessment of all images and the accuracy results of the Spokane image.

V-I-S gradient test (#1)

V-I-S values along a distance gradient varied for each city (Figure 4-6). Generally, impervious cover continually decreased to the background value and all cover types reached a constant value at some distance from the city center.

City center V-I-S values range from 7.2 percent vegetation cover in Seattle to 18 percent in Eugene, and from 43 percent impervious cover in Fairbanks to 72 percent impervious in Phoenix. Some cities have land cover patterns with sharper boundaries than those found in the Seattle image. Kalamazoo has a steep increase in vegetation cover from the city center to two kilometers away at 8 percent and 50 percent respectively. Phoenix and Albuquerque gradients show a decrease in vegetation from the city center to the rural area, although in both cities vegetation cover increases slightly before decreasing to the rural cover values.

The V-I-S ternary diagram shows variation along the gradient from city to rural land cover (Figure 4-7). This diagram closely follows Ridd's (1995) predicted changes in land cover shown in Figure 4-1.

Rural V-I-S comparison with climate (#2)

Rural vegetation cover is correlated with annual precipitation for all 8 cities with a correlation coefficient of $R^2 = 0.84$ and $P < 0.005$ and linear regression of $y = 1.66x + 2.11$. Fairbanks has the highest residual from this relationship with 43 percent rural vegetation cover compared to the predicted 18 percent vegetation cover using the regression. Kalamazoo, Phoenix, and Albuquerque have less vegetation than predicted based on precipitation.

Rural impervious cover values are not closely correlated with precipitation. The correlation coefficient of the relationship is $R^2 = 0.278$, $P > 0.05$.

