URBAN SPRAWL AND ATMOSPHERIC POLLUTION EFFECTS ON FORESTS IN THE GEORGIA PIEDMONT

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URBAN SPRAWL AND ATMOSPHERIC POLLUTION EFFECTS ON FORESTS IN THE GEORGIA PIEDMONT

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URBAN SPRAWL AND ATMOSPHERIC POLLUTION EFFECTS ON FORESTS IN THE GEORGIA PIEDMONT

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DISSERTATION ABSTRACT

URBAN SPRAWL AND ATMOSPHERIC POLLUTION EFFECTS ON FORESTS IN THE GEORGIA PIEDMONT

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Doctor of Philosophy, Auburn University, 10 May 2008
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Current and projected population pressures on natural lands in the South have resulted in extensive amounts of rural forests being converted to human-modified urban uses. Such substantial loss of forest land and wildlife habitat to urbanization renders the health of those remaining forests critical. The overall goal of this project was to examine the effects of urbanization on forest health by investigating forest stand structure, condition, and bioindicators of ecosystem health along an urban-to-rural gradient, as well as assessing landscape-scale indicators of ecosystem health across the region. The specific objectives of this project included: 1) examination of forest stand structure and condition across different land-use types through the measurement of various biotic, abiotic, and anthropogenic variables 2) determining concentrations of selected air-borne contaminants (N, S, and heavy metals) over space and time and relating these to land-use changes, 3) development of a methodology for a land management and planning tool using a land-cover classification to select regional landscape indicators and to correlate these with plot-level bioindicators of forest ecosystem health, and 4) examination of the utility of a regional ecological assessment tool using landscape indicators of ecosystem health. The study area (hereafter referred to as ‘West Georgia’) includes Muscogee, Harris, Meriwether, and Troup counties in west Georgia and represents an urban-to-rural gradient in terms of land development. Thirty-six permanent 0.05-ha circular plots (three plots per site; four sites per land-use type – urban, developing and rural) were established along the gradient using criteria adapted from the USDA Forest Service Forest Inventory and Analysis National Program guidelines. No differences were observed in forest stand structure and species composition from groundcover to upper canopy in any of the sites, except the total number of hardwood trees and tree species richness, which were greatest in developing areas. The percentage of trees with lichens, lichen species richness, and lichen abundance, were least and injury to trees was greatest in urban areas. Of the bioindicator variables measured, lichen tissue collected *in situ* appeared to be the best indicator of urbanization regarding differences in elemental concentrations among land-use types, and Cu, N, Pb, S, and Zn concentrations were all greatest at urban sites. There were significant inverse correlations between forest land-cover and population, housing, and road densities; tree species richness and forest patch density; urban land-cover and lichen species richness; and lichen incidence and forest perimeter-area fractal dimension. The measured regional landscape indicator variables supported the field-based forest condition results for urban and rural but not for developing areas. Overall, these studies were useful for examining human impacts to forest ecosystems at a variety of scales.

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Style manual or journals used:

Urban Ecosystems

Computer software used:

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ArcGIS$^{®}$ version 9.1

ERDAS$^{®}$ Imagine version 9.0

FRAGSTATS version 3.3

Adobe$^{®}$ Photoshop CS

Adobe$^{®}$ Illustrator CS

Endnote$^{®}$ version 10.0

Microsoft$^{®}$ Office 2003

- Word$^{®}$
- Excel$^{®}$

TABLE OF CONTENTS

LIST OF FIGURES ……………………………………………………………..xii
LIST OF TABLES ……………………………………………………………...xiv

1. URBAN SPRAWL AND ATMOSPHERIC POLLUTION EFFECTS ON FORESTS IN THE WEST GEORGIA PIEDMONT: AN INTRODUCTION. 1

2. URBANIZATION EFFECTS ON FOREST STAND STRUCTURE AND CONDITION IN THE WEST GEORGIA PIEDMONT 8

2.1 ABSTRACT 8
2.2 INTRODUCTION 9
2.3 METHODS & MATERIALS 12
  2.3.1 Study Area 12
  2.3.2 Physiography & Climate 13
  2.3.3 Pollution Sources in the Vicinity of Columbus, Georgia 14
  2.3.4 Land-cover & Land-use History 15
  2.3.5 Plot Selection 16
  2.3.6 Plot Measures for Forest Structure 17
  2.3.7 Bioindicator Measures for Forest Condition 18
  2.3.8 Urbanization Metrics for Predicting Forest Condition 19
  2.3.9 Experimental Design & Statistical Analysis 21
2.4 RESULTS 24
  2.4.1 Exploratory Analysis (ANOVA) 24
  2.4.2 Correlation Matrix 27
  2.4.3 Regression Modeling 27
2.5 DISCUSSION 29
  2.5.1 Forest Stand Structure 30
  2.5.2 Pests, Diseases, & Mechanical Injury 31
  2.5.3 Lichen Incidence, Abundance, & Species Richness 33
  2.5.4 Predicting Lichen Occurrence 35
  2.5.5 Predicting Lichen Species Richness 36
2.6 CONCLUSIONS 38
2.8 REFERENCES 42

3. URBANIZATION AND ATMOSPHERIC DEPOSITION: USE OF BIOINDICATORS IN DETERMINING PATTERNS OF LAND-USE CHANGE IN WEST GEORGIA 56

3.1 ABSTRACT 56
3.2 INTRODUCTION 57
3.3 METHODS & MATERIALS 61

3.3.1 Study Area 61
3.3.2 Physiography & Climate 62
3.3.3 Pollution Sources in the Vicinity of Columbus, Georgia 63
3.3.4 Plot Selection 64
3.3.5 *In situ* Lichen Tissue Collections 65
3.3.6 Lichen Tissue Transplants 66
3.3.7 Soil Samples 67
3.3.8 Tree Core Tissue Samples 68
3.3.9 Elemental Analyses 69
3.3.10 Experimental Design & Statistical Analysis 70
3.4 RESULTS & DISCUSSION 71
3.4.1 Elemental Concentrations in *in situ* Lichen Tissue 71
3.4.2 Elemental Concentrations in Transplanted Lichen Tissue 74
3.4.2.1 Elemental Concentration Trends in *U. strigosa vs. P. perforatum* 75
3.4.2.2 Elemental Concentration Trends in *U. strigosa* over Time 76
3.4.3 Elemental Concentrations in Soils 77
3.4.4 Elemental Concentrations in Tree Core Tissues 78
3.4.5 Comparison of Results from Different Assessments 79
3.5 CONCLUSIONS 81
3.7 REFERENCES 85

4. DEVELOPING A LAND-COVER CLASSIFICATION TO SELECT INDICATORS OF FOREST ECOSYSTEM HEALTH IN A RAPIDLY URBANIZING LANDSCAPE 102

4.1 ABSTRACT 102
4.2 INTRODUCTION 103
4.3 METHODS & MATERIALS 105
4.3.1 Study Area 105
4.3.2 Physiography & Topography 106
4.3.3 Land-cover & Land-use History 107
4.3.4 Land-cover Classifications 108
4.3.5 Post-Classification Change Detection Analysis 111
4.3.6 Landscape Indicators of Forest Ecosystem Health 111
4.3.7 Plot-level Biological Indicators of Forest Health 114
4.3.8 Correlation Matrix 114
4.4 RESULTS & DISCUSSION 115
4.4.1 Land-cover Classification 115
4.4.2 Land-cover Change Detection Analysis 116
4.4.3 Landscape Pattern Analysis 117
4.4.4 Correlation Matrix 119
4.4.4.2 Urbanization Variables *vs.* Biological Variables 119
4.5 CONCLUSIONS 122
4.6 ACKNOWLEDGEMENTS 123
4.7 REFERENCES 124
4.8 APPENDIX 144

5. LANDSCAPE INDICATORS OF ECOSYSTEM HEALTH IN THE WEST GEORGIA PIEDMONT: A REGIONAL APPROACH 158

5.1 ABSTRACT 158
5.2 INTRODUCTION 159
5.3 METHODS & MATERIALS 163
  5.3.1 Study Area 163
  5.3.2 Delineation of Experimental Units 164
  5.3.3 Census Demographic and TIGER® Data 166
  5.3.4 Land-cover Classification 167
  5.3.5 Fragmentation Analysis 168
  5.3.6 GIS Overlay Analysis 169
  5.3.7 Landscape Indicator Data Analysis 170
    5.3.7.1 Data Standardization and Multicollinearity Analysis 170
    5.3.7.2 Cluster Analysis 170
    5.3.7.3 Relative Cumulative Environmental impact (RCEI) 171
5.4 RESULTS & DISCUSSION 172
  5.4.1 Landscape Indicators in Urban, Developing, and Rural Areas of West Georgia 172
    5.4.1.1 Population Density, Population Change, and Road Density 173
    5.4.1.2 Urban/Built-up, Bare ground, Grass, and Forest Land-cover 175
    5.4.1.3 Forest Patch Density and Landscape Shannon's Diversity Index 176
    5.4.1.4 Agriculture/Bare ground on Slopes >3% and Streamlength with Adjacent Roads, Agriculture/Bare ground, and Forest Cover 178
  5.4.2 Cluster Ranks and Relative Cumulative Environmental Impact Scores 180
  5.4.3 Regional Environmental Impact vs. Plot-level Forest Stand Condition 183
5.5 CONCLUSIONS 186
5.6 ACKNOWLEDGEMENTS 188
5.7 REFERENCES 189

6. SUMMARY AND CONCLUSIONS 210

6.1 FOREST STAND STRUCTURE AND CONDITION 210
6.2 FOREST ELEMENTAL CONCENTRATIONS 211
6.3 URBANIZATION *VS.* BIOLOGICAL CORRELATIONS 212
6.4 REGIONAL INDICATORS OF ECOSYSTEM HEALTH 212
6.5 SYNTHESIS 213
6.6 FUTURE DIRECTIONS 216

LIST OF FIGURES

Figure 2.1 Map of West Georgia study area 45

Figure 2.2 Diagram of main plot showing vegetation transects and subplots 46

Figure 2.3 Photograph showing lichen sampling grid (with close-up)............................ 47

Figure 3.1 Map of West Georgia study area 89

Figure 3.2 Map showing locations of pollution monitors and emission facilities in West Georgia and surrounding counties in Georgia and Alabama............... 90

Figure 3.3 Photographs showing examples of fruticose and foliose lichen tissues......... 91

Figure 3.4 Photographs showing transplant lichen tissue collection and mounting........ 92

Figure 3.5 Photographs showing soil coring instrument, collection box, and sample..... 93

Figure 3.6 Photographs showing tree coring methods and mounted tree cores............... 94

Figure 4.1 Map of West Georgia study area 128

Figure 4.2 Land-cover classification of West Georgia for 2005 showing locations of the study sites... 129

Figure 4.3 Land-cover classification of West Georgia for 2001 showing locations of the study sites... 130

Figure 4.4 Percent forest land-cover *vs.* population, housing, and road densities in West Georgia 131

Figure 4.5 Percent urban land-cover *vs.* percent combined injury to trees from pests, diseases, and mechanical injury in West Georgia...................................... 132

Figure 4.6 Percent urban land-cover *vs.* lichen species richness in West Georgia........ 133

Figure 4.7 Tree species richness *vs.* forest patch density in West Georgia 134

Figure 4.8 Percent mechanical injury *vs.* landscape Shannon's diversity index in West Georgia 135

Figure 5.1 Map of study area showing cities, counties, and census county subdivisions in West Georgia 192

Figure 5.2 Population density in West Georgia by census county subdivision 193

Figure 5.3 Population change in West Georgia by census county subdivision 194

Figure 5.4 Negative vs. positive population growth in West Georgia by census county subdivision 195

Figure 5.5 Road density in West Georgia by census county subdivision 196

Figure 5.6 Land-cover classification of West Georgia for 2005 showing locations of the study sites..................... 197

Figure 5.7 Forest land-cover in West Georgia by census county subdivision.............. 198

Figure 5.8 Forest patch density in West Georgia by census county subdivision........... 199

Figure 5.9 Landscape SHDI in West Georgia by census county subdivision 200

Figure 5.10 Agriculture/bare ground on slopes >3% in West Georgia by census county subdivision 201

Figure 5.11 Percentage of streamlength within 30 m of a road in West Georgia by census county subdivision..................... 202

Figure 5.12 Percentage of streamlength with adjacent forest land-cover in West Georgia by census county subdivision..................... 203

Figure 5.13 Percentage of streamlength with adjacent agriculture/bare ground in West Georgia by census county subdivision 204

Figure 5.14 Clusters ranked by environmental impact scores for West Georgia 205

LIST OF TABLES

Table 2.1 West Georgia site characteristics measured during study duration 48

Table 2.2 Upland overstory tree species observed during plot establishment in West Georgia 49

Table 2.3 Definitions for each of the variables measured in West Georgia 50

Table 2.4 Standard ANOVA values and means (±SE) for forest stand structure variables collected in West Georgia 52

Table 2.5 Standard ANOVA values and means (±SE) for forest condition variables collected in West Georgia 53

Table 2.6 Standard ANOVA values and means (±SE) for urbanization variables collected in West Georgia 54

Table 2.7 Independent *vs.* dependent variable correlations for lichen models 55

Table 3.1 West Georgia site characteristics measured during the study duration 95

Table 3.2 Elemental concentration means (±SE) for *in situ* lichen tissue samples collected over nine months (December 2005-September 2006) in West Georgia 96

Table 3.3 Comparison of concentrations of selected elements in lichen tissue in several studies 97

Table 3.4 Elemental concentrations for transplanted *U. strigosa vs. P. perforatum* tissues collected over one year (September 2005- September 2006) in West Georgia 98

Table 3.5 Elemental concentrations for transplanted *U. strigosa* tissues collected over one year (September 2005- September 2006) in West Georgia 99

Table 3.6 Elemental concentrations (±SE) for soils collected in West Georgia............ 100

Table 3.7 Elemental concentrations for tree core tissues collected in West Georgia 101

Table 4.1 Definitions for each of the biological and urbanization variables measured in West Georgia 136

Table 4.2 Area and percentages of land-cover types in West Georgia for 2001 and 2005, and land-cover change between the two time periods 138

Table 4.3 Classification accuracy error matrices and Kappa coefficients for 2001 and 2005 West Georgia land-cover classifications 139

Table 4.4 Landscape pattern metrics by site, based on 2005 West Georgia land-cover classification 140

Table 4.5 Ten urbanization metrics calculated using 2005 West Georgia land-cover classification, and corresponding Spearman's Rho correlation coefficients and p-values to population, housing, and road densities in West Georgia ... 141

Table 4.6 Significant Spearman's Rho correlation coefficients and p-values between land-cover classes and other variables 142

Table 4.7 Significant Spearman's Rho correlation coefficients and p-values between landscape pattern metrics and other variables 143

Table 5.1 Census county subdivision values for each of the 10 landscape ecological indicators for the West Georgia region 206

Table 5.2 Area and percentages of land-cover types in West Georgia for 2005 207

Table 5.3 Cluster mean values for 10 landscape ecological indicator variables and corresponding relative cumulative environmental impact scores 208

Table 5.4 Standard ANOVA values and means (±SE) for forest condition variables collected in West Georgia 209

1. URBAN SPRAWL AND ATMOSPHERIC POLLUTION EFFECTS ON FORESTS IN THE WEST GEORGIA PIEDMONT: AN INTRODUCTION

Current and projected population pressures on natural lands are a growing concern in many regions of the United States, particularly in the South (Cordell and Macie, 2002). In many rapidly expanding cities, development trends are outpacing population growth (Hartshorn, 2003). As a result, forested land in this region is converted to human-modified urban uses at astonishing rates. Continual increasing populations will only expand the conversion of land from rural to urban uses, posing a major threat to the sustainability of Southern forests (Wear and Greis, 2002). Daily loss of forest land and wildlife habitat to urbanization renders the health of those forests that remain more critical. As such, studies that quantify forest health conditions and assess correlations to land-use changes in surrounding areas are strongly needed.

Previous reports have documented individual ecosystem component responses to urbanization or have analyzed whole ecosystem condition, but few studies have correlated results from both, and this type of research has not yet been attempted in the Southern U.S. (Jones *et al.*, 1997; Lathrop *et al.*, 2007; Olsen *et al.*, 2007; Smith and Wyatt, 2007). Trends in forest ecosystem health are directly and indirectly linked to patterns of urbanization. As populations migrate farther outside of urban cores, land becomes more modified (less natural), resulting in distinct patterns that can be analyzed using a gradient approach (McDonnell and Pickett, 1990; McDonnell *et al.*, 1997).

The urban-to-rural gradient approach provides researchers a way to evaluate the relationships between land-use change, ecosystem health, and environmental stress. However, it is difficult to extrapolate these small-scale data to broader spatial and temporal scales in an accurate manner (Kerr and Ostrovsky, 2003). Assessments of regional ecosystem health enable correlation of plot-level results to surrounding landscape characteristics, which is necessary to determine what aspects of urban development are linked to ecosystem functions in a given area. These assessments are necessary to examine the potential for declining ecosystem services and human health consequences, as impacts on ecological systems can indirectly influence the economic benefits provided by those systems.

Combining gradient and regional approaches provides a way to evaluate the effects of human modification of land on ecosystem health and environmental stress, and affords a spatial context for the study of forest ecosystem structure and function in a range of land-use types and at a variety of scales (McDonnell and Pickett, 1990; McDonnell *et al.*, 1997). By analyzing plot-level indicators of compositional, structural, and functional characteristics of forest health, the status of forests can be quantified and compared to those in varying locations across a region (McDonnell *et al.*, 1993). Landscape ecological assessments using remotely-sensed data can provide information about a landscape and ecological conditions that may not be detectable at the field plot level. Used in conjunction, fine- and broad-scale ecological assessments can incorporate the strengths of both methods resulting in more robust data collections and modeling capabilities.

The research in this study focused on a rapidly developing region surrounding Columbus, Georgia, and was a part of a large, inter-disciplinary project examining the complex linkages between urbanization and the ecology, economy, and sociology of the West Georgia landscape (Lockaby *et al.*, 2005). Columbus is the third largest metropolitan area in Georgia, and development trends have resulted from changing demographics over the past 15 years. The study area (hereafter referred to as 'West Georgia') included Muscogee, Harris, Meriwether, and Troup counties in the central, west Georgia Piedmont and represents an urban-to-rural gradient of land development. The four-county area varies substantially in degree of land development, consisting of highly-modified land-uses in the urbanized core of Columbus and in several smaller urban clusters within the region, and pasture/grazing lands, managed timber plantations, and mixed pine-hardwood post-primary forests that have established since abandonment of cultivated lands in the 1930s in rural parts of the region (Brown *et al.*, 2005).

The main goal of this project was to examine the effects of urbanization on forest health by examining forest stand structure and condition and bioindicators of ecosystem health along an urban-to-rural gradient, as well as assessing landscape-scale indicators across the region. Specifically, how is land-use change linked to the structure and condition of forests located on lands varying in degree of development? How is exposure to various atmospheric pollutants (e.g., O_3, NO_2, NH_3, and SO_2, metals) linked to bioindicators of ecosystem health? How do adjacent land-uses relate to forest ecosystem response? The overall hypothesis is that forest ecosystems in urban and rapidly developing areas are subjected to more stressful conditions and changes in structure and function generally occur. Additionally, due to increases in urbanization, vegetation in developing and rural areas is exposed to higher amounts of air pollution. The specific objectives of this project helped to determine which components of forest ecosystems are linked to urbanization processes and included: 1) ascertaining the status of forest stand structure and condition across the gradient using industry-standard criteria and testing for significant differences among land-use types, 2) determining elemental concentrations of forest ecosystems along urban-to-rural and historical gradients through the analysis of N, S, and metal concentrations in lichens, soils, and tree cores, 3) assessing regional land-cover patterns and landscape characteristics (indicators) that correlate with plot-level biological indicators of forest ecosystem health, and 4) utilizing data obtained from each of these assessments to provide model input (statistical and GIS) at a broader landscape scale to determine which areas of West Georgia display environmental impacts resulting from ecosystem changes associated with urban development.