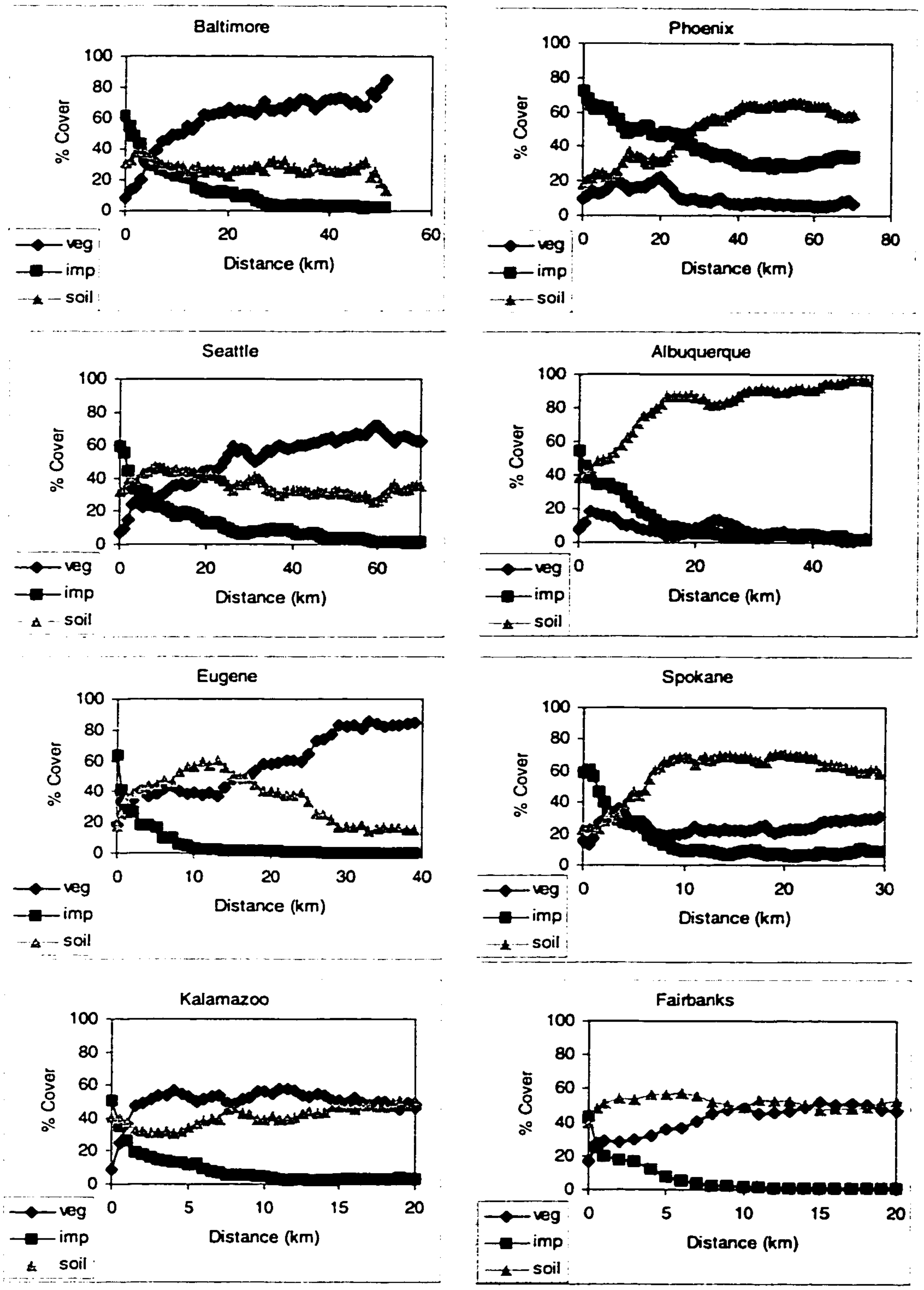


Figure 4-6. Mean cover values at 1- kilometer distance intervals from city center. Cover is measured as percent vegetation, impervious, and soil, and all three must add to 100.