In Chapter 2, a forest stand structure and condition assessment was conducted. Thirty-six permanent 0.05-hectare circular plots (three plots per site; four sites per land-use type – urban, developing and rural) were established along the gradient using criteria adapted from the USDA Forest Inventory and Analysis (FIA) National Program guidelines (USDA Forest Service, 2006). Within each plot, forest stand structure data were recorded for all mature trees, understory trees, saplings, and shrubs; groundcover data were recorded as well. Forest condition was assessed by quantifying and ranking the incidence of pests, diseases, mechanical injury, and lichens. Urbanization metrics were calculated using U.S. Census, land-cover, landscape pattern, and pollution data. Analyses were conducted on a total of 47 variables using ANOVA, Spearman's Rho correlations, and regression modeling to model forest health using the best variables associated with urbanization and forest health.

Chapter 3 is a more in-depth analysis of forest health bioindicators as they relate to atmospheric pollution exposure. Concentrations of N, S, and metals in lichens, soils, and tree cores were examined from each of the 36 plots along the gradient. Datasets were analyzed using ANOVA and repeated measures MANOVA to discern differences in elemental concentrations over time, between land-use types, and between lichen species potentially differing in pollutant sensitivity.

Discussion of the land-cover classifications developed for the West Georgia region, and discussion of correlations between regional landscape characteristics and plot-level bioindicators of forest ecosystem health (from Chapter 2), are the basis for Chapter 4. Landscape indicators of ecosystem health were obtained from a land-cover classification developed for West Georgia and subsequent fragmentation analysis. Spearman's Rho correlations were calculated to compare relationships between 17 landscape indicators and 30 field-collected bioindicators of forest ecosystem health. The validity of using satellite-derived landscape indicator data as a time- and cost-efficient land management and planning tool is discussed in this chapter.

In Chapter 5, a landscape-scale ecological assessment of West Georgia was conducted. Landscape indicators of ecosystem health included population density and change, road density, percent forest land-cover, forest patch density, Landscape Shannon's Diversity Index, proportion of stream that has roads within 30 meters, proportion of area that has agriculture on slopes >3%, proportion of stream with adjacent agriculture, and proportion of stream with adjacent forest cover. Cluster analysis was performed to combine the indicator variables into different groups. Cluster means were then used to rank different areas of the four-county region according to their relative cumulative environmental impact scores. Finally, these data were compared to those obtained from the plot-level forest health assessment from Chapter 2.

Chapter 6 is a synthesis of the results presented in each of the main chapters of the dissertation. Suggestions for future research to effectively assess and monitor the effects of urbanization on forest ecosystem health are discussed.

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2. URBANIZATION EFFECTS ON FOREST STAND STRUCTURE AND CONDITION IN THE WEST GEORGIA PIEDMONT

2.1 Abstract

Urban development is occurring in cities across the Southern U.S., resulting in a reduction of forested land area. The condition of forests that remain becomes critical, as their ability to provide ecosystem services to surrounding urban areas could become more limited. The main objective of this study was to examine forest stand structure and condition across different land-use types through the measurement of various biotic, abiotic, and anthropogenic variables. Thirty-six permanent 0.05-ha circular plots were established along an urban-to-rural gradient near Columbus, Georgia in 2005-2006. Bioindicators of forest health, including the incidence of lichens, pests, diseases, and mechanical injury, were measured and quantified to characterize relative forest condition at each site. Analyses were conducted on 47 variables using ANOVA, Spearman's Rho correlations, and regression modeling to model forest health using the best variables associated with urbanization. Results indicate that lichen incidence and species richness were correlated with canopy height, dbh, housing density, pest + disease + mechanical injury to trees, forest edge density, canopy cover, distance to road, and pasture land-cover. These findings suggest that land-use change may be related to differences in forest condition in urban *vs.* rural areas of the Columbus region.

Keywords: ecosystem, forest health, lichens, urbanization, urban-to-rural gradient

2.2 Introduction

Urbanization is a leading cause of land transformation worldwide and is occurring rapidly in many regions of the United States as a result of an ever-expanding population base (McDonnell *et al.*, 1997). Urbanization describes a process whereby the portion of a population living in cities increases and land-use is transformed into a more human-modified pattern of organization (Erickson, 1983). Current world population is over 6.6 billion, with over 300 million people residing in the U.S. (U.S. Census Bureau, 2007). In sprawling metropolitan areas development is outpacing population growth and Southern cities are among the most rapidly expanding areas of the country (Hartshorn, 2003). As a result, forested land in this region is being converted to human-modified urban utilization at astonishing rates. As populations continue to rise, the conversion of land from rural to urban uses will only increase. This conversion of natural lands to highly-modified urban areas poses a major threat to the sustainability of Southern forests (Wear and Greis, 2002). Having few topographic boundaries to curb sprawl, many areas of the Southern U.S. are experiencing similar patterns. At this rate of loss of our natural areas, the health of those forests that remain is becoming more critical. As such, studies that quantify forest health conditions and assess any correlations to land-use changes in surrounding areas are strongly needed.

McLaughlin and Percy (1999) have defined forest ecosystem health as the capacity to supply sufficient quantities of water, nutrients, and energy to sustain productivity while remaining resistant or resilient to environmental stress. Healthy forest ecosystems display a balance among tree growth, mortality, and regeneration, biological diversity, and the ability to withstand or recover from impacts of stressors such as pest or disease outbreaks, adverse weather and climate conditions, and air pollution exposure (Percy and Ferretti, 2004). The study of urbanization effects on forest health (structure, condition, and function) is a relatively new avenue of research, and urbanization is now considered an ecosystem stressor along with the other factors listed above. Land-use change accompanying urbanization greatly disrupts ecosystem patterns and processes and serves as a precursor to environmental degradation, allowing other biotic and abiotic stressors to follow (Zipperer, 2002).

Forest conditions often associated with urban systems include crown dieback, broken tops and limbs, higher incidence of pests, diseases, and mechanical injury, and lower incidence and species richness of lichen communities (Wear and Greis, 2002). Crown indicators include shape, density, cover, dieback, position, and transparency. Pest and disease incidence are related to crown dieback and are also generally higher in urban systems (Nowak *et al.*, 2001). Stressed forest communities are often more susceptible to invasion and once attacked, act as reservoirs for various pests and pathogens which can then spread to adjacent forests (Nowak and McBride, 1991). Lichens in urban environments are typically less abundant and diverse, and those present are typically weedy, nitrophytic, and/or non-native (McCune *et al.*, 1997; Geiser and Neitlich, 2007). These issues are important not only from an ecological standpoint of diminished ecosystem structure and function, but also because aesthetics and other social factors play a role in urban natural areas (Parsons, 1995; Daniel, 2001; Parsons and Daniel, 2002).

Urban-rural gradient approaches provide a way to evaluate the effects of human modification of land on ecosystem health and environmental stress. Gradients provide a spatial context for the study of forest ecosystem structure and function in a range of land-use types and at a variety of scales (McDonnell and Pickett, 1990; McDonnell *et al.*, 1997). By analyzing indicators of compositional, structural, and functional characteristics of forest health, the status of forests can be quantified and compared to similar forests, as well as to those in varying locations along a regional gradient (McDonnell *et al.*, 1993). Being able to quantify changes resulting from land-use conversion will help answer questions as to the nature of urban impacts on natural ecosystems, aiding the development of new land management strategies.

The goal of this study was to examine forest stand structure and condition along an urban-to-rural gradient through the measurement of various biotic, abiotic, and anthropogenic variables. The overall hypothesis is that urban and rapidly developing forest ecosystems are subject to more stressful conditions and are therefore less vigorous than those in rural environments. Specific objectives included: 1) ascertaining the status of forest stand structure and condition across the gradient, 2) utilizing data obtained from forest condition assessments to test for significant differences among variables in urban, developing, and rural land-use types over a broad landscape scale, 3) constructing correlation matrices to determine if bioindicators and urbanization variables are related, and 4) developing models that predict significant bioindicators as surrogates for forest health by using urbanization data collected in the field and calculated from census data and satellite imagery.

2.3 Methods & Materials

2.3.1 Study Area

The study area (hereafter referred to as 'West Georgia'; Figure 2.1) includes the counties of Muscogee (location of city of Columbus), Harris, and Meriwether in the west-central Georgia Piedmont, and represents an urban-to-rural gradient in terms of land development. Urban expansion around the Columbus area is constrained by Fort Benning (a large U.S. military base) to the south and by the Chattahoochee River to the west; as such, all development occurs to the north and east of Columbus. Development trends in West Georgia have resulted from changing demographics over the past 15 years. Muscogee County has had low recent population growth (3% from 1990-2005) but has high density (333 people/km^2 in 2000). Harris County, adjacent to the northeast of Muscogee County, has had extremely high population growth (56% from 1990-2005), far above the national average (19% from 1990-2005), but still maintains low (20 people/km^2 in 2000) density. Meriwether County, adjacent to the northeast of Harris County, has had low population growth (2% from 1990-2005) and has very low (17 people/km^2 in 2000) density (U.S. Census Bureau, 2006).

For the purposes of this study, I used the U.S. Census Bureau's Census 2000 geographic definitions of urban (U.S. Census Bureau, 2001). The U.S. Census Bureau (2006) identifies four urban areas in the region: one urbanized area (UZA) and three urban clusters (UC). A UZA is defined as a core group of census blocks having a population >50,000 people and a population density of at least 386 people/km^2, while

UC’s are defined as having similar densities but populations between 2,500-49,999 people (U.S. Census Bureau, 2006). The UZA is Columbus (Muscogee County), and the UCs are portions of Valley-Lanett (Harris and Troup Counties), LaGrange (Troup County), and Manchester (Meriwether County). Delineations of these areas are shown in Figure 2.1. According to these definitions, all other land areas in the West Georgia study are classified as rural (U.S. Census Bureau, 2006). For the “developing” land-use classification, I defined plots within census tracts as developing if the population growth within the tract was greater than the national average (19% from 1990-2005).

2.3.2 Physiography & Climate

The city of Columbus is located at approximately 32° 27’ 38” North Latitude, 084° 59’ 16” West Longitude and study sites extend toward the northeast to approximately 33° 07’ 07” North Latitude, 084° 32’ 11” West Longitude (Figure 2.1). The study area lies within the Piedmont Physiographic Province of west-central Georgia, and plot elevations range from approximately 100 to 260 m above mean sea level. This province is characterized by gently rolling hills, deeply weathered bedrock, and isolated occurrences of granitic plutons (University of Georgia, 2007). The topography generally reflects folding and faulting of sediment layers eroded from the Appalachians during the Paleozoic era, which produced such features as Pine Mountain near Warm Springs, GA (University of Georgia, 2007). The climate of the west Georgia Piedmont is moist and temperate. Precipitation is evenly distributed across the region, and is mainly in the form of rainfall, as snowfall in the area is rare (Southeast Regional Climate Center, 2007).

March is the wettest month, as most precipitation occurs during the wet winter season (Southeast Regional Climate Center, 2007). Based on data from the past 50 years, mean annual precipitation in the area is generally around 1245 mm, while annual temperatures range from a mean monthly minimum of 12º C in January to a mean monthly maximum of 24º C in July (Southeast Regional Climate Center, 2007). Prevailing winds during warm months are generally from the south-southwest, flowing up from the Gulf of Mexico, while in winter large frontal systems typically draw air down the eastern side of the Appalachians resulting in strong northwesterly winds across Georgia (Styers, 2005).

2.3.3 Pollution Sources in the Vicinity of Columbus, Georgia

The 21-county pollution-source region includes the study area and surrounding counties in Georgia and Alabama (Figure 3.2). Pollutants monitored by stations in the Columbus, GA/Phenix City, AL metropolitan area include O_3, SO_2, Pb, PM10, and PM2.5. The U.S. EPA AirData database (U.S. Environmental Protection Agency, 2006) indicated there are 105 facilities in the 21-county area that are monitored for emissions of CO, NH_3, NO_X, VOCs, SO_2, PM10, and PM2.5. The majority of the 105 up-wind regional pollution sources are located in Russell and Lee counties, AL, and include industrial, manufacturing, textile, lumber, paper, and brick-making plants, as well as sources from excavation and paving activities (U.S. Environmental Protection Agency, 2006). However, the two Georgia Power coal-fired steam-electric power plants (Wansley and Yates) that are responsible for the greatest overall yearly emissions are located in Heard and Coweta counties, GA, just north of Troup and Meriwether counties, respectively. Other primary point-source emission contributors include Continental Carbon Company and Witco Corporation in Russell County, AL, Kimberly-Clark Corporation in Troup County, GA, and Georgia-Pacific Corporation in Meriwether County, GA. In addition, there are several federal highways in the area (I-85, I-185, US 280, US 431, US 27) that are major routes for automobiles and transfer truck traffic and therefore are mobile sources of pollutants (e.g., CO, NO_X, etc.). Local anthropogenic pollution sources include present and historical applications of fertilizers and pesticides to lawns, golf courses, and agricultural fields. Natural sources of sulfur dioxide include biological decay and forest fires, while those of nitrogen oxides include oceans, biological decay, and lightning strikes. Natural sources of metals include weathering of mineral deposits, brush fires, and windblown dusts.

2.3.4 Land-cover & Land-use History

The overall study area contains urban, agricultural (pasture), and forested ecosystems typical of the Southern Piedmont. Much of the land in this area was historically cleared for agriculture, but has since regenerated back to forest following a wave of Depression-era abandonment of fields (Brown *et al.*, 2005). The resulting mosaic of forested land in West Georgia ranges from natural, pure hardwood stands to intensely-managed pine plantations. Pine-oak forest communities, typical of the plot locations, are generally located on relatively dry, exposed slopes and ridges. Land-cover for 2005, interpreted from Landsat Thematic Mapper (TM) imagery, for the four-county area includes 72% forest cover, 4% water/wetlands, 4% urban/built-up land, and 7%

pasture/lawn (see Chapter 4 for more details). Most of the forest cover (41%) is intensively-managed pine plantations, which are typical of this area of the South (Brown *et al.*, 2005). Additionally, 13% of the area is classified as bare ground, which includes areas under development, cultivation, and harvested timberlands.

2.3.5 Plot Selection

To fully assess the degree and spatial extent of forest ecosystem condition in West Georgia, 36 permanent 0.05-hectare (ha) circular plots (three plots per site; four sites per land-use type – urban, developing and rural) were installed in the winter of 2004-2005. Plots were established along an urban-to-rural gradient using criteria adapted from the USDA Forest Inventory and Analysis (FIA) National Program guidelines (USDA Forest Service, 2006). Approximately ½ of the sites used in this study were previously selected by other researchers conducting water quality experiments in the region (Lockaby *et al.*, 2005). Additional sites selected were added to extend the gradient farther to the northeast. The gradient extends approximately 100 km from southwest to northeast and is approximately 75 km in width. Since other studies for the overall project were conducted within these same sites, there was a more deliberate selection of specific plots. Individual plot locations were selected based on specific criteria: upland, interior (at least 30 m from an edge), forested locations within pine-oak woodlands containing mature loblolly pine (*Pinus taeda* L.) and oak (*Quercus*) species of a similar age class, elevation, slope, aspect, uniformity of soils, and site histories (Table 2.1; see Table 2.2 for a list of other common species).

2.3.6 Plot Measures for Forest Structure

Once established, each plot (Figure 2.2) was initially characterized in winter/spring 2005 to determine forest structure and condition (the reader is referred to Table 2.3 for definitions of each of the variables). Within each plot, data for mature trees (those greater than 10 cm in diameter) were recorded including total number of trees, percentage of hardwoods, percentage of pines, total number of tree species, and diameter (dbh), and basal area was then calculated. A total count of all understory trees (2.5-10 cm dbh) was also recorded. The number of saplings and shrubs 0.635-2.5 cm diameter and at least 1 m in height were counted and averaged to the plot-level by recording the count along three transects across the plot area (Figure 2.2). Groundcover data were recorded as the percentages of woody stems, herbaceous plants, leaf litter, and bare ground within five 0.25 m^2 subplots averaged to plot-level (Figure 2.2). A count of the number of seedlings (<0.635 cm diameter and <1 m in height) within each of these subplots was also noted and averaged per plot. Plot-based metrics calculated included median stand age using tree cores from dominant loblolly pine specimens, upper canopy height (clinometer-derived heights averaged from three each of the dominant pine and hardwood specimens), lower canopy height (using the same criteria as above), and mean percent peak canopy cover using a moosehorn canopy cover scope (provided by Dr. B. Boyd, Auburn University) derived from three randomly selected points within each plot during mid-June.

2.3.7 Bioindicator Measures for Forest Condition

Forest health was assessed by surveying features such as incidence of pests, diseases, mechanical injury, and lichens and quantified using a ranking system designed by the FIA Program (USDA Forest Service, 2006). Using this system, a field crew can assign rating scores for relative abundance and species richness from the data collected. Lichen incidence and abundance surveys were conducted on all mature (> 10 cm dbh) woody plants above 0.5 m from the base within each of the 0.05-ha circular "main" plot as in Figure 2.2 (USDA Forest Service, 2006). The size of the lichen survey plots was adjusted from FIA Protocol (0.378-ha plot) such that these data would coincide with other data from the "main" plots.

Since lichens are known to be very sensitive indicators of ecosystem health, more detailed data were collected from a single tree species. This survey was conducted to eliminate the variability observed in the data from all tree species (e.g., *Acer* species have diversely abundant lichen cover and species richness while *Liquidambar styraciflua* has very little). A 20 cm by 50 cm grid (1,000 cm^2) was installed in September 2005 on two water oak (*Quercus nigra* L.) specimens approximately 10 cm to 15 cm dbh within each plot (Figure 2.3). Each grid was centered on the northeast side of each tree at approximately breast height (1.55 m). Numbers of crustose and foliose lichen species were noted, as was total percent cover (abundance), and the dominant lichen type within each grid quadrant (10 cm by 25 cm). Data from each of the four grid quadrants were then averaged for each tree, and data from the two trees were averaged to represent a single plot value. This procedure was repeated after 12 months, in September 2006, to detect any changes over the course of one year.

2.3.8 Urbanization Metrics for Predicting Forest Condition

Lichen incidence and species richness can be influenced by biological (e.g., bark roughness, bark pH, canopy cover) and climatic (e.g., temperature, moisture, light, wind) factors, as well as by exposure to atmospheric pollutants and landscape patterns (e.g., forest edge habitats). Therefore, I attempted to quantify as many of these factors as possible. In addition to the forest stand structure and condition data, I examined U.S. Census demographic data, land-cover, and landscape pattern metrics. Each of these factors was used to examine relationships between various metrics of urbanization and lichen incidence and species richness in West Georgia.

Land-cover and landscape pattern data were used to provide the urbanization metrics across the landscape of West Georgia. For more detailed information on the land-cover classification system developed for use in this study, the reader is referred to Chapter 4. The land-cover classification system used with these data included the percent cover of the following characterization classes for the year 2005 delineated at the census tract level: urban/built-up, bare ground, pasture, urban lawn, urban vegetation, deciduous forest, evergreen forest, and water/wetlands. Some of these characterization classes were combined for analysis resulting in the following five new model variables: urban/built-up, non-vegetated land (urban/built-up + bare ground), pasture, grass (pasture + urban lawn), and forest (urban vegetation + deciduous forest + evergreen forest). Landscape pattern data were calculated using the 2005 land-cover classification as input into Fragstats with the patch neighbor rule set to 8-cells (McGarigal *et al.*, 2002) resulting in the following landscape pattern variables: forest patch density (FORPD), forest edge density (FORED), forest perimeter-area fractal dimension (PAFRAC), Landscape Shannon's Diversity Index (SHDI), and Landscape Shannon's Evenness Index (SHEI).

The forest patch density metric expresses the number of forest patches per 100 ha within each of the sampling units (i.e., census tract). Only information about the number of patches per area is given, but no information is given about the sizes or spatial distribution of the patches. The forest edge density metric reports the length of forest edge (in m/ha) within each of the sampling units. These values are the total amount of edge per unit area, although no details about areal size is reported. The forest perimeter-area fractal dimension reflects patch shape complexity and is appealing because it can be used across a range of spatial scales. Fractal dimension ranges from 1 to 2, or from shapes with very simple perimeters (e.g., managed forests) to those with very complex ones (e.g., “natural” forests), respectively. Landscape Shannon’s diversity index expresses the proportion of the landscape occupied by a patch type of a particular class. Landscape diversity is 0 where there is only one patch type, and increases to infinity as the number of different patch types increases and/or the areal distribution among patch types becomes more even. Similarly, landscape Shannon’s evenness index reports the evenness of areal distribution among patch types. Landscape evenness is 0 where the areal distribution among patch types is uneven, or where there is dominance of only one patch type, and increases toward 1, where there is perfect evenness among distribution of area among patch types. Since small experimental units (e.g., census tracts *vs.*

watersheds) were used to calculate these metrics, the spatial distribution shortcomings of some of these metrics are not a substantial issue.

The census tract was used as the unit of delineation so that census demographic and topologically integrated geographic encoding and referencing system (TIGER®) data could be used in these analyses (U.S. Census Bureau, 2005). Only census tracts containing the locations of field plots were included in these analyses. Data from the 2000 Decennial Census were used to calculate population, housing, and road densities for each of the census tracts that contained field plots so these could be used as urbanization variables (U.S. Census Bureau, 2005). TIGER® data were used to determine the distance of each plot to the nearest road and also to the nearest major (paved) road, since many of the roads in rural areas were dirt or gravel roads (U.S. Census Bureau, 2005).

2.3.9 Experimental Design & Statistical Analysis

Forest condition variables were evaluated through incidence surveys and quantified using a ranking system following FIA Program guidelines (USDA Forest Service, 2006). A total of 47 variables were extracted from these data and were summed, averaged, and/or combined from the plot-level to represent data for each of the 12 sites for use in data analysis.

Initially, several exploratory analyses were conducted to better understand the data. First, distributions and descriptive statistics for each variable were examined for the 12 sites (averaged from the 36 plots – 3 each site) using JMP IN® 5.1.2 (SAS Institute Inc., 2003), which was the statistical software package used in all analyses described hereafter.

Since these means were calculated using data from three plots, they each displayed approximately normal distributions. This allowed the variables to be used without transformation in analyses. Next, the variances between plots for each land-use type and the variances between sites for each land-use type were examined. Since the variances between plots and also between sites was approximately the same for all land-use types, then the assumption of equal variances inherent in the one-way analysis of variance (ANOVA) is valid. Further, the variances between plots and the variances between sites were examined to determine if the study was designed efficiently. Since there was more variability between plots than between sites, it is recommended that in the future studies the number of plots within each site be increased, even if it means decreasing the number of sites.

Following these preliminary explorations of the data, ANOVA was performed to test if land-use type significantly affected each variable, with the p value set at $p < 0.10$ due to the inherent variability in field studies. If so, group means were then compared using Tukey-Kramer HSD, which is a post-hoc test that is sized for all differences among the means. This test adjusts for multiple comparisons by controlling for the overall error rate.

Once the ANOVA tests were complete, a multivariate correlation matrix was constructed to determine which of the variables were highly correlated (JMP IN® 5.1.2, SAS Institute Inc., 2003). The goal was to retain those variables shown to correlate well with the dependent variables, while eliminating potential predictor variables displaying multicollinearity. Since lichen indices proved to correlate well with many of the biological, urbanization, and landscape pattern variables, two of these ('percentage of trees with lichens' and 'mean number of lichen species per tree') were selected as dependent variables for the regression modeling. For the purposes of this study, 'percentage of trees with lichens,' or lichen incidence, is defined as the percent hardwood trees with the presence or absence of lichens, while 'mean number of lichen species per tree,' or species richness, is defined as the mean number of species per hardwood tree. These variables were selected because of the relative ease of data collection and lichen presence on all hardwood species. The mean abundance rank was not selected for inclusion in the model because of the large range in rank values (1-20%, 21-40%, etc.) and potential bias in evaluation due to inexperience of the crew. It was decided that any of the variables measured on only water oaks were too limiting in their ability to predict lichen coverage for forest stands in which water oaks were not present and therefore were not used. The decision to use lichens as surrogates for forest health was also based on literature that lichens are good bioindicators of forest health, specifically relating to air pollution exposure (Nash and Gries, 1986; McCune *et al.*, 1997; Geiser and Neitlich, 2007) and edge effects resulting from forest fragmentation, or urbanization (Esseen and Renhorn, 1998; Kalwij *et al.*, 2005; Frati *et al.*, 2006). Each of the potential independent variables was then analyzed using stepwise regression modeling for data reduction and significant variable selection (JMP IN® 5.1.2, SAS Institute Inc., 2003). Finally, standard least squares regression was used to predict lichen incidence and species richness from a combination of various biological, urbanization, and landscape pattern variables.

2.4 Results

2.4.1 Exploratory Analysis (ANOVA)

Forest structure data collected within each plot included the number of trees, number of hardwoods and pines, hardwood:pine ratio, number of tree species, mean dbh (in cm) of all mature trees, basal area, and median age of stand (Table 2.4). Where applicable, the variable values are reported on a per hectare basis. Of these eight variables, there were no significant differences between land-use types in the ‘number of trees,’ ‘number of pines,’ ‘hardwood:pine ratio,’ ‘mean dbh of all trees,’ ‘basal area,’ and ‘median age of stand’ variables. The ‘number of hardwoods’ was 1.61- and 1.47-fold greater in developing (mean=430) and rural (mean=388) locations, respectively, than in urban areas (mean=265). Additionally, the ‘number of tree species’ was 1.71- and 1.41-fold greater in developing (mean=8) and rural areas (mean=6.58), respectively, than in urban areas (mean=4.67).

Additional forest stand data collected included information about canopy, understory, and ground cover vegetation structure. The ‘percent peak canopy cover,’ ‘mean upper canopy height,’ and ‘mean subcanopy height’ variables did not significantly differ between land-use types. Further, none of the understory or ground cover variables measured were statistically different between urban, developing, and rural land-use types (Table 2.4).

Tree condition data collected within each plot included percent pest (e.g., bark beetles, tent caterpillars, oakworms), disease (e.g., galls, cankers, dieback, Fusiform rust), and mechanical injury to all trees, as well as the combined amount of injury from all three of these factors (Table 2.5). Regarding ‘percent pest incidence for all trees’ and ‘percent disease incidence for all trees’, there were no significant differences observed between the land-use types. The ‘percent mechanical injury incidence to all trees’ variable was 2.19-fold greater in urban areas (mean=30.25%) than in rural land-use types (mean=13.83%), while injury in developing areas was not significantly different from either (mean=19.25%). Similarly, the combined injury to trees resulting from pest + disease + mechanical injury was 2.31-fold greater in urban areas (mean=37%) than in rural land-use types (mean=16%), while injury to trees in developing areas was not significantly different from either (mean=23.58%).

Initial lichen data were collected from all hardwood trees within each plot and included ‘percentage of trees with lichens,’ ‘mean number of lichen species per tree,’ and ‘mean lichen abundance rank’ (Table 2.5). ‘Percentage of trees with lichens’ in rural areas (mean=87.83%) was 1.69-fold greater than in urban land-use types (mean=51.83%). No differences were observed between developing areas and the other land-use types (mean=74.08%). The ‘mean number of lichen species per tree’ were 4.22- and 3.33-fold greater in rural (mean=3.17) and developing land-uses (mean=2.5), respectively, than in urban areas (mean=0.75). ‘Mean lichen abundance rank (for all hardwoods)’ was 3.8- and 3-fold greater in rural (mean=1.58) and developing areas (mean=1.25), respectively, than in urban areas (mean=0.42).

Additional lichen data were collected from two water oak trees within each plot and included ‘mean number of crustose species,’ ‘mean number of foliose species,’ ‘crustose:foliose ratio,’ ‘mean lichen abundance rank,’ and ‘mean dominance of crustose over foliose' (Table 2.5). 'Mean number of foliose species' was 2.61-fold greater in rural land-use types (mean=1.77) than in developing areas (mean=0.68), while no differences were observed between urban areas and the other land-use types (mean=1.29). There were no significant differences observed between the land-use types in any of the other lichen variables measured.

A diverse assortment of 17 variables representing "urbanization" was calculated to discern which would be the best potential predictors (X variables) of forest condition (Table 2.6). These included population, housing, and road densities, plot distances to any road and nearest major road, percentage of land-cover occupied by forest (urban vegetation + deciduous forest + evergreen forest), pasture, grass (pasture + urban lawn), urban/built-up, and non-vegetated land (urban/built-up + bare ground), forest patch and edge densities, forest perimeter-area fractal shape, landscape Shannon's diversity and evenness indices, and maximum seasonal ozone (O_3) and nitrogen oxide (NO_X) concentrations (indicators of potential air pollution stress). In all but 4 of the 17 variables, there were highly significant differences in urban *vs.* rural land-use types (see Table 2.6). However, due to broad ranges in the data from developing land-use types, these areas did not, in any case, stand out as significantly different from rural land-use types. It is for this reason that Tukey-Kramer comparisons were used to discern any significant differences in group means of the forest structure and condition variables in urban *vs.* rural areas rather than the overall differences between all land-use types as identified by the standard ANOVA procedure.

2.4.2 Correlation Matrix

The next data analysis step was to develop a multivariate correlation matrix (as a data reduction technique) to determine which of the potential predictor variables were highly correlated with one another. Many of these variables displayed multicollinearity and were thus dropped from further analyses. Those shown to be independent amongst one another and that displayed potential to predict lichen incidence (the percentage of trees with lichens; Model 1) or lichen species richness (the number of lichen species per tree; Model 2) were selected as independent variables for use in the regression models as shown in Table 2.7. Variables positively correlated with lichen incidence included percent canopy cover and distance to nearest road, while those negatively correlated were upper canopy height, basal area, housing density, dbh, forest edge density, and total percent injury to trees (pest + disease + mechanical), as shown in Table 2.7. Variables positively correlated with lichen species richness were distance to nearest road, percent pasture land-cover, percent canopy cover, and percent forest land-cover, while those negatively correlated included housing density, subcanopy height, forest edge density, percent total non-vegetated land-cover, basal area, and dbh (Table 2.7).

2.4.3 Regression Modeling

Based on the findings from the correlation matrix, regression models were then developed. The first regression model objective was to predict lichen incidence as measured by the percentage of forest hardwood trees with lichens present. Different combinations of variables were used to develop eight different scenarios for this part of the analysis. Stepwise regression modeling was conducted first for data reduction and significant variable selection, followed by standard least squares using the selected variables to predict lichen incidence. For the purposes of this paper, only the most robust lichen incidence model will be discussed. Independent variables entered into this model by the mixed stepwise fit procedure were upper canopy height, housing density, dbh, forest edge density, and total percent injury to trees (pest + disease + mechanical). These variables were the best indicators of lichen incidence in West Georgia forests, resulting in the following model:

$$y = 63.620368 - 2.239278 \text{ upper canopy height} + 1.3165475 \text{ mean dbh} - 0.310389 \text{ housing density} - 0.292817 \text{ \% I+D+M injury} + 0.8843282 \text{ forest edge density}$$

Housing density alone accounted for 46% of the variance in the data, with forest edge density adding another 12% and upper canopy height adding another 9%. The remaining two variables accounted for another 6% for a total estimated r^2 of 0.73. Once the standard least squares regression model was run, these estimates proved to be accurate (r^2 of 0.73, RMSE=17.61). The model indicates that lichen incidence may be related to housing density, upper canopy height, forest edge, and tree dbh.

The second regression model predicted lichen species richness as measured by the number of lichen species present per forest hardwood tree. Again, different combinations of variables were used to develop eight different scenarios for this analysis. Stepwise regression was used to select potential significant predictor variables, which were then entered into the standard least squares models to predict lichen species richness. Again, for the purposes of this paper, only the most robust lichen species richness model will be discussed. Only percent pasture land-cover, distance to nearest road, and percent canopy cover were entered into the model by the mixed stepwise fit procedure. These variables were the best indicators of lichen species richness in West Georgia forests:

$$y = -3.20434 + 0.0459367 \text{ \% canopy cover} + 0.0024509 \text{ distance to any road} + 24.954566 \text{ \% pasture}$$

Percent pasture land accounted for 31% of the variance in the data, with distance to nearest road adding another 9% and percent canopy cover adding another 5%, for a total estimated r^2 of 0.45. Once the standard least squares regression model was run, these estimates proved to be accurate (r^2 of 0.45, RMSE=1.43). Although the r^2 is relatively low the model results suggest that lichen species richness may be related to percent pasture land, distance to nearest road, and percent canopy cover, but that other unmeasured factors may have also been involved.

2.5 Discussion

The goal of this study was to examine urbanization effects on forest stand structure and condition along an urban-to-rural gradient through the use of forest plot characterizations and bioindicators of ecosystem health. More specifically, are there forest health bioindicators (e.g., lichens) that can be modeled, predicted, and used as a surrogate for forest condition through the use of remotely-sensed and/or field-based independent variables? These results suggest that this may be possible. According to three separate statistical analyses, there are significant differences in several potential bioindicator variables between urban and rural land-use types. Moreover, there are strong correlations between lichen bioindicator variables and various urbanization metrics. For lichen incidence, these include distance to nearest road, housing density, and forest edge density. For lichen species richness, each of those listed above are well-correlated, as are the percentages of pasture land-cover and total non-vegetated land-cover. These variables were used to produce models with good predictive capabilities.

2.5.1 Forest Stand Structure

One of the major purposes of the site characterization data was to determine if and how the variables differed among sites. Of the 18 forest stand structure variables measured, only two of these differed among land-use types. I observed that urban areas contained fewer tree species than either rural or developing sites. Developing areas contained the most diverse species mix. However, this might be expected, since urban areas typically have lower species richness than rural areas (McKinney, 2002; Burton *et al.*, 2005). It could also imply that rural areas that are currently under development still have greater native species diversity than urban centers, yet that diversity might tend to decrease as development increases and areas become more urbanized (Miller and Hobbs, 2002).

These results also suggest that hardwood density is greatest in developing and rural areas implying that these urban forests could be less diverse because, in the plots I selected, they are less dense than those in more rural locations. The observed results could also possibly be attributed to altered forest structure due to disturbance (McKinney, 2006), dieback of species sensitive to air pollutant exposure (McLaughlin and Percy, 1999) and other anthropogenic stressors (Miller and Hobbs, 2002), or that they were simply removed due to injury or for development.

Since there were no significant differences in the forest stand variables measured (median age, percent peak canopy cover, upper and subcanopy heights), nor in the understory or ground cover variables, it was assumed that the microclimates (i.e., temperature, humidity, light, wind, friction) of these forested plots also do not vary significantly. My assumption was supported by the small ranges in maximum seasonal forest stand temperatures and seasonal diurnal relative humidity I measured at several of these plots as part of a different study (see Chapter 3). This observation has important implications for lichen community dynamics, as temperature is a major factor controlling lichen incidence (McCune *et al.*, 1997). As such, I feel that these data are sufficient to state that I have minimized between-plot microclimatic variability.

2.5.2 Pests, Diseases, & Mechanical Injury

"Tree injury" variables measured were overall, not significantly different between land-use types. Of the four variables measured, only percent incidence of mechanical injury to all trees and the combined injury resulting from pests, diseases, and mechanical injury were significantly different. The measurements suggest that there were more mechanically injured trees in urban plots (30% of trees sampled). However, it is interesting that 14% and 19% of trees sampled in rural and developing areas (respectively) were injured, and this could be explained by two back-to-back large-scale disturbances in the West Georgia region. On September 16-17, 2004, Hurricane Ivan (a Category 5 hurricane at sea and Category 3 at landfall) traversed through the region, with its high-speed winds toppling and weakening trees and creating gaps in the canopy. This was followed four months later by a major ice storm on January 28-29, 2005 that injured trees weakened from the prior disturbance. Since these two major disturbances occurred just prior to sampling, it is possible that this is the reason many of the sites, regardless of land-use type, had relatively high mechanical injury scores.

Typically, forests that have experienced disturbance are often more susceptible to other forms of environmental stress (Zipperer, 2002). Interestingly, symptoms of injury by pests and/or diseases were negligible in each of the plots. These results are contrary to the findings of previous studies in which urban systems were found to have a higher incidence of pests and diseases (McLaughlin and Percy, 1999; McIntyre, 2000; McKinney, 2006). The difference in results could be attributed to natural fluctuations in pest and disease cycles resulting in minimal signs or symptoms of activity during the sampling period, or the use of pesticides/herbicides that is typical in urban and agricultural areas (McIntyre, 2000). It also could be due to rapid harvesting of diseased or pest-infested timber after an outbreak (i.e., southern pine beetle), which is typical in city parks and residential areas.

2.5.3 Lichen Incidence, Abundance, & Species Richness

In the exploratory analyses, there were noted differences in lichen incidence, abundance, and species richness between urban *vs.* rural (and sometimes rural and developing) land-use types. Rather than existing somewhere in the middle of the continuum of data points, values for most of the variables measured at sites in developing areas were more closely related to those of rural sites while a few were not significantly different from the urban sites. The percentage of lichens on all trees was significantly greater in rural locations followed by developing areas, with the least incidence in the urban plots. My findings confirm the results of McCune *et al.* (1997) and Geiser and Neitlich (2007), who observed far less lichen coverage on trees in urban areas of the Southeastern and Northwestern U.S., respectively. Differences were attributed to temperature and/or air pollution gradients in those regions (McCune *et al.* 1997; Geiser and Neitlich 2007). Esseen and Renhorn (1998) found lower lichen abundance along forest edges in Sweden as a result of forest edge effects. Sillet (1994) reported decreased growth in forest-interior lichens transplanted to edge habitats in Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco var. *menziesii*) forests in Oregon, which was due to less time spent in a photosynthetically active state resulting from the higher drying rates at the forest edge because of higher light intensity and increased winds.

Possibly more importantly, the number of lichen species in each of the land-use types was different. There was greater lichen species richness in rural and developing regions than in urban areas. Gombert (2004) reported that lichen species diversity was influenced by an increase in “environmental artificiality” in Grenoble, France rather than air pollution exposure alone, with urban areas having lower lichen species diversity than rural areas. Lichen species diversity has also been shown to vary greatly with exposure to air pollutants such as SO_2 and NO_2 (McCune *et al.*, 1997; van Dobben *et al.*, 2001; Frati *et al.*, 2006; Fenn *et al.*, 2007; Geiser and Neitlich, 2007). As with lichen abundance, edge effects can also play a major role in lichen species diversity (Renhorn *et al.*, 1997; Esseen and Renhorn, 1998). My results suggest that lichen species richness is greater in rural areas of West Georgia and could possibly signify healthier forest ecosystems. Significantly fewer species in urban areas, combined with relatively low abundance, suggests that lichen community composition is different than in rural areas. Some species may be disappearing from urban forests (McCune *et al.*, 1997), while those present in urban forests could possibly be nitrophytic, or nitrogen-demanding species (Gombert *et al.*, 2004; Fenn *et al.*, 2007). However, more in-depth taxonomic surveys of the lichen communities present are needed to validate this hypothesis. Lichen abundance rank has often been used as a forest health variable (Muir and McCune, 1988; McCune *et al.*, 1997). Again, the greatest mean rank values were found in rural and developing forests. Although these data were not greatly different between land-use types, a difference was observed. Given that mean lichen rank is an average of the relative abundance of species, one would expect these data to correlate, at least to some extent, with the lichen incidence and species richness variables.

2.5.4 Predicting Lichen Occurrence

From the regression modeling of lichen incidence (Model 1) I observed that as housing density and upper canopy height decreased, and as forest edge density and dbh increased, the percentage of trees with lichens increased. High housing densities are typically indicative of urbanized areas (U.S. Census Bureau, 2005). Prior studies have reported that in urban residential areas, forest patches are typically small, with little to no interior lichen species (Sillett, 1994; Esseen and Renhorn, 1998) but more edge (Sillett, 1994; Esseen and Renhorn, 1998), exotic (McCune *et al.*, 1997; Geiser and Neitlich, 2007), or nitrophytic (Gombert *et al.*, 2004; Fenn *et al.*, 2007) species. However, these edges could possibly be exposed to more pollutants – from nearby stationary emission sources (Jovan and McCune, 2005), herbicides and/or pesticides (McIntyre, 2000), and/or vehicular traffic (Cape *et al.*, 2004). Consequently, there could be increased mortality, and a lower incidence of lichens in these urban forest patches (Gombert *et al.*, 2004). That forest edge density (amount of forest edge on a per area basis) was also a significant variable in this model, suggests that edge effects could possibly be linked to lichen incidence (Renhorn *et al.*, 1997; Esseen and Renhorn, 1998; Gombert *et al.*, 2004). What is more interesting is that, even though all of these factors were important in predicting lichen incidence in this model, and even though lichens can have a greater occurrence along forest edges than in deep forest interiors, it is conceivable that greater air pollutant exposure potential in urban environments may contribute more to lichen occurrence (or absence) than forest patch size and amount of forest edge. These results contradict the findings of Gombert (2004), who reported that it is “environmental artificiality” that controls lichen abundance rather than pollution exposure, and those of Cape (2004), who reported that emissions from vehicular traffic usually diminish within 10 m of roadsides and thus do not penetrate forest edges beyond that distance.