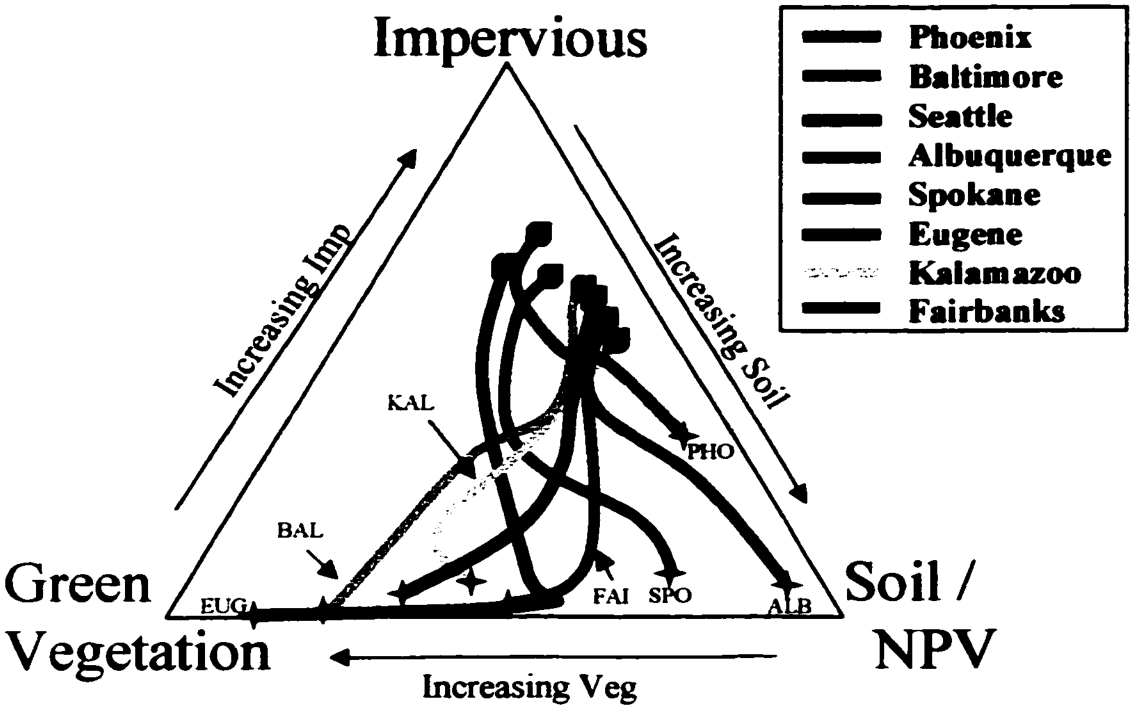


Figure 4-7. Ternary diagram of change in cover of selected cities from city center marked with a box, to the surrounding cover type shown as a star. Note:, Path is generalized based on the mean values of 1km radius bands.

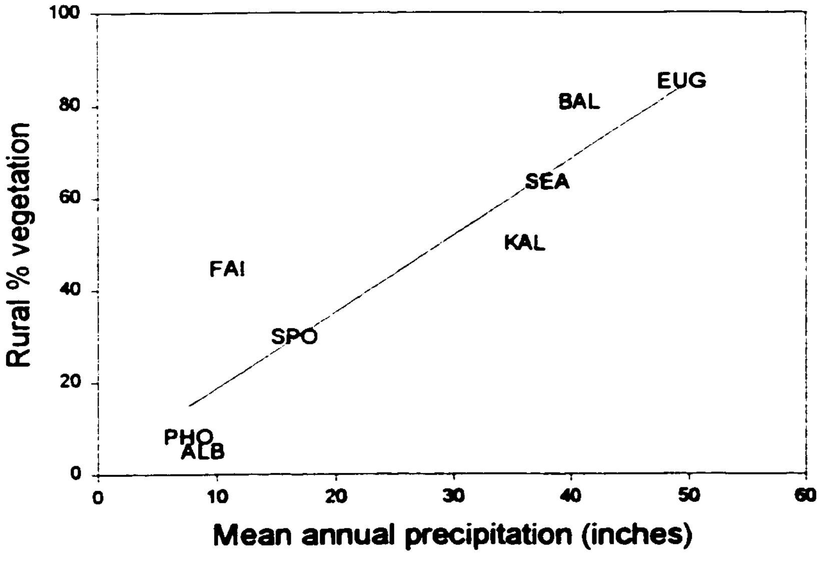


Figure 4-8. Comparison of annual precipitation and rural vegetation cover. $y = 1.66x + 2.11$ $R^2 = 0.84$, $P < 0.005$, $n=8$.

Rural cover values relation with urban cover value (#3)

There is no correlation between rural cover values and urban cover values of the 8 cities studied (Figure 4-9). Vegetation cover has a correlation coefficient of $R^2 = 0.33$ $P > 0.05$ (Figure 4-9a), and impervious cover has a correlation coefficient of $R^2 = 0.022$, $P > 0.05$ (Figure 4-9b). There does not seem to be any pattern in the residuals that can easily be explained based on climate.

Comparisons of city and rural cover types illustrate very small differences between urban and rural vegetation cover for Phoenix and Albuquerque; larger differences were found in all the wet cities. Impervious cover is higher in the urban than rural regions for all cities. The rural impervious cover, however, is quite high in Phoenix (34 percent) compared to other city background rates.