Certain forest structural variables appear to be linked to the establishment and maintenance of lichen communities within a forest ecosystem (McCune *et al.*, 1997). As dbh increases, or as the surface area of a suitable lichen substrate increases, so does lichen incidence (van Dobben *et al.*, 2001). Similarly, as the upper canopy height decreases, or as more light and throughfall are able to penetrate the canopy to reach the lichens growing within, lichen incidence increases (Gauslaa and Solhaug, 2000; Weathers *et al.*, 2001). It is likely, however, that it is the combination of each of these variables (and possibly others unknown) that may influence lichen incidence, rather than any one variable alone.

2.5.5 Predicting Lichen Species Richness

The second model attempted to predict lichen species richness within a given forested stand. As percent pasture land-cover, distance to nearest road, and percent canopy cover increased, the number of lichen species per tree also increased. The significance of percent pasture land might suggest two things. First, pasture land tends to fragment the landscape but sometimes a certain amount of forest cover is maintained, especially along riparian areas, however minimal (Platts, 1987). As such, small forest patches occasionally remain, but these have a higher edge-to-interior ratio (Zipperer *et al.*, 1990; Zipperer, 1993). This may result in a greater number of lichen edge species colonizing the forest patch (Esseen and Renhorn, 1998; Gombert *et al.*, 2004). In the absence of pollutant exposure, these lichens might be able to thrive in these edge environments, unlike lichens in urban environments where edge locations would render them more vulnerable to pollution exposure (Esseen and Renhorn, 1998; Gombert *et al.*, 2004). The distance to nearest road variable suggests this could possibly be a factor. Lichen communities located farther away from roads and mobile pollution sources tend to be more species rich (McIntyre, 2000; Cape *et al.*, 2004). Roads create edges, as do other interruptions in forest cover; however, it may be possible that there is greater mortality of pollution-sensitive edge lichens due to pollutant exposure from vehicular traffic which could mask any increases in lichen species richness resulting from new edges created by roads (Cape *et al.*, 2004).

As percent forest canopy increased, so did species richness. This finding was initially contrary to expectations based on the available literature. Lichens need some light and nutrient throughfall to penetrate the canopy in order to survive (Conti and Cecchetti, 2001), so a very dense canopy might provide less of these resources than one that is less dense. It is possible that more open canopies allow too little moisture and too much light and wind, and pollutant exposure for the lichens (McCune *et al.*, 1997; Jovan and McCune, 2005; Fenn *et al.*, 2007; Geiser and Neitlich, 2007). My analysis suggests that patches with a greater amount of canopy cover appear to have a greater number of lichen species. However, more in-depth canopy density measurements and throughfall assessments should be conducted to confirm the results.

Results from prior studies have suggested that lichen incidence, abundance, and species richness are correlated with differences in various climatic and air pollution-related variables (McCune *et al.*, 1997; van Dobben *et al.*, 2001; Frati *et al.*, 2006; Fenn *et al.*, 2007; Geiser and Neitlich, 2007) and edge effects from forest fragmentation (Renhorn *et al.*, 1997; Esseen and Renhorn, 1998) and other forms of landscape disturbance (Gombert *et al.*, 2004). My results seem to exhibit similar linkages between "urbanization" and lichen incidence and species richness. The major biological variables related to lichen incidence and species richness as suggested by these models were percent canopy cover, upper canopy height, and tree dbh. Urbanization and landscape pattern variables related to lichens in these models were housing density, forest edge density, percent pasture land-cover, and distance to nearest road. Again, it is likely that some combination of each of these variables (and possibly others unknown) that influence lichen species richness, rather than any single variable alone. However, results suggest these "urbanization" variables are linked to lichen incidence and species richness, corroborating the findings of the previous studies discussed herein, and are sufficient to predict lichen incidence and species richness in West Georgia.

2.6 Conclusions

These results indicate differences in forest conditions across land-use types in West Georgia but little to no differences in forest stand structure. Most notably, lichen communities differ between these forest stands. Lichen incidence, abundance, and species richness were greatest in rural forests and least in urban locations. Although the variability within the developing sites may have masked statistical significance in some cases, lichens appeared to be a good indicator for predicting forest condition in West

Georgia. The incidence of lichens was most closely related to urbanization variables such as housing density and forest edge density. A possible explanation for the lower incidence of lichens in these urban forests could be greater pollution exposure potential in these small forest patches. Lichen species richness, however, was closely related with amount of edge habitat created by agricultural lands and roads. Percent canopy cover was also linked to lichen species richness. Each of these three variables could also possibly be related to differences in unmeasured climatic variables (e.g., light and wind) within each of the forest stands between urban *vs.* rural sites.

Incidence, abundance, and species richness of lichens in West Georgia were relatively low overall. McCune *et al.* (1997) reported that the Southeastern Piedmont had the least lichen species richness of any of the physiographic provinces in the Southeastern U.S. My findings support their conclusions; however, none of the other provinces were sampled as part of this study. Although pollution-sensitive lichen species are sparse compared to others areas of the U.S. (e.g., Pacific Northwest, Great Lakes, Northeast), I was still able to observe differences between land-use types. Since measured climatic conditions and pollution concentrations were generally uniform across the West Georgia region, the differences observed could be linked to forest fragmentation (i.e., creation of forest edge) associated with urban development or to mobile pollution sources (i.e., vehicular traffic).

It was expected that forest health variable values in urban *vs.* rural areas would have been much more distinct. This might have been the case had more plots been selected for sampling, had there been a greater number of sites in each of the land-use types, or if sampling had occurred over a broader spatial scale. Quite possibly, the developing sites selected may have been more indicative of rural land-use types, given the low values of the various urbanization variables calculated (e.g., housing density, forest cover). The selection of new sampling sites in developing areas of more intermediate "urbanized" values might improve these analyses, since the ranges between developing and urban area values in several of the measured variables was great. Regardless, the results obtained suggest that there are differences in several of the forest health variables measured, specifically those of lichens. By refining these methods and adding more sampling plots, more distinct results could be obtained from this type of assessment. Further, since lichens are slow-growing and long-lived, long-term monitoring is necessary to observe changes that take place at longer temporal scales. Research regarding air pollution effects on Southern lichen communities may provide insight about the relationship between lichens and their functions within forest ecosystems. Statistical and simulation models could be strengthened using this information and by incorporating robust indicators as predictors of land-use change and corresponding forest health status.

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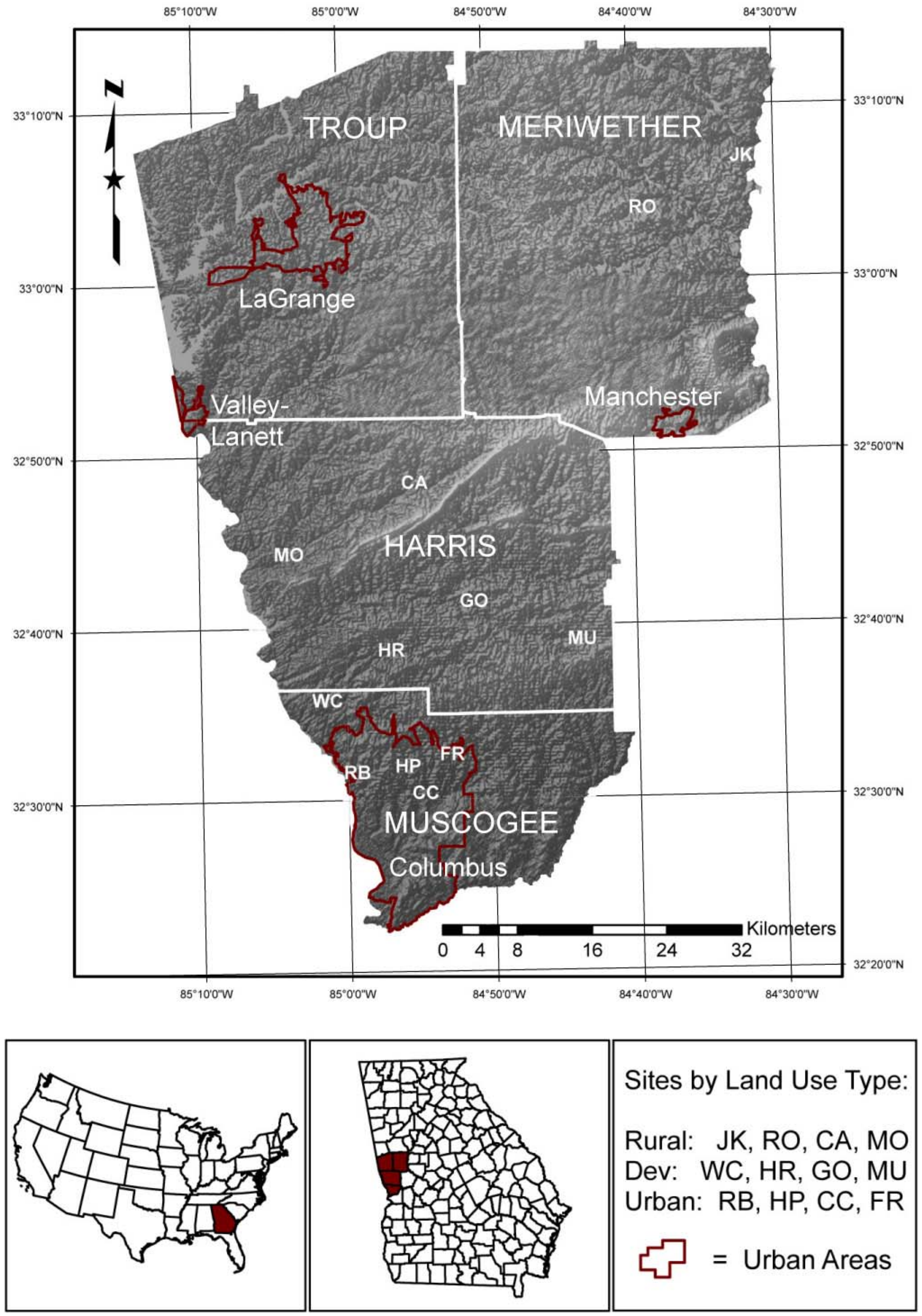

Figure 2.1 Map of West Georgia study area. Urban Sites: RB=Roaring Branch; HP=Heath Park; CC=Cooper Creek; FR=Flat Rock; Developing Sites: WC=Whiskey Creek; HR=Hunter Road; GO=Goolsby; MU=Mulberry Creek; Rural Sites: MO=Mountain Oak; CA=Callaway; RO=Red Oak: JK=Joe Kurz WMA. Source: Diane M. Styers, 2008.

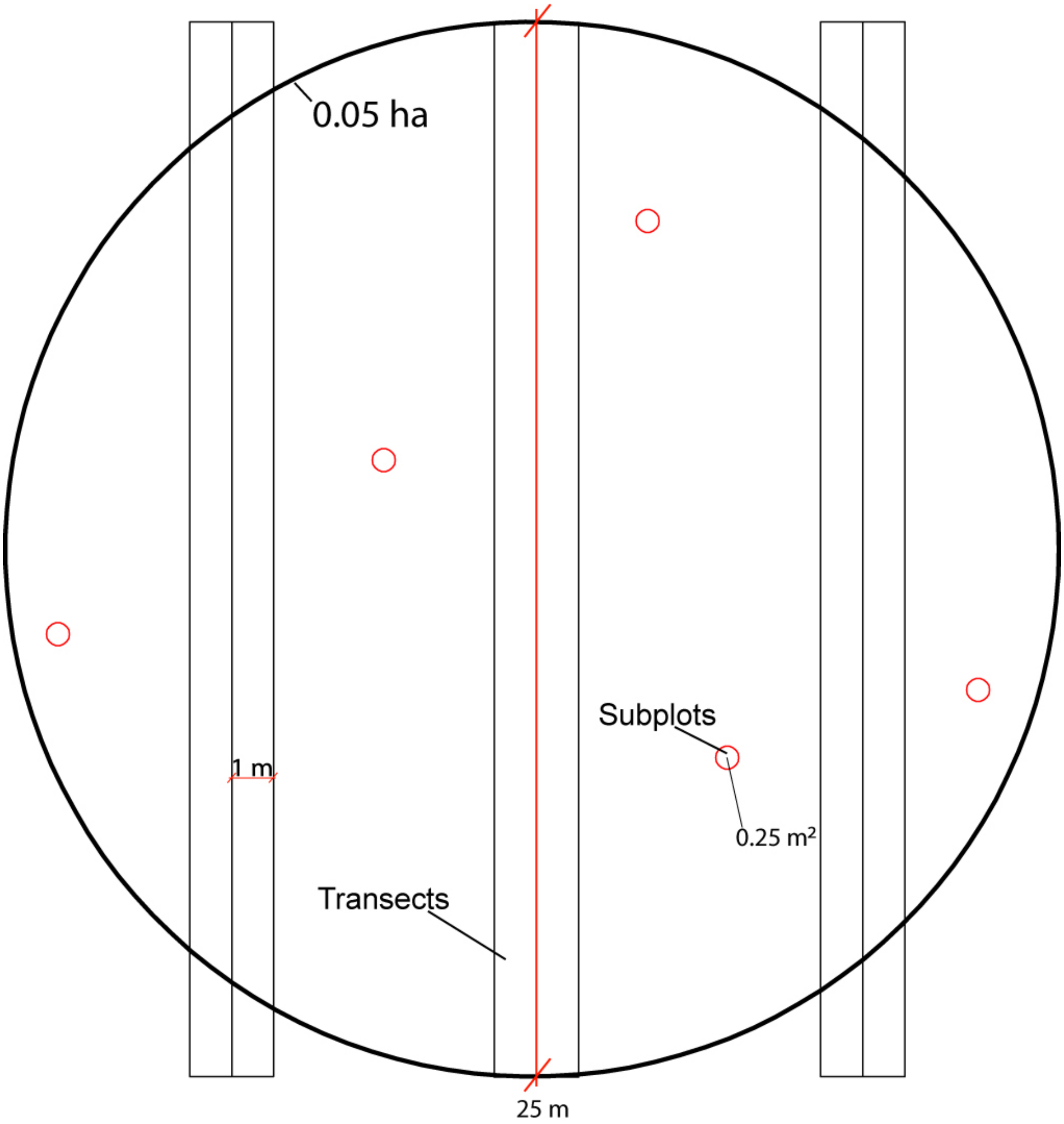

Figure 2.2 Diagram of main plot showing vegetation transects and subplots. Source: Diane M. Styers, 2008.

Figure 2.3 Photograph showing lichen sampling grid (with close-up). Source: Diane M. Styers, 2008.

Table 2.1 West Georgia site characteristics measured during study duration (2005-2006).

Site	Latitude	Longitude	Elev (m)	Soil Series	%Hardwood	%Canopy	BA (m^2/ha)	Stand Age (Yr)
RB	32.5271	-84.9903	106	Wedowee sandy loam, 10 - 35% slopes	69	95	26.59	34
HP	32.5336	-84.9321	101	Dothan-Urban land complex, 2 - 5% slopes	74	74	39.15	45
CC	32.5076	-84.9125	100	Esto-Urban land complex, 8 - 25% slopes	70	90	37.08	53
FR	32.5448	-84.8814	208	Pacolet sandy clay loam, 10 - 15% slopes	54	70	41.53	51
WC	32.6016	-85.0226	126	Pacolet sandy loam, 15 - 25% slopes	83	94	32.89	40
HR	32.6456	-84.9489	188	Pacolet sandy loam, 6 - 10% slopes	94	94	39.30	47
GO	32.6920	-84.8534	139	Pacolet sandy loam, 10 - 15% slopes	77	85	26.83	47
MU	32.6541	-84.7304	205	Chewacla sandy loam, 0 - 2% slopes	100	91	21.45	30
MO	32.7393	-85.0642	157	Pacolet sandy loam, 6 - 10% slopes	71	94	30.25	48
CA	32.8068	-84.9186	246	Cecil sandy loam, 6 - 10% slopes	57	94	31.11	60
RO	33.0687	-84.6508	254	Cecil sandy clay loam, 10 - 15% slopes	89	90	35.07	53
JK	33.1165	-84.5360	239	Cecil sandy clay loam, 6 - 10% slopes	97	95	35.02	39

Note:

[1] Urban Sites: RB=Roaring Branch; HP=Heath Park; CC=Cooper Creek; FR=Flat Rock; Developing Sites: WC=Whiskey Creek; HR=Hunter Road; GO=Goolsby; MU=Mulberry Creek; Rural Sites: MO=Mountain Oak; CA=Callaway; RO=Red Oak: JK=Joe Kurz WMA.

Table 2.2 Upland overstory tree species observed during plot establishment in West Georgia.

Scientific Name	**Common Name**
Acer barbatum Michx.	florida maple
Acer negundo L.	box elder
Acer rubrum L.	red maple
Carpinus caroliniana Walt.	american hornbeam
Carya glabra (P. Mill.) Sweet	pignut hickory
Carya ovata (P. Mill.) K. Koch	shagbark hickory
Carya tomentosa (Lam. ex Poir.) Nutt.	mockernut hickory
Celtis laevigata Willd.	sugarberry
Celtis occidentalis L.	hackberry
Cornus florida L.	flowering dogwood
Fagus grandifolia Ehrh.	American beech
Fraxinus pennsylvanica Marsh.	green ash
Juniperus virginiana L.	eastern redcedar
Ligustrum sinense Lour.	Chinese privet
Liquidambar styraciflua L.	sweetgum
Liriodendron tulipifera L.	yellow poplar / tuliptree
Morus rubra L.	red mulberry
Nyssa sylvatica Marsh.	blackgum / black tupelo
Ostrya virginiana (P. Mill.) K. Koch	hophornbeam
Oxydendrum arboreum (L.) DC.	sourwood
Pinus echinata P. Mill.	shortleaf pine
Pinus taeda L.	loblolly pine
Prunus serotina Ehrh.	black cherry
Quercus alba L.	white oak
Quercus coccinea Muenchh.	scarlet oak
Quercus falcata Michx.	southern red oak
Quercus laurifolia Michx.	laurel oak
Quercus michauxii Nutt.	swamp chestnut oak
Quercus nigra L.	water oak
Quercus phellos L.	willow oak
Quercus prinus L.	chestnut oak
Quercus stellata Wangenh.	post oak
Quercus velutina Lam.	black oak
Robinia pseudoacacia L.	black locust
Ulmus alata Michx.	winged elm
Ulmus americana L.	American elm
Ulmus rubra Muhl.	slippery elm

Table 2.3 Definitions for each of the variables measured in West Georgia.

Variables	**Definitions**
Total number of trees >10cm dbh /ha	Total number of mature trees (>10cm dbh) per hectare (ha)
Total number of hardwoods /ha	Total number of mature hardwoods (>10cm dbh) per ha
Total number of pines /ha	Total number of mature pines (>10cm dbh) per ha
Hardwood:Pine ratio	Ratio of hardwood to pine trees per ha
Total number of tree species	Total number of different tree species measured at each site
Mean dbh (cm) of all mature trees	Mean dbh (in cm) of all mature trees (>10cm) measured
Basal Area (m^2/ha)	Basal area (m^2/ha)
Median age of stand	Median age of forest stand as measured by six dominant pines at each site
% Peak canopy cover	Peak canopy cover percentage at each site (measured in mid-June)
Mean upper canopy height (m)	Mean height of upper canopy at each site (measured by six dominant trees in main canopy)
Mean subcanopy height (m)	Mean height of subcanopy at each site (measured by six average trees in secondary canopy)
Total number of trees 2.5-10cm dbh/ha	Total number of trees (2.5-10cm dbh) per ha
Mean number of saplings & shrubs 0.635-2.5cm/ha	Mean number of saplings & shrubs (0.635-2.5cm diameter & at least 1m in height) per ha
Mean number of seedlings <0.635cm /ha	Mean number of seedlings (<0.635cm diameter and <1m in height) per ha
% Woody stems /ha	Percentage of groundcover occupied by small woody stems (<0.635cm diameter) per ha
% Herbaceous plants /ha	Percentage of groundcover occupied by herbaceous plants per ha
% Leaf litter /ha	Percentage of groundcover occupied by leaf litter per ha
% Bare ground /ha	Percentage of groundcover occupied by bare ground (or dirt) per ha
% Trees with insect injury	Percentage of trees with evidence of insect injury
% Trees with disease injury	Percentage of trees with evidence of disease injury
% Trees with mechanical damage injury	Percentage of trees with evidence of mechanical injury
% Insect + Disease + Mech damage for all trees	Percentage of trees with evidence of insect, disease, &/or mechanical injury
% Trees with lichens	Percentage of trees with lichen incidence (presence *vs.* absence)
Mean number of lichen species per tree	Mean number of lichen species per tree
Mean lichen abundance rank for all hardwoods	Mean lichen abundance rank for all hardwoods (percentage of cover: 1=0%; 2=1-20%; 3=21-40%; 4=41-60%; 5=61-80%; 6=81-100%)

Table 2.3 con't. Definitions for each of the variables measured in West Georgia.

Variables	**Definitions**
Mean number of crustose lichen species on water oaks	Mean number of crustose lichen species per tree
Mean number of foliose lichen species on water oaks	Mean number of foliose lichen species per tree
Crustose:Foliose ratio (on water oaks)	Ratio of crustose to foliose lichen species per tree
Mean lichen abundance rank for water oaks	Mean lichen abundance rank for water oaks (percentage of cover: 1=0%; 2=1-20%; 3=21-40%; 4=41-60%; 5=61-80%; 6=81-100%)
Mean dominance of crustose over foliose (on water oaks)	Mean dominance of crustose over foliose lichens (1= crustose; 2= foliose)
Population density	Population density (number of people/km^2) for census tract containing site
Housing density	Housing density (number of houses/km^2) for census tract containing site
Road density	Road density (length of road in km/km^2) for census tract containing site
Plot distance to any road (m)	Measure of distance (in m) from each plot to the nearest road
Plot distance to major road (m)	Measure of distance (in m) from each plot to the nearest paved road
% Forest	Percentage of forest cover for census tract containing site
% Pasture	Percentage of pasture cover for census tract containing site
% Grasses (pasture + lawn)	Percentage of grass cover (pasture & urban lawn) for census tract containing site
% Urban	Percentage of urban/built-up land cover for census tract containing site
% Non-vegetated land (urban + bare ground)	Percentage of urban/built-up land & bare ground (dirt) cover for census tract containing site
Forest patch density	Number of forest patches per 100 ha within census tract containing site
Forest edge density	Total length of forest edge (in m/ha) within census tract containing site
Forest perimeter-area fractal shape	Forest patch shape complexity, ranging from simple (1) to complex (2) perimeter shapes
Shannon's landscape diversity index	Proportion of landscape occupied by a patch type of a particular class, where 0=only one patch type, increasing as the number of different patch types increases
Shannon's landscape evenness index	Evenness of areal distribution among patch types, where 0=uneven areal distribution or dominance of only one patch type, increasing toward 1, where there is perfect evenness
Maximum seasonal ozone concentration	Maximum ozone concentration measured at site from May - Sept, 2006
Maximum seasonal NO_x concentration	Maximum NO_x concentration measured at site from May - Sept, 2006

Table 2.4 Standard ANOVA values and means (±SE) for forest stand structure variables collected in West Georgia.

	Standard ANOVA		Tukey-Kramer HSD Comparisons		
Variable	**Mean Square**	**Prob > F**	**Urban (n=4)**	**Developing (n=4)**	**Rural (n=4)**
Total number of trees >10cm dbh /ha	19048	0.37	391.67 ± 75.69	523.33 ± 42.60	493.33 ± 72.75
Total number of hardwoods /ha	29448	0.04	265.00 ± 56.53 (a)	430.00 ± 33.17 (b)	388.33 ± 15.96 (a,b)
Total number of pines /ha	6100	0.51	126.67 ± 23.73	63.58 ± 27.63	135.00 ± 70.52
Hardwood:Pine ratio	7578	0.28	2.90 ± 0.26	89.59 ± 52.28	53.12 ± 33.40
Total number of tree species	11.19	0.04	4.67 ± 0.54 (a)	8.00 ± 1.03 (b)	6.58 ± 0.58 (a,b)
Mean dbh (cm) of all mature trees	77.78	0.07	31.33 ± 3.00	23.25 ± 1.29	24.22 ± 2.21
Basal Area (m^2/ha)	35.68	0.41	36.09 ± 3.29	30.12 ± 3.85	32.86 ± 1.27
Median age of stand	87.74	0.36	45.81 ± 4.39	40.71 ± 4.15	50.06 ± 4.49
% Peak canopy cover	135.83	0.15	82.28 ± 6.02	91.00 ± 2.16	93.33 ± 1.16
Mean upper canopy height (m)	2.31	0.92	26.53 ± 2.05	25.27 ± 3.47	25.16 ± 2.13
Mean subcanopy height (m)	7.46	0.44	18.46 ± 1.70	16.56 ± 1.45	15.82 ± 1.07
Total number of trees 2.5-10cm dbh	415969	0.14	244.17 ± 161.80	875.00 ± 281.60	675.83 ± 148.92
Mean number of saplings 0.635-2.5cm	595.47	0.41	30.56 ± 16.76	31.67 ± 12.62	52.22 ± 4.30
Mean number of seedlings <0.635cm	4.84	0.47	1.80 ± 0.85	3.33 ± 0.98	3.93 ± 1.64
% Woody stems /ha	0.11	0.56	0.40 ± 0.18	0.64 ± 0.23	0.71 ± 0.20
% Herbaceous plants /ha	124.92	0.29	16.38 ± 5.78	6.15 ± 1.94	7.38 ± 5.36
% Leaf litter /ha	34.01	0.77	88.83 ± 6.01	90.17 ± 7.10	94.42 ± 3.07
% Bare ground /ha	33.54	0.58	3.79 ± 2.97	7.92 ± 5.82	2.33 ± 1.01

Notes:

[1] SE = standard error of the mean.

[2] n = number of study sites sampled.

[3] Elemental concentrations reported in milligrams per kilogram (mg kg $^{-1}$).

[4] Mean values in a row with different letters (variables in bold) are significantly different ($p < 0.05$) based on Tukey-adjusted least squares means.

Table 2.5 Standard ANOVA values and means (±SE) for forest condition variables collected in West Georgia.

	Standard ANOVA		**Tukey-Kramer HSD Comparisons**		
Variable	**Mean Square**	**Prob > F**	**Urban (n=4)**	**Developing (n=4)**	**Rural (n=4)**
% Insect incidence for all trees	4.70	0.48	2.50 ± 1.81	0.33 ± 0.33	1.33 ± 1.03
% Disease incidence for all trees	14.51	0.59	4.25 ± 1.75	4.00 ± 4.00	0.83 ± 0.63
% Mechanical damage incidence for all trees	279.90	0.09	30.25 ± 2.96 (a)	19.25 ± 3.18 (a,b)	13.83 ± 6.96 (b)
% Insect + Disease + Mech damage for all trees	452.34	0.04	37.00 ± 3.82 (a)	23.58 ± 3.91 (a,b)	16.00 ± 6.53 (b)
% Trees with lichens	1320.08	0.22	51.83 ± 21.46 (a)	74.08 ± 11.67 (a,b)	87.83 ± 5.78 (b)
Mean number of lichen species per tree	6.23	0.14	0.75 ± 0.43 (a)	2.50 ± 1.04 (b)	3.17 ± 0.90 (b)
Mean lichen abundance rank for all hardwoods	1.44	0.13	0.42 ± 0.16 (a)	1.25 ± 0.48 (b)	1.58 ± 0.42 (b)
Mean number of crustose species on water oaks	0.90	0.68	4.61 ± 0.85	4.15 ± 0.66	5.09 ± 0.70
Mean number of foliose species on water oaks	1.19	0.24	1.29 ± 0.53 (a,b)	0.68 ± 0.30 (a)	1.77 ± 0.39 (b)
Crustose:Foliose ratio (on water oaks)	131.15	0.10	9.72 ± 3.65	15.95 ± 4.03	4.52 ± 1.83
Mean lichen abundance rank for water oaks	91.97	0.57	26.15 ± 8.15	17.50 ± 4.00	25.42 ± 5.66
Mean dominance of crustose over foliose	0.16	0.21	1.23 ± 0.18	1.04 ± 0.04	1.44 ± 0.17

Notes:

[1] SE = standard error of the mean.

[2] n = number of study sites sampled.

[3] Mean values in a row with different letters (variables in bold) are significantly different ($p < 0.05$) based on Tukey-adjusted least squares means.

Table 2.6 Standard ANOVA values and means (±SE) for urbanization variables collected in West Georgia.

	Standard ANOVA		Tukey-Kramer HSD Comparisons					
Variable	**Mean Square**	**Prob > F**	**Urban (n=4)**		**Developing (n=4)**		**Rural (n=4)**	
Population density	729062	<0.01	771.11 ± 191.73	(a)	51.40 ± 23.97	(b)	13.37 ± 1.79	(b)
Housing density	119322	<0.01	311.32 ± 79.97	(a)	18.76 ± 8.12	(b)	5.99 ± 1.10	(b)
Road density	44.86	<0.01	7.40 ± 0.99	(a)	1.77 ± 0.15	(b)	1.45 ± 0.10	(b)
Plot distance to any road (m)	59371	0.20	111.58 ± 9.29		341.75 ± 97.68		295.92 ± 116.07	
Plot distance to major road (m)	25767	0.79	486.67 ± 128.18		378.33 ± 83.33		535.08 ± 236.19	
% Forest	1781	<0.01	42.28 ± 3.20	(a)	79.13 ± 0.91	(b)	78.51 ± 2.92	(b)
% Pasture	29.60	0.02	0.51 ± 0.17	(a)	3.63 ± 1.03	(a,b)	5.93 ± 1.61	(b)
% Grasses (pasture + lawn)	0.34	0.93	5.82 ± 0.87		5.54 ± 0.55		6.12 ± 1.48	
% Urban	3054	<0.01	50.01 ± 3.22	(a)	4.26 ± 2.24	(b)	0.29 ± 0.26	(b)
% Non-vegetated (urban + bare ground)	1762	<0.01	50.01 ± 3.22	(a)	13.72 ± 0.49	(b)	13.59 ± 2.02	(b)
Forest patch density	223	<0.01	14.54 ± 2.66	(a)	1.85 ± 0.13	(b)	1.40 ± 0.33	(b)
Forest edge density	7147	<0.01	137.66 ± 8.72	(a)	70.10 ± 1.90	(b)	59.87 ± 3.34	(b)
Forest perimeter-area fractal shape	0.004	0.05	1.49 ± 0.02	(a)	1.45 ± 0.00	(b)	1.44 ± 0.01	(b)
Shannon's landscape diversity index	0.07	<0.01	0.94 ± 0.01	(a)	0.74 ± 0.02	(b)	0.70 ± 0.05	(b)
Shannon's landscape evenness index	0.06	<0.01	0.68 ± 0.01	(a)	0.46 ± 0.01	(b)	0.47 ± 0.05	(b)
Maximum seasonal ozone concentration	9.53	<0.01	15.26 ± 1.95		11.24 ± 1.11		14.73 ± 0.12	
Maximum seasonal NO_x concentration	7.44	0.02	6.03 ± 0.29	(a)	2.88 ± 0.47	(b)	2.52 ± 0.53	(b)

Notes:

[1] SE = standard error of the mean.

[2] n = number of study sites sampled.

[3] Mean values in a row with different letters (variables in bold) are significantly different ($p < 0.05$) based on Tukey-adjusted least squares means.

Table 2.7 Independent *vs.* dependent variable correlations for lichen prediction models.

Model 1

Dependent Variable: Percentage of Trees with Lichens		
Independent Variables:	**Rho**	**p**
% Peak canopy cover	0.55	0.07
Plot distance to any road (m)	0.34	0.28
Mean upper canopy height (m)	-0.64	0.03
Basal Area (m^2/ha)	-0.53	0.08
Housing density	-0.48	0.11
Mean dbh (cm) of all mature trees	-0.20	0.53
Forest edge density	-0.27	0.40
% Insect + Disease + Mech damage for all trees	-0.35	0.27

Model 2

Dependent Variable: Number of Lichen Species per Tree		
Independent Variables:	**Rho**	**p**
Plot distance to any road (m)	0.57	0.05
% Pasture	0.55	0.06
% Peak canopy cover	0.55	0.07
% Forest	0.46	0.13
Housing density	-0.61	0.03
Mean subcanopy height (m)	-0.47	0.12
Forest edge density	-0.35	0.26
% Urban + Bareground	-0.39	0.20
Basal Area (m^2/ha)	-0.45	0.14
Mean dbh (cm) of all mature trees	-0.42	0.17

Note:

[1] Correlation coefficients (Rho) and p-values (p=Prob>|Rho|) derived using Spearman's Rank multivariate correlation matrix.

3. URBANIZATION AND ATMOSPHERIC DEPOSITION: USE OF BIOINDICATORS IN DETERMINING PATTERNS OF LAND-USE CHANGE IN WEST GEORGIA

3.1 Abstract

Land-use changes disrupt ecosystem patterns and processes, and serve as precursors to other biotic and abiotic stressors. Forest ecosystems in the urban core typically differ structurally and functionally from those in rural areas. The overall objective of the study was to determine concentrations of selected air-borne contaminants (N, S, and heavy metals) over space and time and relate these to land-use changes by 1) obtaining lichen tissue samples for information about localized pollutant exposure, 2) utilizing soil sample data for broader spatial coverage, and 3) using tree cores for historical records of exposure. Elemental concentrations in lichens, soils, and tree cores were examined from 36 plots distributed along an urban-to-rural gradient surrounding Columbus, Georgia. ANOVA was used to discern differences in concentrations between land-use types, and repeated measures MANOVA was used to detect differences over time. *In situ* lichen tissue appeared to exhibit the most differences among land-use types, with Cu, N, Pb, S, and Zn concentrations all significantly greater at urban sites. Lichen transplants revealed differences in concentrations between species, but not between land-use types. No discernable trends were observed regarding concentrations in soil and tree core data.

Keywords: atmospheric deposition, bioindicator, ecosystem, forest health, land-use change, lichens, metals, urbanization, urban-to-rural gradient

3.2 Introduction

Forest ecosystems in urban and urbanizing centers are exposed to many sources of air pollution because of increased human presence and may be subject to higher amounts of injury than those in rural areas. Atmospheric deposition of pollutants can affect various processes within a forest community, from individual plant to ecosystem levels, and exposure responses are often complex and not well understood (Muir and McCune, 1988; McDonnell *et al.*, 1997; Chappelka and Samuelson, 1998). Forest health depends on many ecosystem processes that balance tree growth, mortality, and regeneration, and maintain homoeostasis (Hyland, 1994). For example, air pollutants such as O_3, NO_2, NH_3, SO_2, and toxic metals can affect plants at the leaf-level, decreasing photosynthetic rates (Lefohn *et al.*, 1997; McDonnell *et al.*, 1997; Lovett *et al.*, 2000; Gregg *et al.*, 2003). Impaired photosynthetic processes can then disrupt overall plant growth and root dynamics, which can indirectly alter stand-level processes such as net primary productivity, decomposition rates, and soil nutrient cycling (Pouyat *et al.*, 1995; Chappelka and Samuelson, 1998; Lovett *et al.*, 2000; Gregg *et al.*, 2003). When these processes become impaired and the system is stressed, observations of pests, disease, and exotic plant species in these forests may increase (Percy and Ferretti, 2004), while the incidence and abundance of sensitive lichen communities may decrease (McCune *et al.*, 1997). Therefore, analysis of bioindicators of these and other processes serve as useful tools in forest ecosystem health assessments.

A bioindicator is an organism that can be used to indicate an alteration in the environment, and these changes can be physical or chemical, as well as positive or negative (Conti and Cecchetti, 2001). Typically, a good bioindicator is one whose anatomy and/or physiology (e.g., high surface area, lack of roots, rapid water absorption) are such that they are sensitive to small changes in the environment (Geiser and Reynolds, 2002). For example, lichens are non-vascular composite organisms that lack a cuticle: they are readily affected by pollutants that are deposited onto their bodies or absorbed into their tissue with the water and nutrients they largely obtain from the air for survival (Bergamaschi *et al.*, 2007; Fenn *et al.*, 2007). The anatomical structure and physiological processes by which lichens live and grow are such that pollutant deposition, accumulation, and uptake can be monitored using lichen species (McCune, 2000; Conti and Cecchetti, 2001; Bergamaschi *et al.*, 2007; Fenn *et al.*, 2007; Geiser and Neitlich, 2007). Use of lichens as bioindicators is especially valuable in ecological field research because the field methods are repeatable, the data are meaningful and more economical than instrumented monitoring, they allow rapid assessment, and changes can be tracked over space and time (McCune, 2000; Geiser and Reynolds, 2002).

Forest characterizations provide information about the structure and composition of a forest, but bioindicators give us a good idea about the current state of ecosystem function. Standards for assessing forest health have been established and usually include a combination of several bioindicators of ecosystem health (McDonnell *et al.*, 1993; McDonnell *et al.*, 1997). These bioindicators have proven useful in previous studies and are generally accepted as standard protocols for forest health assessments. Bioindicators best suited for air pollution analyses as well as overall forest health include foliar injury, soil and tree nutrient status, and lichen incidence, abundance, species richness, and elemental concentrations in tissue. Previous research has shown that lichens provide a much clearer biological response to air pollution exposure than tree growth rate or foliar symptoms (Muir and McCune, 1988). Lichens are extremely sensitive to NO_2, NH_3, and SO_2 pollution (Nash and Gries, 1986; McCune, 2000; Gombert *et al.*, 2004). It has been widely reported that lichen species diversity varies greatly with exposure to SO_2 and NO_2 (McCune *et al.*, 1997; van Dobben *et al.*, 2001; Frati *et al.*, 2006; Fenn *et al.*, 2007; Geiser and Neitlich, 2007). The longevity of lichens and the processes by which they absorb air pollutants also make them useful as biomonitors of heavy metal deposition that has occurred within a forest in the recent past (Nash and Gries, 1986; McCune, 2000).

Heavy metal concentrations (e.g., Pb, Ni, Zn) in soils is also a good indicator of forest health because these elements tend to accumulate and can alter biogeochemical cycles (Pouyat and McDonnell, 1991). Prior studies have reported strong relationships between Pb concentrations in soil and proximity to major urban centers (Johnson *et al.*, 1982; Pouyat and McDonnell, 1991).

Where as soil analyses can provide data over a broad spatial scale, tree-core investigations offer an abundance of easily obtainable historical data. Positive relationships have been observed between soil and tree-core lead concentrations (Baes and McLaughlin, 1984; Alberici *et al.*, 1989; Jordan *et al.*, 1990; McClenahen and Vimmerstedt, 1993; Anderson *et al.*, 2000). Mechanisms of Pb entry into tree xylem tissues probably include some combination of translocation from foliage (following deposition onto the tree) and root uptake from soil (Friedland, 1990; Jordan *et al.*, 1990; Anderson *et al.*, 2000). Combining each of these methodologies enables researchers to gain a broader, more complete view of the forest landscape such that inference about landscape processes may be possible.