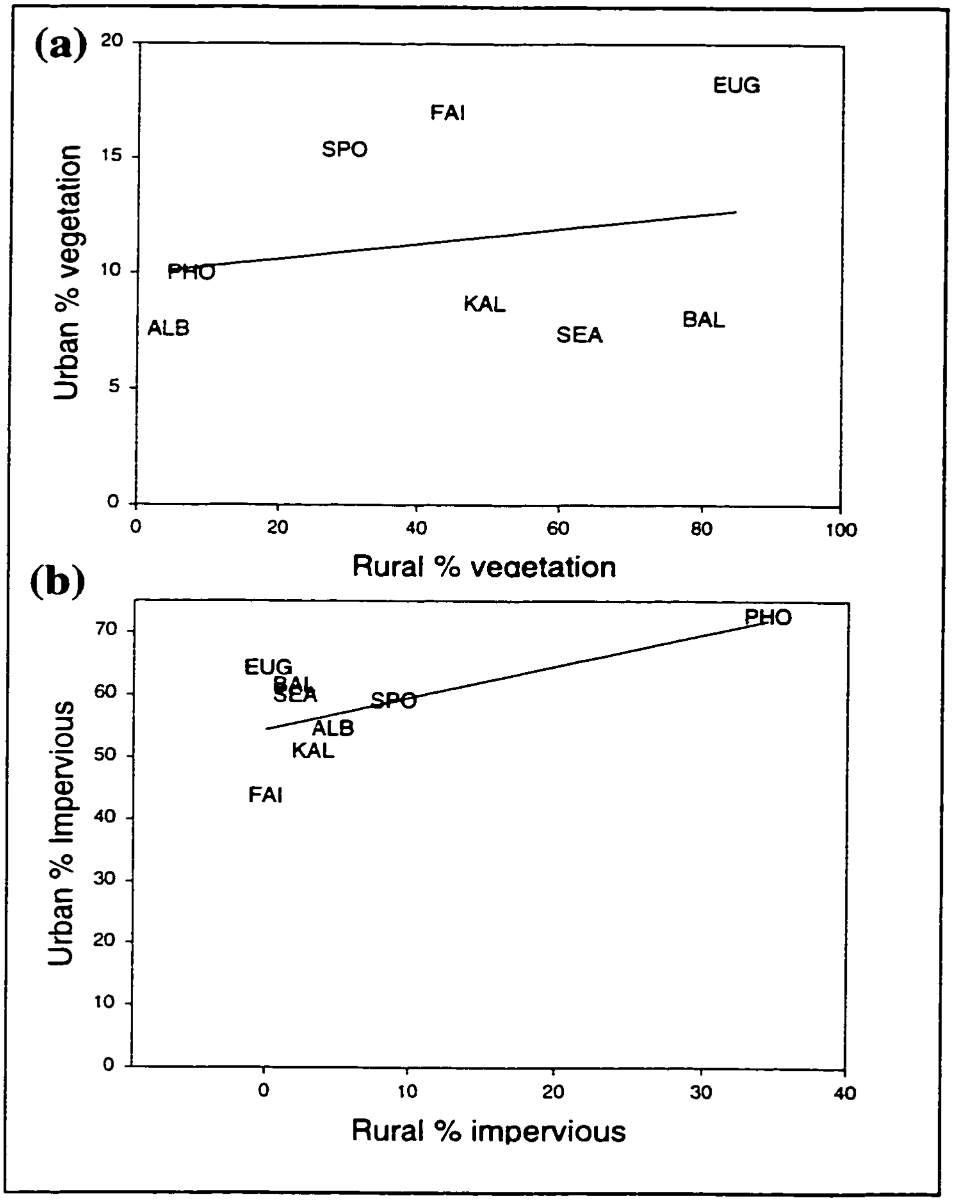


Figure 4-9. Average cover for city center and rural surroundings: (a) vegetation, and (b) impervious.

Relationship of population and impervious cover (#4 & #5)

The distance to impervious background values varies from 42 kilometers for Phoenix to 8 kilometers for Fairbanks (Figure 4-10).

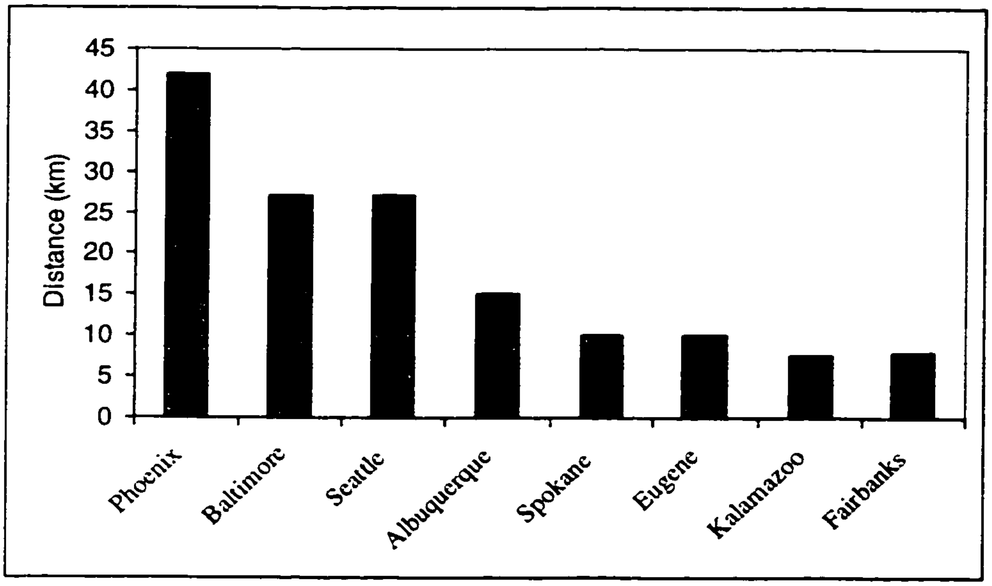


Figure 4-10. Distance to background impervious cover values for each city.

The relationship between the extent of the built environment (measured as distance to rural impervious cover) and the population of the city is linear with $y = 0.0000351x + 5.0382$ (Figure 4-11) and a correlation coefficient of $R^2 = 0.95$, $P < 0.005$.

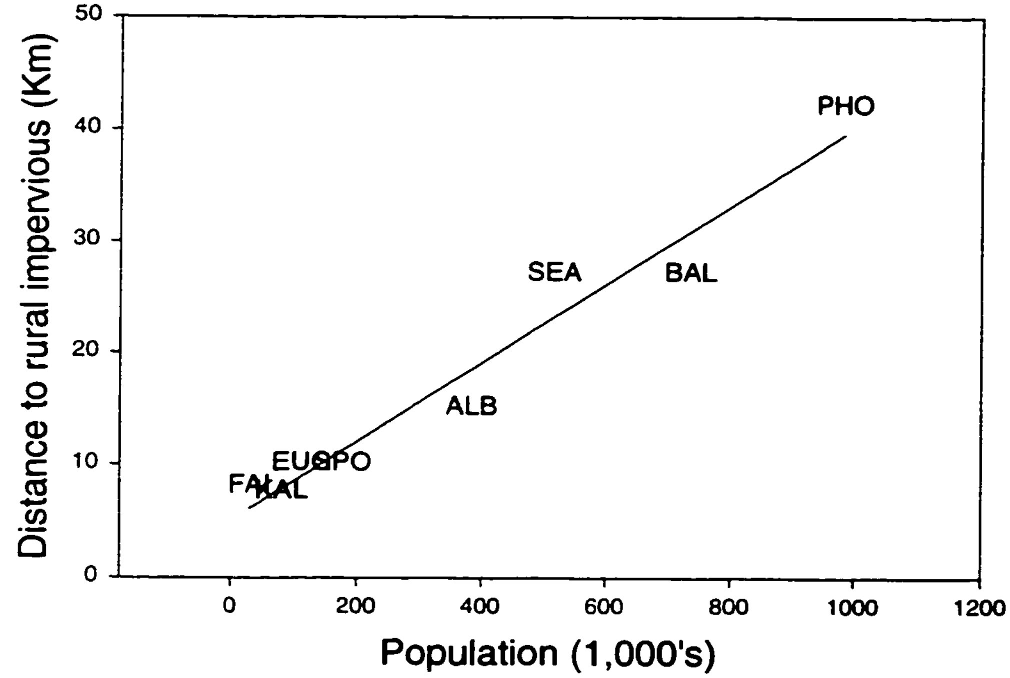


Figure 4-11. Comparison of distance to extent of built environment, and city population.