The overall goal of this project was to examine spatial and temporal trends of elemental concentrations (N, S, metals) in forests of West Georgia using bioindicators along an urban-to-rural gradient. The overall hypothesis is that forest ecosystems in urban and rapidly developing areas are exposed to greater amounts of air pollution as a consequence of increased human presence, and thus are subject to higher elemental concentrations in soils and plant tissues than those located in rural environments. Specific objectives were: 1) determining current background elemental concentrations at each site through the collection of *in situ* lichen tissue samples from plots across the gradient, 2) detecting short, temporal deposition trends (one year) across the region through the use of two common lichen species collected from a "reference" area and transplanted into plots along the gradient, 3) establishing broad spatial deposition trends in West Georgia by obtaining soil samples from each plot, and 4) ascertaining long temporal (50 years) trends in the region by acquiring tree cores from stand dominants (*Pinus taeda* L.) within each forest stand. Each of these datasets was analyzed for N, S, and metals (Cd, Cr, Cu, Ni, Pb, Zn) to provide information about deposition sufficient to establish trends in West Georgia over space and time. By assessing a variety of different media for elemental concentrations, commonalities in response could be evaluated to determine consistency in overall deposition trends.

3.3 Methods & Materials

3.3.1 Study Area

The study area (hereafter referred to as 'West Georgia'; Figure 3.1) includes Muscogee (location of the Columbus metropolitan area), Harris, and Meriwether counties in the west-central Georgia Piedmont, and represents an urban-to-rural gradient in terms of land development (urban, developing, and rural, respectively). Urban growth around Columbus is constrained by Fort Benning (a large U.S. military base) to the south and by the Chattahoochee River to the west, such that development is occurring to the north and east of Columbus. Development in West Georgia has resulted in different demographic measures in these counties over the past 15 years. Muscogee County, which contains the city of Columbus, has had low population growth (3% from 1990-2005) but has high density (333 people/km^2 in 2000). Harris County, adjacent to the northeast of Muscogee County, has had extremely high population growth (56% from 1990-2005), far above the national average (19% from 1990-2005), but still maintains low (20 people/km^2 in 2000) density. Meriwether County, adjacent to the northeast of Harris County, has had reduced population growth (2% from 1990-2005) and very low (17 people/km^2 in 2000) density (U.S. Census Bureau, 2006).

For the purposes of this study, I used the U.S. Census Bureau's Census 2000 geographic definitions of urban areas (U.S. Census Bureau, 2001). The U.S. Census Bureau (2006) identifies four urban areas in the region: one urbanized area (UZA), defined by a population >50,000 people and a population density of at least 386 people/km^2, and three urban clusters (UCs), characterized by a population between 2,500-49,999 people and a population density of at least 386 people/km^2. The UZA is Columbus (Muscogee County), and the UCs are portions of Valley-Lanett (Harris and Troup Counties), LaGrange (Troup County), and Manchester (Meriwether County). Delineations of these areas are shown in Figure 3.1. According to these definitions, all other land areas in the West Georgia study are classified as rural (U.S. Census Bureau, 2006). For the developing land-use classification, I defined plots as developing if population growth between 1990-2005 in the census tract containing the plot was higher than the national average (19%).

3.3.2 Physiography & Climate

The city of Columbus is located at approximately 32° 27’ 38” North Latitude, 084° 59’ 16” West Longitude and study sites extend toward the northeast to approximately 33° 07’ 07” North Latitude, 084° 32’ 11” West Longitude (Figure 3.1). The study area lies within the Piedmont Physiographic Province of west-central Georgia, and plot elevations range from approximately 100 to 260 meters above mean sea level. This province is characterized by gently rolling hills, deeply weathered bedrock, and isolated occurrences of granitic plutons (University of Georgia, 2007). Soils in West Georgia are typical of the Piedmont Province and study sites are generally located on upland sandy loams (Table 3.1). The climate of the west Georgia Piedmont is moist and temperate. Precipitation is evenly distributed across the region, and is mainly in the form of rainfall, as snowfall in the area is rare (Southeast Regional Climate Center, 2007). March is the wettest month, as most precipitation typically occurs during the wet winter season (Southeast Regional Climate Center, 2007). The fifty-year average of mean annual precipitation in the area is 1245 millimeters, while annual temperatures range from a mean monthly minimum of 12º C in January to a mean monthly maximum of 24º C in July (Southeast Regional Climate Center, 2007). Prevailing winds during warm months are from the south-southwest, flowing up from the Gulf of Mexico, while in winter large frontal systems typically force air down the eastern side of the Appalachian Mountains resulting in strong northwesterly winds across Georgia (Styers, 2005).

3.3.3 Pollution Sources in the Vicinity of Columbus, Georgia

The 21-county pollution source region includes the study area and surrounding counties in Georgia and Alabama (Figure 3.2). Pollutants monitored by stations in the Columbus, GA/Phenix City, AL metropolitan area include O_3, SO_2, Pb, PM10, and PM2.5. The U.S. EPA AirData database (U.S. Environmental Protection Agency, 2006) indicated there are 105 facilities in the 21-county area that are monitored for emissions of CO, NH_3, NO_X, VOCs, SO_2, PM10, and PM2.5. The majority of the 105 up-wind regional pollution sources are located in Russell and Lee counties, AL, and include industrial, manufacturing, textile, lumber, paper, and brick-making plants, as well as sources from excavation and paving activities (U.S. Environmental Protection Agency, 2006). However, the two Georgia Power coal-fired steam-electric power plants (Wansley and Yates) that are responsible for the greatest overall yearly emissions are located in Heard and Coweta counties, GA, just north of Troup and Meriwether counties, respectively. Other primary point-source emission contributors include Continental Carbon Company and Witco Corporation in Russell County, AL, Kimberly-Clark Corporation in Troup County, GA, and Georgia-Pacific Corporation in Meriwether County, GA. In addition, there are several highways in the area (I-85, I-185, US 280, US 431, US 27) that are major routes for automobiles and transfer truck traffic and therefore are mobile sources of pollutants (e.g., CO, NO_X, etc.). Local anthropogenic pollution sources include present and historical applications of fertilizers and pesticides to lawns, golf courses, and agricultural fields. Natural sources of sulfur dioxide include biological decay and forest fires, while those of nitrogen oxides include oceans, biological decay, and lightning strikes. Natural sources of metals include weathering of mineral deposits, brush fires, and windblown dusts.

3.3.4 Plot Selection

To assess the spatial extent of elemental concentrations in West Georgia, 36 permanent 0.05-hectare (ha) circular plots (three plots per site; four sites per land-use type – urban, developing and rural) were established in the winter of 2004-2005 along an urban-to-rural gradient using criteria adapted from the USDA Forest Inventory and Analysis National Program (FIA) guidelines (USDA Forest Service, 2006). Approximately ½ of the sites used in this study were previously selected by other researchers conducting water quality experiments in the region (Lockaby *et al.*, 2005). Additional sites selected were added to extend the gradient farther to the northeast, so that the gradient extends approximately 100 km from southwest to northeast and is approximately 75 km in width. Since other studies were conducted within these same sites, there was a more deliberate selection of specific plots. Individual plot locations were selected based on specific criteria: upland, interior (at least 30 m from an edge), forested locations within pine-oak woodlands containing mature loblolly pine (*Pinus taeda* L.) and oak (*Quercus*) species of a similar age class, elevation, slope, aspect, uniformity of soils, and site histories (Table 3.1; see Chapter 2 for more information).

3.3.5 **In situ** ***Lichen Tissue Collections***

Lichens are known to be very sensitive indicators of ecosystem health, so tissue samples were collected and analyzed for elemental concentrations. Since exposure time was unknown in the *in situ* lichen collection and to account for any seasonal variability encountered due to seasonal differences (time of year collected), three separate collections were conducted over the course of nine months (December 2005 and June and September 2006). A minimum of 20 g (dry weight) of lichen tissue (any fruticose and foliose species) was collected from trees and recently fallen branches for elemental analysis to determine background N, S, and metal concentrations for each site (Figure 3.3). Due to difficulty in removal no crustose lichen species were collected. According to Geiser (2004), 20 g of tissue is sufficient to offset any variability due to differences in lichen age within a single sample. Dead or dying tissue was not collected, as these samples could introduce error into the dataset. To prevent cross-contamination, non-powdered vinyl gloves were used and discarded between plots. Lichen tissue samples were immediately transported from the field to the Auburn University Soil and Plant Tissue Testing Lab for elemental analysis (see *Elemental Analyses* below).

3.3.6 Lichen Tissue Transplants

To control for unknown plot variability within the *in situ* lichen tissue collection, a lichen transplant experiment was conducted. Healthy samples of *Usnea strigosa* (Ach.) Eaton and *Parmotrema perforatum* (Jacq.) A. Massal located on *Prunus serotina* Ehrh. bark were collected from a common reference area (The Preserve at Callaway, located in West Georgia) during August 2005. Pollution emission concentrations in this area are generally regarded as low (Maxwell-Meier and Chang, 2005). *U. strigosa* and *P. perforatum* are both common and conspicuous lichen species in the Georgia Piedmont (McCune *et al.*, 1997; Morin *et al.*, 2006; Georgia Botanical Society, 2007; Will-Wolf, 2007). Although pollution sensitivity has not previously been determined for *U. strigosa*, many eastern *Usnea* species are highly pollution-sensitive (McCune *et al.*, 1997; Morin *et al.*, 2006; Will-Wolf, 2006; USDA Forest Service, 2007). Similarly, pollution sensitivity for *P. perforatum* has not been previously reported, and other eastern *Parmotrema* species are ranked all along the pollution sensitivity range, from tolerant to intermediate to sensitive (McCune *et al.*, 1997; Morin *et al.*, 2006; Will-Wolf, 2006; USDA Forest Service, 2007). Based on these references, it is suggested here that *U. strigosa* is relatively pollution-sensitive, while the sensitivity of *P. perforatum* is unknown. A tentative pollution sensitivity ranking of “intermediate” is suggested by the author for *P. perforatum* based on the results of this research (Styers, unpublished data).

An initial elemental analysis was conducted on a portion of the lichen tissue samples to determine the average nutrient concentrations of the entire collection prior to transplantation. For each transplant sample (Figure 3.4), approximately six grams of tissue was mounted onto a 10 cm x 10 cm wooden board using liquid nails (Pearson, 1993) and then transplanted to nine sites (18 plots – 3 each urban, developing, and rural). Transplants were placed on the northeast side of *Liquidambar styraciflua* L. trees at heights ranging between 1.4 m to 1.7 m (see Figure 3.4b) to maintain consistency, mimic optimum habitat location, and avoid interference with simultaneous lichen cover analyses on the water oak (see Chapter 2). An elemental analysis was conducted on one randomly selected transplant sample every three months for *U. strigosa* and every six months for *P. perforatum* (due to less available tissue sample material) during a 12-month exposure period (September 2005 through September 2006). Lichen tissue transplant samples were immediately transported from the field to the Auburn University Soil and Plant Tissue Testing Lab for elemental analysis (see *Elemental Analyses* below).

3.3.7 Soil Samples

Soil samples were collected from each plot along the gradient to gain additional information about spatial differences in background elemental concentrations between sites. Sampling locations were selected at the four cardinal directions at the plot boundary within each of the study plots and were cored using standard National Forest Health Monitoring Program methods (USDA Forest Service 2004). O horizon material was brushed aside until the top of the A horizon was reached and then soil was sampled to a depth of 10 cm using a standard 5 cm diameter stainless steel hand auger (Figure 3.5). To prevent cross-contamination, the hand auger was washed with Alconox and rinsed with deionized water between sample collections. Soils were sieved (5.6 mm mesh size) to remove roots and rocks in the field and were immediately transported from the field to the Auburn University Soil and Plant Tissue Testing Lab for drying and elemental analysis (see *Elemental Analyses* below). Samples were collected during December 2005 concurrent with tree core sampling.

3.3.8 Tree Core Tissue Samples

Tree core samples were collected in an attempt to establish a longer historical record of elemental concentrations in the West Georgia region. Up to six *P. taeda* individuals per plot were randomly selected from within each of the study plots and cored using standard dendrochronological methods (Swetnam *et al.*, 1985). These trees were chosen because they were present in plots at all sites, and based on their dominance within the study area and potential to provide the longest chronologies for elemental analyses. Samples were collected during December 2005 concurrent with soil sampling.

Trees were cored using 5.15 mm inside diameter increment borers (Figure 3.6). A minimum of two cores were extracted from each tree at breast height (1.55 m), parallel to the slope. To prevent cross-contamination, the increment borers were washed with Alconox and rinsed with deionized water between samples. Cores were temporarily stored in paper straws and allowed to air dry for one week at 25° C prior to preparation for analysis. One core from each tree was used to determine age. These cores were mounted onto grooved, wooden mounts then sanded with a series of three grits (120, 400, 600) of sandpaper to enhance ring visibility (Swetnam *et al.*, 1985). The ring patterns were measured and cross-dated and chronologies were developed. The other core was used for elemental analyses. These cores were cut into ten-year increments (up to 50-years) using the aged cores as a guide. The woody tissue samples were then transported to the Auburn University Soil and Plant Tissue Testing Lab for elemental analysis (see *Elemental Analyses* below).

3.3.9 Elemental Analyses

Preparation of soil and plant materials and elemental analyses were conducted by the Auburn University Soil and Plant Tissue Testing Lab (Kirsten, 1979; Plank, 1992; Odom and Kone, 1997). All samples were dried in a forced air oven at 60º C to a constant weight. Soil and plant materials were then weighed (0.1 g and 0.2 g, respectively) and placed into tinfoil cups. Nitrogen was analyzed by combustion at 950º C using a LECO TruSpec CN and S by combustion at 1450º C using a LECO SC-432 (Kirsten, 1979). Soil minerals were determined by Melich I extraction (Odom and Kone, 1997) and solutions were analyzed by inductively coupled plasma emission spectroscopy (ICP) using a Varian Vista-MPX Radial Spectrometer.

Plant tissue minerals were determined by dry-ashing (organic matter destruction). Approximately 0.5 g of dried plant material was weighed into ceramic crucibles and ashed for 8 hours in a muffle furnace at 500º C. Samples were digested on a hot plate using 1 N Nitric Acid and 1 N Hydrochloric Acid and filtered into approximately 50 ml volumetrics brought to volume with deionized water. Solutions were then analyzed by inductively coupled plasma emission spectroscopy (ICP) using a Varian Vista-MPX Radial Spectrometer to obtain mineral concentrations in each of the lichen and tree core samples (Odom and Kone, 1997).

Of the elements analyzed by the aforementioned laboratory methods, only the following were statistically analyzed as part of this study: cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), nitrogen (N), lead (Pb), sulfur (S), and zinc (Zn). The primary goal of this research was to examine atmospheric deposition trends across the West Georgia region and a full analysis of nutrient dynamics was beyond the scope of this study. Where insufficient sample amounts limited elemental analyses, it is noted within the text. All elemental concentrations are reported in milligrams per kilogram (mg kg $^{-1}$) in plant tissue or soil. Due to a calibration error in the LECO TruSpec CN machine, N data for the June 2006 lichen transplant collection were omitted from the study.

3.3.10 Experimental Design & Statistical Analysis

Distributions and descriptive statistics for each variable were examined for the 12 sites (averaged from the 36 plots – 3 each site) using JMP IN® 5.1.2 (SAS Institute Inc., 2003), which was the statistical software package used in each of the analyses described hereafter. Since the data values were an average of three plots, they each displayed approximately normal distributions and were thus kept in their original format for analysis. Following preliminary explorations of the data, standard one-way analysis of variance (ANOVA) was performed to test for differences among the means between each land-use type for soil samples, since they were collected at one point in time. The p value for the overall ANOVA was set at $p < 0.10$ due to the inherent variability in field studies. Differences observed in group means were then compared using Tukey-Kramer HSD, which tests for all differences among the means and adjusts for multiple comparisons made by controlling for the overall error rate. Tukey-Kramer comparisons were used to evaluate significance ($p < 0.05$) since a broad range in elemental values for developing land-uses may have obscured significant differences between urban and rural land-use types in the standard ANOVA analysis. *In situ* lichen samples, lichen transplants, and tree core samples were evaluated using repeated measures MANOVA to account for both spatial and temporal differences. Lichen transplant data were analyzed in two distinct ways: one to compare differences in elemental concentrations between the two lichen species (*U. strigosa vs. P. perforatum*), and another to examine alterations in *U. strigosa* over time (seasonal changes) as well as across the land-use gradient.

3.4 Results & Discussion

3.4.1 Elemental Concentrations in **in situ** *Lichen Tissue*

Elemental concentration means are reported as the overall collective mean from the three bulk *in situ* lichen collections. Of the nine elements analyzed, Cd, Cr, and Ni concentrations were not significantly different between land-use types (Table 3.2). F test comparisons suggest that urban environments consistently had significantly (Prob>F

$\leq$0.01) higher concentrations of Cu, N, Pb, S, and Zn than either rural or developing land-use types. Overall Cu concentrations in urban areas (mean=26.75 mg kg $^{-1}$) were 1.5-fold greater in lichens from developing (mean=18.27 mg kg $^{-1}$) and rural forests (mean=17.47 mg kg $^{-1}$). Lead in the U.S. has dramatically decreased since the 1970s (Mielke, 1999); small yet significant differences were found in urban (mean=3.39 mg kg $^{-1}$) *vs.* rural (mean=1.73 mg kg $^{-1}$) and developing (mean=1.79 mg kg $^{-}$1) areas. Zinc concentrations in West Georgia lichens varied greatly between land-use types, with concentrations in urban areas (mean=41.61 mg kg $^{-1}$) 2.18- and 1.75-fold greater in rural (mean=19.06 mg kg $^{-1}$) and developing (mean=23.77 mg kg $^{-1}$) areas, respectively. F test comparisons also suggest significant (Prob>F $\leq$0.01) differences in concentrations of N and S between urban *vs.* rural and developing areas. Lichens collected in urban land-use types had higher N (mean=14340 mg kg $^{-1}$) and S (mean=2064 mg kg $^{-1}$), which were 1.4- to 1.5-fold greater than those in developing (N mean=10329 mg kg $^{-1}$; S mean=1454 mg kg $^{-1}$) and rural (N mean=9768 mg kg $^{-1}$; S mean=1444 mg kg $^{-1}$) areas, respectively.

Natural background elemental concentration ranges for lichen species in the Southeast have not been previously reported. A literature search was conducted to find any reported concentrations for these elements in any lichens of the same genera used in this study. Geiser and Neitlich (2007) proposed that lichens located in western Washington and Oregon in the northwestern U.S. having values of N >5900 mg kg $^{-1}$, S >730 mg kg $^{-1}$, and Pb >15 mg kg $^{-1}$ be considered “enhanced.” Based on these criteria, percent background N and S in lichen tissue across West Georgia could be considered enhanced; however, individual and interspecific variation in lichen tissue chemical composition prevents this conclusion (Table 3.3). A relative comparison of elemental concentrations between these sites is still noteworthy, however, since there are no reported species-specific data with which to compare. The concentrations reported in the West Georgia study are slightly higher than those reported by Fenn *et al.* (2007) for lichens in urban areas near the Columbia River Gorge, located along the Washington/Oregon border. However, N concentrations in Naples, Italy reported by Vingiani *et al.* (2004) were 8-fold greater and S concentrations were15-fold greater than those reported for West Georgia (Table 3.3). Naples is a major seaport in a highly industrialized area of Italy, which could explain the extremely high N and S concentrations observed there. With the exception of Cu and Ni, metal concentrations were all substantially higher in Naples and Pavia, Italy (Adamo *et al.*, 2003; Bergamaschi *et al.*, 2007) than in West Georgia.

Anthropogenic sources of atmospheric N and S can be emitted and deposited both locally from vehicles and roadways (mobile sources), and regionally from power plants and other industrial point sources (Lovett *et al.*, 2000; Gregg *et al.*, 2003; Pitcairn *et al.*, 2006; Fenn *et al.*, 2007; Geiser and Neitlich, 2007). Several stationary pollution emission sources are present in the West Georgia region (Figure 3.2). However, without the analysis of pollutant-specific transport models, the exact locations of pollutant deposition from these sources cannot be determined.

The largest anthropogenic sources of metals, however, originate locally as dry-deposited particulate matter from roadways, and deposition typically decreases with distance from roads (Zechmeister *et al.*, 2005). Road density values within census tracts in urban areas of Columbus are 4- and 5-fold greater than those in developing and rural census tracts, respectively (see Chapter 2). Sources of roadway particulate matter responsible for metal deposition include tire wear (Cd, Pb, Zn), brake wear (Cr, Cu, Pb, Zn), vehicle body degradation (Ni), engine fluid spills (Cr, Ni, Zn), and exhaust emissions (Cr, Cu, Pb, Zn), and deposition is typically greater where braking and/or accelerating are greatest (Tam *et al.*, 1987; Sutherland and Tolosa, 2000; Charlesworth *et al.*, 2003; Adachi and Tainosho, 2004; Zanders, 2005; Zechmeister *et al.*, 2005; Sabin *et al.*, 2006). It is possible that the greater concentrations of Cu and Ni in West Georgia compared to Naples and Pavia may be attributed to deposition from these sources. However, cause and effect relationships cannot be proven in the current study. Further, natural elemental sources (e.g., biological decay, lightning strikes, forest fires, oceans, bedrock weathering, windblown dusts) and other anthropogenic sources (e.g., present and historical applications of fertilizers and pesticides to lawns, golf courses, and agricultural fields) cannot be entirely ruled out. It is also possible that observed differences between land-use types are due to natural variation in soil and/or lichen tissue chemical compositions. However, based on the consistently higher elemental concentrations observed in urban *vs.* rural and developing areas, it is possible that pollution could be a contributing factor to the greater elemental concentrations in the metropolitan Columbus, GA area.

3.4.2 Elemental Concentrations in Transplanted Lichen Tissue

Transplanted lichen tissue samples were analyzed for N, S, and metals, but due to limited sample quantities, not all analyses could be conducted for each of the sampling sites. Transplants were placed into several sites within each land-use type and site-specific values were averaged to land-use type for statistical analysis. Further, due to calibration error in the LECO TruSpec CN machine, N data from the June 2006 collection were omitted from the study (G. Somers, personal communication).

3.4.2.1 Elemental Concentration Trends in **U. strigosa vs. P. perforatum**

Significant species-specific differences were observed between *U. strigosa* and *P. perforatum* regarding concentrations of N and S (Table 3.4). In each case *P. perforatum* had significantly (Prob>F ≤0.01) greater concentrations of N and S based on least squares means across the entire one-year exposure period. This could be due to natural variation in lichen tissue chemical composition, but may also indicate that *P. perforatum* has a greater tolerance to these elements than *U. strigosa*. Further, *P. perforatum* exhibited greater elemental concentrations for all of the metals analyzed except Pb, although these differences were not statistically significant. In other studies, some eastern lichen species in the genus *Parmotrema* have been identified as pollution-tolerant (McCune et al., 1997; Will-Wolf, 2006). Based on my results, I would suggest a tentative pollution sensitivity ranking for *P. perforatum* of “intermediate” given that the concentrations of N and S found in *P. perforatum* are greater than the maximum N and S concentrations exhibited by other sensitive species (USDA Forest Service, 2007). These data support the findings from the background lichen study where urban land-use types had the greatest N and S concentrations. Further, although N and S concentrations were greater in *in situ* lichen tissues, concentrations in both *U. strigosa* and *P. perforatum* transplanted tissue were higher after only 6 months of exposure than the threshold concentrations suggested by Geiser and Neitlich (2007) (Table 3.3).

Lead had distinct differences across land-use types, while a unique species/land-use interaction was observed with S (Table 3.4). Several significant differences were observed over time, but there were no time/species interactions observed. Time/land-use interactions were observed only in Pb while no time/species/land-use interaction was observed (Table 3.4).

3.4.2.2 Elemental Concentration Trends in **U. strigosa** *over Time*

The lichen transplant study also revealed significant temporal (seasonal) differences in elemental concentrations in *U. strigosa* tissue samples. Pollution sensitivity has not previously been determined for *U. strigosa*, but many other eastern *Usnea* species have been documented as pollution-sensitive (McCune et al., 1997; Morin et al., 2006; Will-Wolf, 2006; USDA Forest Service, 2007). Since a greater amount of *U. strigosa* reference sample material was available for collection, these transplants were collected every three months resulting in elemental concentration data for each season over the course of one year. Least squares means indicate only N was significantly different (Prob>F $\leq$0.10) between land-use type, in which urban (mean=6782 mg kg $^{-1}$) and developing (mean=6681 mg kg $^{-1}$) land-use types had higher concentrations of N than rural (mean=6332 mg kg $^{-1}$) areas (Table 3.5). This enabled analysis of seasonal fluctuations in elemental concentrations over time for a single species. Significant differences over time were observed for Cr, N, Ni, S, and Zn (Table 3.5). However, these data were not further examined since an in-depth analysis of seasonal nutrient cycling dynamics for *U. strigosa* was beyond the scope of this project (Hovenden, 2000). When each of the individual time periods was analyzed separately, the differences observed were difficult to interpret. Results suggest, however, that although differences over the entire year were significant, and attributed to seasonal fluctuations, changes attributable to land-use type within a single time period were not observed.

3.4.3 Elemental Concentrations in Soils

Soil samples were obtained to gain additional information about spatial differences in background elemental concentrations between sites. However, the majority of the elements analyzed were either below detectable limits (<0.1 mg kg $^{-1}$; Cd, Cr, and Ni), or not significantly different between land-use types (Table 3.6). The only exception is N, where Tukey-Kramer comparisons suggest that urban environments had significantly ($p < 0.05$) higher concentrations of N (mean=833 mg kg $^{-1}$) than either rural (mean=92 mg kg $^{-1}$) or developing (mean=150 mg kg $^{-1}$) land-use types. These results may be attributed to natural variation in soil chemical composition, natural elemental sources, fertilizer applications, emissions from fossil fuel combustion, particle dust from roadways, demolition, and construction activities, or to some combination of these factors (Lovett *et al.*, 2000; Gregg *et al.*, 2003; Pitcairn *et al.*, 2006; Fenn *et al.*, 2007; Geiser and Neitlich, 2007).

3.4.4 Elemental Concentrations in Tree Core Tissues

Tree core samples were collected to ascertain a long-term historical record (50 years) of elemental concentrations in West Georgia forests. Decadal tree core samples were first statistically analyzed to gain a better understanding of temporal trends in the region by examining changes in metal concentrations from 1956-2005. After these long-term trends had been established, changes between land-use types during the past decade (1996-2005) were examined in more detail. Due to the small tissue sample amounts, there was only enough tissue to analyze for metals, and as a result N and S concentrations were not examined in tree core tissues.

For all elements except Zn, metal concentrations in almost all decades for all samples were below the detectable limit (<0.1 mg kg $^{-1}$). Zinc is considered a micronutrient necessary for plant growth and vitality, and all concentrations observed fell within the sufficiency range (28-53 mg kg $^{-1}$) for *P. taeda* (Mills and Jones, 1996) indicating the concentrations were not high enough to be considered toxic (i.e., a pollutant). The exceptions were several plots (all at developing sites) which at different times during the 50-year period had higher concentrations of one or more of the metals analyzed. However, there were no consistencies between site, decade, or metal (Table 3.7), thereby making interpretation of the data difficult and rendering the results inconclusive. Further, since a majority of the “high” values occurred during the 1996-2005 decade, any significant differences observed between land-use type were due to these values at a single plot and were thus, not representative of the entire land-use type category. For the purposes of this study these data points were considered anomalies and it was concluded that there were no consistent significant differences in metal concentrations between land-use types as evident from tree core tissues.

3.4.5 Comparison of Results from Different Assessments

Four different assessments were conducted allowing an examination of commonality and consistency within forest stand elemental concentration trends. Since tree growth and nutrient uptake can be influenced by soil nutrients, and lichen growth can be related to the physical traits of a particular tree (e.g., bark roughness, bark pH, canopy cover), it is possible that each medium is potentially exposed to similar elemental concentrations, and that those could be transferred from one to another (Muir and McCune, 1988). However, my results suggest that correlations between each the different media used in this study are inconclusive, or simply may not exist. Much of the bulk lichen tissue collected was from recently fallen crown branches (majority of material on the ground), which are potentially exposed to greater amounts of atmospheric deposition since exposure is typically greater (and duration is longer) in tree canopies due to their elevated locations (Weathers *et al.*, 2001). Results indicate land-use differences in the bulk lichen samples but not in the lichen transplants, which were located at breast height and implies an urban association across time and irrespective of species. Had only lichen transplant samples been collected, one might have reported that there are no differences in elemental concentrations between land-use types. Further studies are needed to examine atmospheric deposition using transplants located at different tree heights to test this hypothesis.

Soil scientists regularly test soils for elemental concentrations, and had that been the only assessment conducted one might have also concluded that there were essentially no differences in elemental concentrations in urban *vs.* rural areas. It is possible that plant uptake and leaching from the A horizon is possibly the reason concentrations were so low in the soils sampled, but without further analysis this hypothesis cannot be tested. The results could also be due to natural variation in soil chemical composition. Dendroecologists, on the other hand, would have a very difficult time determining elemental concentrations using tree rings in West Georgia, although this method has worked in many other locations (Baes and McLaughlin, 1984; Alberici *et al.*, 1989; Jordan *et al.*, 1990; McClenahen and Vimmerstedt, 1993; Anderson *et al.*, 2000). It is also possible that there is no correlation between elemental concentrations in soils and tree cores. Jordan *et al.* (1990) conducted a similar study within 50 km of the present research study area (in Auburn, AL) and also failed to correlate metal concentrations in decadal tree core samples with those obtained from soils. Since it is known that some trees translocate various elements to their leaves (Jordan *et al.*, 1990; Anderson *et al.*, 2000), an analysis of leaf tissue elemental concentrations may have been more appropriate for comparison to lichen tissues. However, since the original goal was to obtain long-term historical data about elemental concentrations in West Georgia forests, tree cores were selected instead.

While, the bulk lichen data overall suggest greater elemental concentrations in urban areas, these trends were not observed in soils and lichen tissue transplants. One exception is that of N, in which differences were also observed between land-use types in soils and in transplanted *U. strigosa* tissues. Continuous and passive NO_X monitoring data for the West Georgia region from 2006 indicate that atmospheric NO_X concentrations in urban areas (mean=6.03 mg kg $^{-1}$) were 2.4- and 2.1-fold greater than in rural (mean=2.52 mg kg $^{-1}$) and developing (mean=2.88 mg kg $^{-1}$) areas, respectively (see Chapter 2, Table 2.6). Overall, however, these concentrations are relatively low. Results from a separate study (Chapter 2) examining the incidence, abundance, and species richness of lichens located on trees within the same sample plots imply similar land-use-related trends. Values for each of these lichen community attributes were significantly greatest in rural and least in urban forests of West Georgia. The differences observed could possibly be linked to greater pollution emissions and increased forest fragmentation, both resulting from rapid increases in urbanization in the Columbus area.

3.5 Conclusions

Results reported in this study suggest the necessity of testing several different media in forest elemental concentration assessments due to the likelihood that each will result in different conclusions. Each media has its own strengths and weaknesses, but can used in combination to gain a better understanding of elemental concentrations at various locations within the ecosystem and to discern spatial and temporal differences. Tree cores may provide long-term historical records, while soil data can provide broad spatial documentations of elemental concentrations. Overall, results from this study suggest that lichens appear to be the most useful bioindicator of potential pollution exposure to Southern forests. Elemental concentrations in West Georgia are lower compared to larger metropolitan areas in the world (Adamo *et al.*, 2003; Vingiani *et al.*, 2004; Frati *et* *al.*, 2006; Bergamaschi *et al.*, 2007); however, discernable trends are still evident. Overall, land-use type is related to Cu, N, Pb, S, and Zn concentrations in urban environments, where values are significantly greater than in rural locations. Although natural sources cannot be eliminated, these values could potentially be attributed to greater emissions in urban areas, as a greater number of stationary and mobile sources are usually found in cities (Lovett *et al.*, 2000; Gregg *et al.*, 2003; Pitcairn *et al.*, 2006; Fenn *et al.*, 2007; Geiser and Neitlich, 2007). These findings illustrate the utility of the urban-to-rural gradient approach, since analyses suggest that elemental concentrations observed in urban areas (and not in rural or developing areas) may be related to pollution exposure.

Differences in elemental concentrations between lichen species were also observed. *P. perforatum*, had overall higher concentrations of each of the metals tested except Pb, and significant differences were observed in N and S values. Again, this could be due to natural variation in lichen tissue chemical composition, but could also possibly be related to the ability of *P. perforatum* to tolerate or even thrive under "N- and S-enhanced" atmospheric conditions. Based on these findings and published literature, and compared to results for *U. strigosa*, it is suggested that *P. perforatum* has an "intermediate" pollution sensitivity ranking while *U. strigosa* is possibly relatively pollution-sensitive.

However, this study was correlative in nature and cause and effect relationships cannot be proven. Further, natural elemental sources (e.g., biological decay, lightning strikes, forest fires, oceans, bedrock weathering, windblown dusts) and other anthropogenic sources (e.g., present and historical applications of fertilizers and pesticides to lawns, golf courses, and agricultural fields) could have contributed to the deposition total. It is also possible that observed differences between land-use types are due to natural variation in soil and/or lichen tissue chemical compositions. However, based on the consistently higher elemental concentrations observed in urban *vs.* rural and developing areas, air pollution cannot be ruled out as a contributing factor to the greater elemental concentrations observed in the metropolitan Columbus, GA area. Further studies are needed to verify these results, such as those using radioisotopic markers of pollutants from selected emission sources, or lichens in controlled-environment studies.

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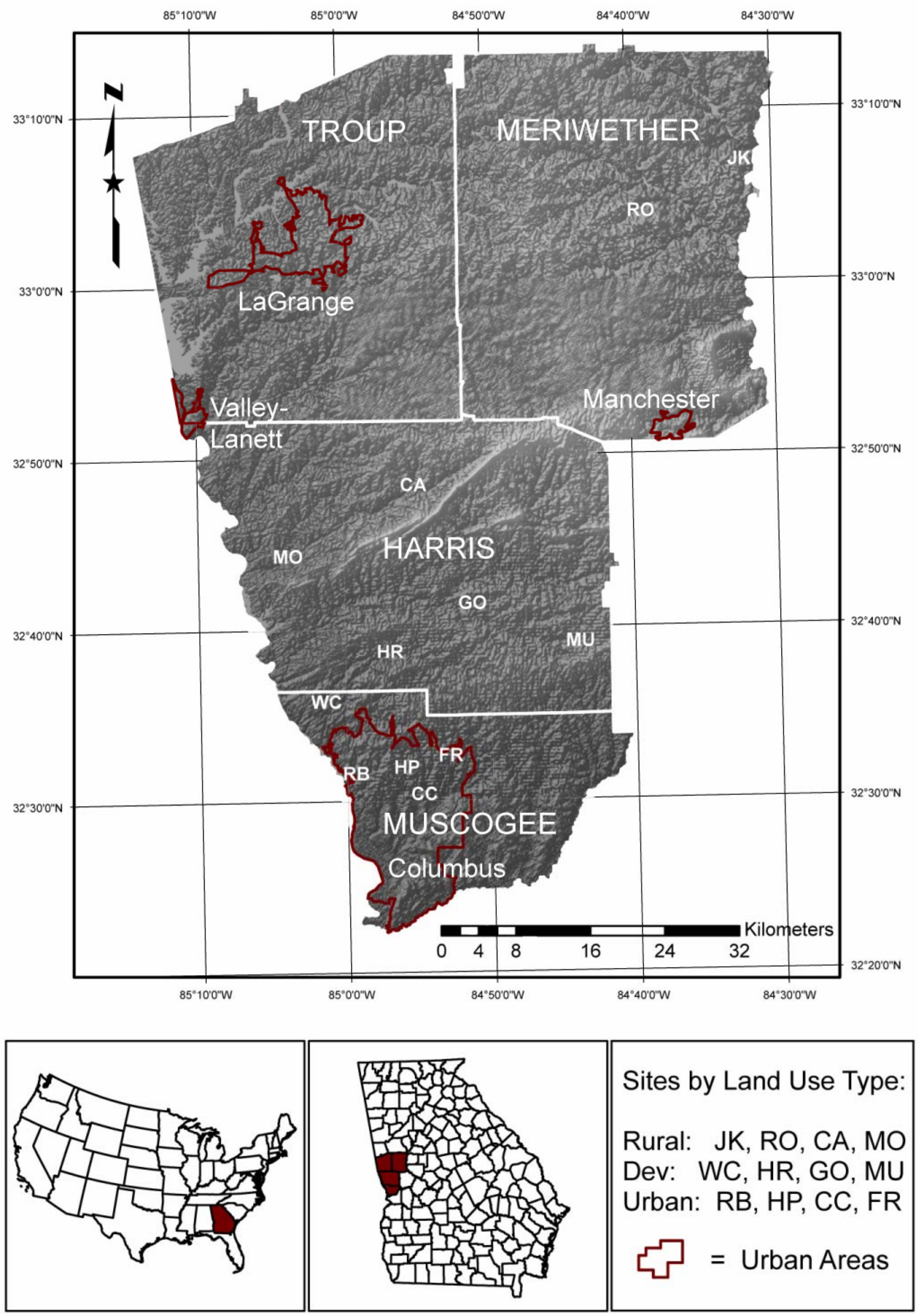

Figure 3.1 Map of West Georgia study area. Urban Sites: RB=Roaring Branch; HP=Heath Park; CC=Cooper Creek; FR=Flat Rock; Developing Sites: WC=Whiskey Creek; HR=Hunter Road; GO=Goolsby; MU=Mulberry Creek; Rural Sites: MO=Mountain Oak; CA=Callaway; RO=Red Oak: JK=Joe Kurz WMA. Source: Diane M. Styers, 2008.

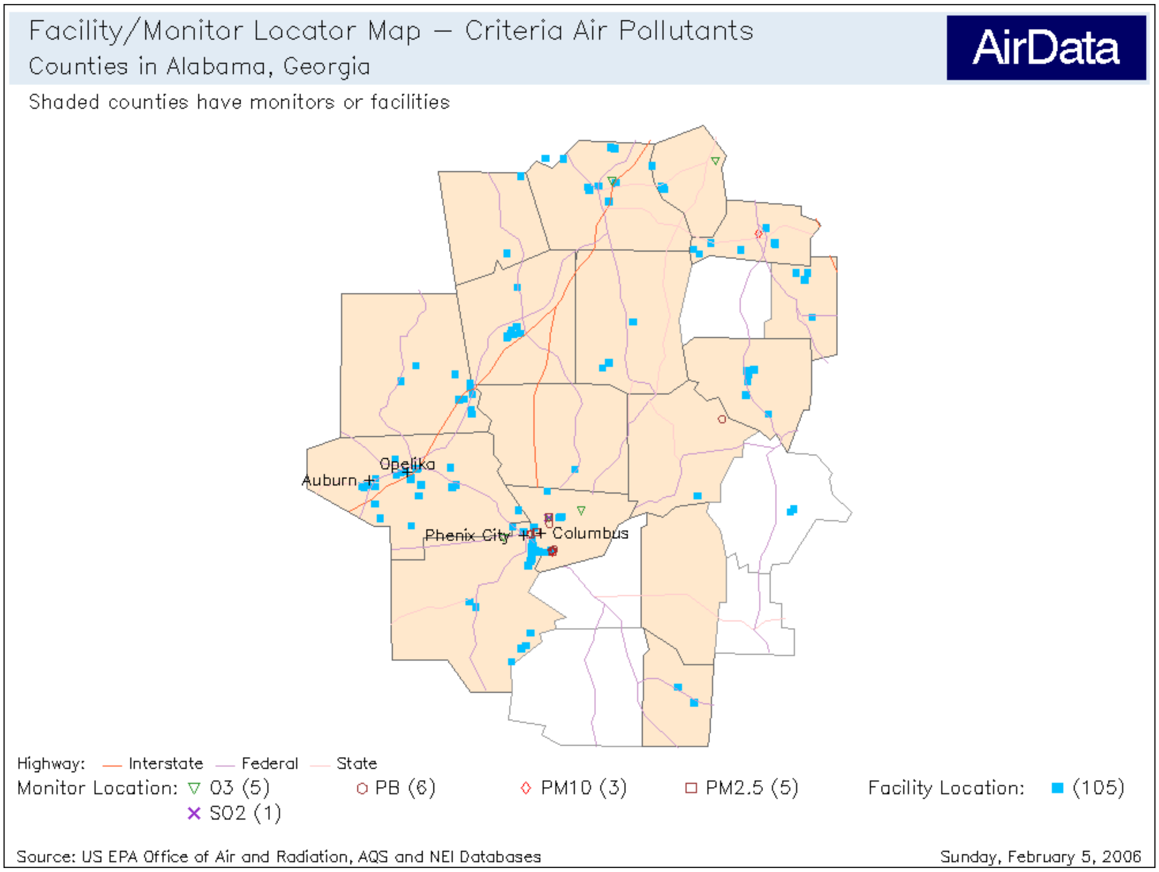

Figure 3.2 Map showing locations of pollution monitors and emission facilities in West Georgia and surrounding counties in Georgia and Alabama. Source: U.S. EPA, AirData, 2006.