The rate of impervious cover loss from the city center to the edge of the built environment is similarly correlated (Figure 4-12). The correlation coefficient is R2 = 0.896, $P < 0.005$, and the equation of the regression line is $y = -0.00575x + 6.12$.

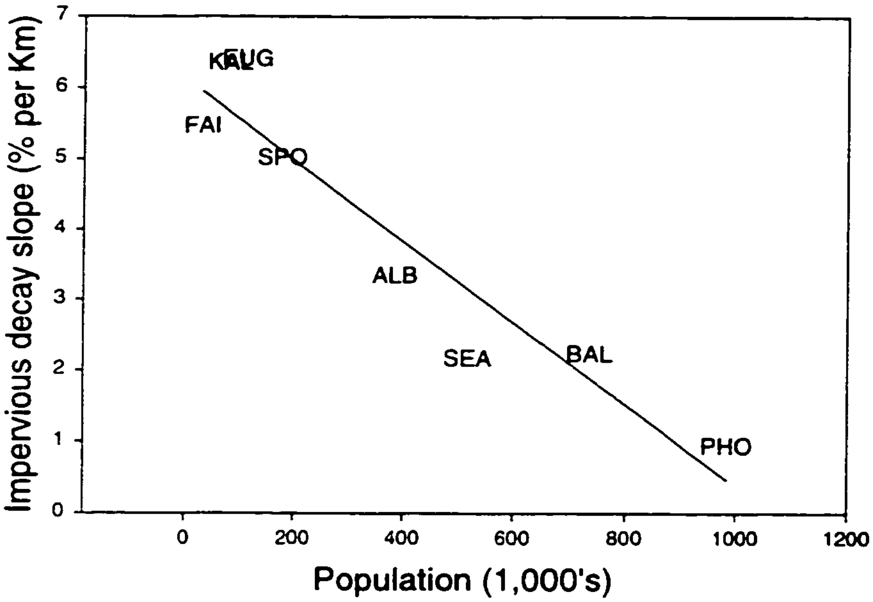


Figure 4-12. Relationship between population shown in thousands of people and the slope of the impervious decay from the city.

Population was not significantly correlated with the percent of cover in the urban environments. The relationship between population and urban vegetation has a correlation coefficient of $R^2 = 0.33$, $P > 0.05$, and impervious cover of $R^2 = 0.022$, $P > 0.05$.

Discussion

The number of cities compared is small and therefore extrapolating these findings to other cities should be done cautiously. Ideally, this study would be extended to include many cities within as well as outside the United States. Additionally, more ground truthing is required at multiple sites to determine accuracy. The five relationships studied are only a few of the many that could be tested using V-I-S data. In this study I explored the possibilities of V-I-S data but my analysis was not meant to be comprehensive. Some of the results of this study are very intuitive. Dry cities have less vegetation surrounding them than wet cities, and population is correlated with impervious cover. However, this chapter presents a method of objectively quantifying these measures. Additionally, some unexpected patterns appeared. The landscapes in and around the cities vary based on many factors from physical landscape, to social and political constraints, but many of these variations can be predicted with a few variables.

V-I-S gradients with distance

All of the cities exhibit a gradient of land cover with distance from city for at least one of the V-I-S cover types. For all cities, impervious cover decreased from city center. This suggests that vegetation increases with distance from city center at all of the cities with higher precipitation. In contrast, the drier cities (Phoenix, Albuquerque) vegetation decreased from the city center, while soil cover increased. These two cities are also the only examples in this study of hot dry desert environments. Spokane is on the edge of a ponderosa pine and mixed-conifer environment and Fairbanks is a cold dry environment. The hot dry cities appear to have vegetation that is being irrigated for settlement and agriculture near the urban environment. Annual precipitation is a good predictor of rural vegetation cover found outside of a city (Question #2 in Table 4-1). However, this relationship is not found in the urban environment (Question #3 in Table 4-1).

Land cover within cities is surprisingly similar. Considering the vast variation between environment, size, and socioeconomic factors in each city, the observed variability of mean cover values is low. Areas with high rural vegetation show a greater difference in vegetation cover than rural areas with low rural vegetation along the gradient. Finding vegetation levels slightly higher in the smaller cities is not surprising considering the urban morphology of a city such as Eugene is quite different from Seattle. Skyscrapers, large industrial zones, and multi-lane highways are structures not often found in smaller cities. These structures preclude the establishment of vegetation even in landscaping. However, unlike vegetation, the impervious levels in the cities are all within 15 percent of each other. This similarity suggests that development patterns in city interiors are similar with respect to land cover. These patterns are best illustrated in Figure 4-7 where the rural covers are disparate and urban covers are comparable.

Impervious gradient

Background impervious levels for all cities approach zero, with the exception of Phoenix. The Phoenix rural region has many rocky outcrops of basalt with a desert varnish. These features were likely detected as impervious cover using the mixing model spectrum. This assumption was not field-verified, and as with all the cities, it is necessary before strong inferences can be drawn. In all cities impervious land cover decreased with distance at a similar rate best described with a natural log regression. This rate of decrease is similar to rates described for population density in a study of over 100 cities (Berry et al. 1974). Since impervious cover is related to population at regional scales (Chapter 2), the impervious cover trend was expected and supports the use of these techniques to calculate land cover. The ability to estimate city population based on biophysical cover has some interesting potential but should be tested at more cities.

There is a close relationship between the extent of the built environment determined with the satellite data and the city population (Question #4). Similarly, the rate of decrease in impervious cover is closely associated with city population (Question #5). The extent of the built environment increases with increased population, yet the percent impervious cover in the city center remains relatively constant with increased population. Therefore, with increased city population, the rate of change of impervious cover will decrease. Impervious cover in a large city such as Phoenix will gradually decrease over a long distance compared to a small city.

Implications of V-I-S comparisons

Each city is unique when examined in the full context of historical settlement, natural environment, policies, and physical constraints to development. Even with the large differences between cities, comparisons can still be made using biophysical land cover. In addition a host of additional research questions can be made when using the V-I-S approach to gradient analysis. The results of this study imply that the extent of the built environment in cities varies closely with the population of the city. The difference in the extent is described by the regression equation $y = 0.0000351x + 5.0382$ (Figure 4-11). Using this regression equation, the extent of a city can be predicted to increase 1 kilometer in radius for every additional 28,500 people. Processes that are affected by the built environment such as albedo, overland water flow, and increased temperature can be compared between cities using a distance measure if distance is adjusted for population. As demonstrated in earlier chapters, these relationships are regional in scale and may not occur at the site level (Chapter 2).

Studies investigating processes related to vegetation cover should incorporate the regional climate; for the 8 cities in this study, annual precipitation was a good predictor. Even though precipitation did not appear to have an influence on city vegetation cover, the rate of vegetation change along the gradient is strongly influenced by climate variables. Wet cities will have a large positive vegetation gradient, while dry cities will have a small negative relationship.

Implications for planning and urban restoration

After investigating only 8 cities, sweeping inferences are unjustified. For the purpose of stimulating more thought and research on the gradient concept, however I present a couple propositions. First, cities seem to be similar in land cover regardless of regional conditions. Development that mimics the natural setting might have less impact on natural ecosystem process. Using the gradient path along the ternary diagram, land cover goals could attempt to move land cover backwards along the path towards the rural land cover. Xeric landscaping in dry regions minimizes water consumption, but these benefits need to be weighed against the financial benefits trees provide as shading, pollution mitigation, and aesthetic value. Wet regions could maintain higher vegetation to help intercept rain water and reduce overland flow. A city like Seattle with 60 percent rural vegetation and only 7 percent urban vegetation might be a candidate for increased vegetation in the city. Constraints on open space and locations that actually support vegetation are often limiting. Increasing vegetation, however, appears possible when considering the urban-rural differences in vegetation cover for the Seattle region.

Conclusion

The urban-rural gradients of multiple cities can be compared using biophysical land cover, while additional variables help explain the cover trends urban-rural gradients. Vegetation on the rural end of the gradient is related to precipitation. The extent of the built environment as well as the rate of change of the impervious cover are related to city population. Overall, city centers have similar urban V-I-S values while no relationships were found that explains any variability that does exist. This study is only a small example of the many analyses possible using the V-I-S model, but it does demonstrate the potential utility of this approach. Planners, policy makers and researchers can gain a better understanding of urban impacts by the use of biophysical land cover to compare the urban-rural gradients of multiple cities.

Summary

The techniques presented in this dissertation allow urban-rural gradient studies to use satellite data in way that is inexpensive, informative about ecosystem processes, and comparable at multiple sites and in multiple time periods. The V-I-S model allows a simplified depiction of land cover that is useful for tracking changes along an urban-rural gradient. Accurate data for the V-I-S model can be gathered using a spectral mixing model.

Results of analysis for the Seattle, Washington area successfully in demonstrated the benefits of these techniques. Vegetation cover was low in the city and increased steadily for 60 kilometers. Impervious cover decreased from the city center and became constant at 24 kilometers. The patterns in land cover, however, were not similar in all directions from the city center. Comparisons of V-I-S cover values and measures of population density, land use, and distance from city were well correlated at large scales, but not at fine scales. The V-I-S techniques are a better measure of land cover and presumably ecosystem processes at fine scales.

When comparing multiple cities with the V-I-S model, patterns in land cover varied for the different urban-rural gradients. Some of the variations in pattern were explained by variations in rural cover that correlated to climate, and impervious cover values were influenced by the human population of the city. While the cities have divergent rural land cover values, variability of city center land cover values were surprisingly similar considering the differences in the cities population, physical setting, and socio-economic conditions.

The methods and techniques outlined in this dissertation are useful in designing and assessing any urban-rural gradient analysis that has a focus on ecosystem processes. While land use is a beneficial data source, land cover is more closely related to ecosystem processes and can be determined more directly with satellite data.

Future analysis

Although this dissertation presented several techniques and comparisons using V-I-S data, the analysis was not comprehensive. Additional studies could be made to incorporate changes in time, assess more cities, and investigate relations between land cover and ecosystem processes.

Changes in land cover over time could be assessed both for annual and long-term variations. Annual variations in V-I-S cover are be influenced by agricultural practices, deciduous tree cover, and irrigation. Monthly satellite images could be assessed and the urban-rural gradient could be compared using the V-I-S model. The amount of seasonal change and gradient changes of land cover will provide insight into potential short term variations in ecosystem processes. Additionally, the annual variation will be useful in determining the importance of image capture time for the analysis outlined in this dissertation.

There is Landsat data for many cities for the past 25 years, and this archived data could be used to examine how land cover has changed in a single city. The change in V-I-S values might follow the path of the beginning gradient, or the gradient path might move within the ternary space (Figure 4-7). For example, 25 years ago the Seattle gradient shown in Figure 4-7 might have appeared more like the Eugene, Oregon gradient. From these large time intervals inferences could be made about changes in ecosystem processes during the development of a city.

Only 8 cities were compared in this dissertation, and the addition of more cities would improve the validity of the results. Additional cities that do not follow the trends found in this dissertation will be useful in determining what factors create the exceptions. Cities outside the United States, including developing countries, would also be interesting to compare. Specific patterns at cities could also be investigated to determine how road networks, physical setting and socio-economic factors influence the land cover in and around cities.

One last suggestion for additional research using the techniques presented in this dissertation is to quantify the connections between land cover and ecosystem processes. Throughout this dissertation I have inferred the connections between land cover and ecosystem processes, but there is little information available about these relationships in urban environments. Processes such as photosynthesis, water flow, carbon sequestration, and decomposition could be measured and compared to the land cover both for a point and the landscape context. The techniques presented in this dissertation allow quantitative analysis of land cover that can be related to measures of processes. Understanding human impacts on the ecosystem will not be complete until the relationship between land cover and ecosystem processes are better understood.

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