Figure 3.3 Photographs showing examples of (a) fruticose and (b) foliose *in situ* lichen tissue collections. Source: Diane M. Styers, 2008.

Figure 3.4 Photographs showing (a) transplant lichen tissue collection, and (b) transplant mounting. Source: Diane M. Styers, 2008.

a. b.

Figure 3.5 Photographs showing (a) soil coring instrument and collection box and (b) example soil sample. Source: Diane M. Styers, 2008.

Figure 3.6 Photographs showing (a) tree coring methods and (b) mounted tree cores. Source: Diane M. Styers, 2008.

Table 3.1 West Georgia site characteristics measured during the study (2005-2006).

Site	Latitude	Longitude	Elev (m)	Soil Series	%Hardwood	%Canopy	BA (m^2/ha)	Stand Age (Yr)
RB	32.5271	-84.9903	106	Wedowee sandy loam, 10 - 35% slopes	69	95	26.59	34
HP	32.5336	-84.9321	101	Dothan-Urban land complex, 2 - 5% slopes	74	74	39.15	45
CC	32.5076	-84.9125	100	Esto-Urban land complex, 8 - 25% slopes	70	90	37.08	53
FR	32.5448	-84.8814	208	Pacolet sandy clay loam, 10 - 15% slopes	54	70	41.53	51
WC	32.6016	-85.0226	126	Pacolet sandy loam, 15 - 25% slopes	83	94	32.89	40
HR	32.6456	-84.9489	188	Pacolet sandy loam, 6 - 10% slopes	94	94	39.30	47
GO	32.6920	-84.8534	139	Pacolet sandy loam, 10 - 15% slopes	77	85	26.83	47
MU	32.6541	-84.7304	205	Chewacla sandy loam, 0 - 2% slopes	100	91	21.45	30
MO	32.7393	-85.0642	157	Pacolet sandy loam, 6 - 10% slopes	71	94	30.25	48
CA	32.8068	-84.9186	246	Cecil sandy loam, 6 - 10% slopes	57	94	31.11	60
RO	33.0687	-84.6508	254	Cecil sandy clay loam, 10 - 15% slopes	89	90	35.07	53
JK	33.1165	-84.5360	239	Cecil sandy clay loam, 6 - 10% slopes	97	95	35.02	39

Note:

[1] Urban Sites: RB=Roaring Branch; HP=Heath Park; CC=Cooper Creek; FR=Flat Rock; Developing Sites: WC=Whiskey Creek; HR=Hunter Road; GO=Goolsby; MU=Mulberry Creek; Rural Sites: MO=Mountain Oak; CA=Callaway; RO=Red Oak: JK=Joe Kurz WMA.

Table 3.2 Elemental concentration means (±SE) for *in situ* lichen tissue samples collected over nine months (December 2005-September 2006) in West Georgia.

	Overall Means (mg kg $^{-1}$) ± SE						Prob>F		
Element	**Urban (n=4)**		**Developing (n=4)**		**Rural (n=4)**		**Land Use**	**Time**	**Time*LU**
Cadmium (Cd)	<0.1 ± 0.02		<0.1 ± 0.01		<0.1 ± 0.01		--	--	--
Chromium (Cr)	3.73 ± 1.17		3.45 ± 0.91		2.97 ± 0.89		0.86	<0.01	0.96
Copper (Cu)	26.75 ± 0.99	(a)	18.27 ± 0.84	(b)	17.47 ± 1.86	(b)	<0.01 ***	<0.01	0.48
Nitrogen (N)	14340 ± 995	(a)	10329 ± 280	(b)	9768 ± 627	(b)	<0.01 ***	0.06	0.13
Nickel (Ni)	13.36 ± 6.11		9.06 ± 2.82		10.73 ± 3.48		0.79	0.07	0.69
Lead (Pb)	3.39 ± 0.47	(a)	1.79 ± 0.16	(b)	1.73 ± 0.09	(b)	<0.01 ***	0.06	0.82
Sulfur (S)	2064 ± 108	(a)	1454 ± 41	(b)	1444 ± 84	(b)	<0.01 ***	<0.01	0.06
Zinc (Zn)	41.61 ± 2.25	(a)	23.77 ± 1.75	(b)	19.06 ± 1.06	(b)	<0.01 ***	<0.01	0.10

Notes:

[1] SE = standard error of the mean.
[2] n = number of study sites sampled.
[3] Elemental concentrations reported in milligrams per kilogram (mg kg $^{-1}$).
[4] Significant differences in Land-use and Time assessed by F Test and in Interaction term (Land-use*Time) by Wilks' Lambda.
[5] Mean values in a row with different letters (variables in bold) are significantly different ($p < 0.05$) based on overall means from 3 collections.
[6] *** = Prob>F ≤0.01; ** = Prob>F ≤0.05; * = Prob>F ≤0.10.
[7] Cd was below detectable limits and therefore not analyzed (--).

Table 3.3 Comparison of concentrations of selected elements in lichen tissue in several studies.

Author(s)	**Location**	**Lichen Species**	**Cd**	**Cr**	**Cu**	**N**	**Ni**	**Pb**	**S**	**Zn**	**Exposure**
Geiser & Neitlich 2007 [1]	Western WA/OR, USA	locally abundant target species (bulk collection)	--	--	--	>5900	--	>15	730	--	if values > "enhanced"
Fenn *et al.* 2007 [1]	Columbia River, WA/OR, USA	locally abundant target species (bulk collection)	--	--	--	13600	--	--	1220	--	urban mean
Vingiani *et al.* 2004 [1]	Naples, Italy	*Pseudevernia furfuracea* (L.) Zopf (fruticose transplants)	--	--	--	119900	--	--	31600	--	urban mean (after 17 wk exposure)
Adamo *et al.* 2003 [1]	Naples, Italy	*Pseudevernia furfuracea* (L.) Zopf (fruticose transplants)	0.64	4.09	42.78	--	9.07	59.95	--	171.59	urban mean (after 17 wk exposure)
Bergamaschi *et al.* 2007 [1]	Pavia, N. Italy	*Pseudevernia furfuracea* (L.) Zopf (fruticose transplants)	0.48	8.4	23	--	4.6	36	--	162	urban mean (after 5 mo exposure)
Bergamaschi *et al.* 2007 [1]	Pavia, N. Italy	*Usnea* gr. *hirta* (fruticose transplants)	0.23	4.3	17	--	2.3	16	--	106	urban mean (after 5 mo exposure)
Present Study [2]	Columbus, GA, USA	locally abundant fruticose and foliose species (bulk collection)	<0.1	3.73	26.75	14300	13.36	3.39	2060	41.61	urban mean
Present Study [2]	Columbus, GA, USA	*Usnea strigosa* (Ach.) Eaton (fruticose transplants)	<0.1	1.2	23.01	6800	<0.1	1.18	1360	0.11	urban mean (after 6 mo exposure)
Present Study [2]	Columbus, GA, USA	*Parmotrema perforatum* (Jacq.) A. Massal (foliose transplants)	<0.1	1.11	14.5	8300	<0.1	1.01	1560	1.14	urban mean (after 6 mo exposure)

Notes:

[1] Concentrations reported in $\mu g\ g^{-1}$.

[2] Concentrations reported in $mg\ kg^{-1}$.

[3] $\mu g\ g^{-1} = mg\ kg^{-1}$.

Table 3.4 Elemental concentration means for transplanted *U. strigosa vs. P. perforatum* tissues collected over one year (September 2005- September 2006) in West Georgia.

	Species LS Means (mg kg $^{-1}$)		**Prob>F**						
Element	***P. perforatum*** **(n=7)**	***U. strigosa*** **(n=7)**	**Species**	**Land Use**	**Spp*LU**	**Time**	**Time*Spp**	**Time*LU**	**Time*Spp*LU**
Cadmium (Cd)	<0.1	<0.1	--	--	--	--	--	--	--
Chromium (Cr)	3.64	1.71	0.14	0.63	0.59	0.01	0.52	0.22	0.95
Copper (Cu)	21.17	17.27	0.68	0.68	0.79	0.46	0.52	0.59	0.79
Nitrogen (N)	7970.39 (a)	6506.78 (b)	0.01 ***	0.48	0.48	0.06	0.82	0.29	0.36
Nickel (Ni)	0.51	0.45	0.81	0.32	0.59	0.04	0.81	0.32	0.59
Lead (Pb)	0.95	1.02	0.54	0.01	0.54	0.72	0.21	0.03	0.97
Sulfur (S)	1490.42 (a)	1055.92 (b)	<0.01 ***	0.80	<0.01	<0.01	0.74	0.68	0.31
Zinc (Zn)	15.23	13.24	0.50	0.33	0.87	<0.01	0.61	0.47	0.92

Notes:

[1] n = number of study sites sampled.

[2] Elemental concentrations reported in milligrams per kilogram (mg kg $^{-1}$).

[3] Significant differences in Species, Land-use, and Time assessed by F Test and in Interaction terms by Wilks' Lambda.

[4] Mean values in a row with different letters (variables in bold) are significantly different ($p < 0.05$) based on least squares means.

[5] *** = Prob>F ≤0.01; ** = Prob>F ≤0.05; * = Prob>F ≤0.10.

[6] Cd was below detectable limits and therefore not analyzed (--).

Table 3.5 Elemental concentration means for transplanted *U. strigosa* tissues collected over one year (September 2005- September 2006) in West Georgia.

	Land Use LS Means (mg kg $^{-1}$)			**Prob>F**		
Element	**Urban (n=3)**	**Developing (n=3)**	**Rural (n=3)**	**Land Use**	**Time**	**Time*LU**
Cadmium (Cd)	<0.1	<0.1	<0.1	--	--	--
Chromium (Cr)	3.90	4.05	5.74	0.46	0.10 *	0.51
Copper (Cu)	23.87	15.41	18.49	0.16	0.26	0.20
Nitrogen (N)	6782.82	6681.73	6332.71	0.09	0.27	0.34
Nickel (Ni)	0.98	1.95	2.54	0.28	0.01 ***	0.21
Lead (Pb)	1.13	1.04	0.97	0.69	0.41	0.27
Sulfur (S)	1069.50	1056.69	990.25	0.41	<0.01 ***	0.20
Zinc (Zn)	13.60	13.29	13.37	0.87	<0.01 ***	0.81

Notes:

[1] n = number of study sites sampled.

[2] Elemental concentrations reported in milligrams per kilogram (mg kg $^{-1}$).

[3] Significant differences in Land-use and Time assessed by F Test and in Interaction term (Land-use*Time) by Wilks' Lambda.

[4] *** = Prob>F ≤0.01; ** = Prob>F ≤0.05; * = Prob>F ≤0.10.

[5] Cd was below detectable limits and therefore not analyzed (--).

Table 3.6 Elemental concentration means (±SE) for soils collected in West Georgia.

	Standard ANOVA		**Tukey-Kramer HSD Comparisons**		
Element	**Mean Square**	**Prob > F**	**Urban (n=4)**	**Developing (n=4)**	**Rural (n=4)**
Cadmium (Cd)	0.00049	0.41	0.119 ± 0.019	0.100 ± 0	0.100 ± 0
Chromium (Cr)	0.00032	0.14	0.100 ± 0	0.100 ± 0.0005	0.116 ± 0.010
Copper (Cu)	2.06170	0.74	3.441 ± 2.214	2.247 ± 0.329	2.153 ± 0.242
Nitrogen (N)	68.0300	0.002	833.330 ± 150.923 (a)	150.000 ± 117.458 (b)	91.670 ± 53.359 (b)
Nickel (Ni)	0.01499	0.23	0.230 ± 0.074	0.139 ± 0.028	0.114 ± 0.012
Lead (Pb)	0.27851	0.55	1.185 ± 0.457	0.684 ± 0.322	1.076 ± 0.109
Sulfur (S)	0.7300	0.42	255.170 ± 62.026	232.370 ± 34.506	172.540 ± 26.267
Zinc (Zn)	44.2483	0.35	7.185 ± 5.262	2.186 ± 0.352	0.885 ± 0.171

Notes:
[1] SE = standard error of the mean.
[2] n = number of study sites sampled.
[3] Elemental concentrations reported in milligrams per kilogram (mg kg $^{-1}$).
[4] Mean values in a row with different letters (variables in bold) are significantly different ($p < 0.05$) based on Tukey-adjusted least squares means.

Table 3.7 Elemental concentration means for tree core tissues collected in West Georgia.

	Standard ANOVA		**Tukey-Kramer HSD Comparisons**		
Element	**Mean Square**	**Prob > F**	**Urban (n=4)**	**Developing (n=4)**	**Rural (n=4)**
Cadmium (Cd)	18.0064	0.4053	<0.1	3.77	<0.1
Chromium (Cr)	1.16E-33	--	<0.1	<0.1	<0.1
Copper (Cu)	2.87949	0.4053	<0.1	1.57	<0.1
Nitrogen (N)	--	--	--	--	--
Nickel (Ni)	33.5817	0.1859	<0.1	5.12	<0.1
Lead (Pb)	34.2542	0.1918	<0.1	5.17	<0.1
Sulfur (S)	--	--	--	--	--
Zinc (Zn)	52.2723	0.3859	8.55	13.14	6.01

Notes:

[1] n = number of study sites sampled.

[2] Elemental concentrations reported in milligrams per kilogram (mg kg $^{-1}$).

[3] Insufficient sample size to analyze N and S (--).

4. DEVELOPING A LAND-COVER CLASSIFICATION TO SELECT INDICATORS OF FOREST ECOSYSTEM HEALTH IN A RAPIDLY URBANIZING LANDSCAPE

4.1 Abstract

As moderate-sized cities become more urbanized, ecosystems are altered by land-use changes. Key ecological services, such as clean air and water, drought and flood protection, soil generation and preservation, and detoxification of wastes are disrupted, risking the health and welfare of society. An understanding of ecosystem responses to urbanization is necessary to evaluate and balance short-term needs with long-term sustainability goals. The main objective of this study was to develop a land management and planning tool using a land-cover classification to select landscape characteristics and to correlate these with bioindicators of ecosystem health near Columbus, Georgia. Spearman's Rho correlations were calculated to compare landscape indicators with field-collected bioindicators of forest health. Results suggest there are significant inverse correlations between percent forest land-cover and population, housing, and road densities; tree species richness and forest patch density; percent urban land-cover and lichen species richness; and lichen incidence and forest perimeter-area fractal dimension. In all there were 168 significant urban/biological correlations obtained from this assessment ($Rho \geq |0.50|$ and $p \leq 0.10$).

Keywords: bioindicators, correlation analysis, ecosystem health, forest, land-cover classification, landscape indicators, urbanization

4.2 Introduction

The transformation of landscapes from natural to urbanized is a necessity for the progression of civilization (DeFries *et al.*, 2004; Kremen and Ostfeld, 2005). While humans depend on essential ecological goods to support their immediate needs, ecosystem processes are often altered by land-use changes, thus disrupting a variety of ecological services provided to humans by the environment (DeFries *et al.*, 2004). Such services provide us with clean air and water, drought and flood protection, soil generation and preservation, and detoxification of wastes. When fundamental ecosystem services are altered by population growth, land development, and over-consumption of natural resources, enduring societal welfare is at risk (Kremen and Ostfeld, 2005). Thus, a thorough understanding of ecosystem responses to land-use change is imperative to evaluate the balance between short-term human needs with long-term ecosystem sustainability (DeFries *et al.*, 2004; Kremen and Ostfeld, 2005).

Assessments of ecosystem health are necessary to determine the decline of ecosystem services resulting from human modification of the environment (Kremen and Ostfeld, 2005). To quantify impacts of urbanization in a given area, correlations of measured forest stand metrics to surrounding landscape characteristics are necessary to examine what aspects of urban development may be linked to ecosystem functions in that area. Healthy forest ecosystems have the capacity to supply sufficient quantities of water, nutrients, and energy to sustain ecosystem productivity while remaining resistant and resilient to stress (McLaughlin and Percy, 1999). Historically, ground-based data collections in individual forest stands have been the method selected by ecologists to assess forest ecosystem health (Pettorelli *et al.*, 2005). Forest ecosystem health parameters typically examined by ecologists include crown condition, incidences of lichens, pests, diseases, and mechanical injury to trees, and visible air pollution-induced foliar injury on vascular plants (Stolte, 1997; Wear and Greis, 2002). Additionally, nutrient status and trace metals in tree rings, soils, and lichens can be measured and quantified to determine current and historical concentrations at a specific site and then can be compared to those observed at similar sites in neighboring areas (Wear and Greis, 2002). However, these plot-level data represent only a small portion of the landscape in which they are contained. To relate this information to adjacent land-uses for the purpose of land management, policy, and planning activities, the surrounding region in which the plots are located must be evaluated. As such, studies that attempt to correlate broad-scale landscape indicators of urbanization and ecosystem health with forest stand structure and condition are needed to identify regions of concern based on land-use, land-cover, and landscape pattern change and associated forest ecosystem response.

The main goal of this study was to develop a land-cover classification that can be used to assess regional land-cover patterns and landscape characteristics correlated with plot-level biological indicators of forest ecosystem health in a rapidly developing area of West Georgia. The overall hypothesis was that landscape indicators of urbanization are correlated to certain plot-level bioindicators of ecosystem health, and that these can be quantified regionally to predict localized areas of high environmental impact. Specific objectives include: 1) developing a current land-cover classification that can be used to obtain landscape-scale metrics of forest ecosystem health, 2) examining land-cover change in West Georgia between 2001 and 2005, 3) utilizing data obtained from the land-cover classifications and fragmentation analysis as correlatives to field-collected plot-level data, and 4) testing the utility of these data correlations as a cost-effective and time-efficient land management tool.

4.3 Methods & Materials

4.3.1 Study Area

The study area (hereafter referred to as 'West Georgia'; Figure 4.1) encompasses Muscogee (location of the urban core of Columbus), Harris, Meriwether, and Troup counties in the west-central Georgia Piedmont. The region varies greatly in terms of amount of development, and includes highly modified land-uses in the urban core of Columbus and several smaller urban clusters, interspersed with pasture/grazing lands, managed pine plantations, and "natural" forests that have established since post-Depression era abandonment of agricultural lands (Cordell and Macie, 2002; Brown *et al.*, 2005). Urban expansion around the Columbus area is constrained by Fort Benning (a large U.S. military base) to the south and by the Chattahoochee River to the west, such that urbanization mainly occurs to the north and east of Columbus.

For the purposes of this study, U.S. Census Bureau's Census 2000 geographic definitions of urban landscapes were used (U.S. Census Bureau, 2001). Four urban areas in the region were identified: one urbanized area (UZA) and three urban clusters (UC). An UZA is defined as a core group of census blocks having a population >50,000 people and a population density of at least 386 people/km^2, while an UC is defined as having the same density but a population between 2,500-49,999 people (U.S. Census Bureau, 2001). The UZA is Columbus (Muscogee County), and the UCs are portions of Valley-Lanett (Harris and Troup Counties), LaGrange (Troup County), and Manchester (Meriwether County), and are delineated as shown in Figure 4.1. According to these definitions, all other land areas in the West Georgia study area are classified as rural (U.S. Census Bureau, 2001). For the "developing" land-use classification, plots were defined as developing if the population growth between 1990-2005 within the surrounding census tract was greater than the national average (19%).

4.3.2 Physiography & Topography

The extent of the study region lies between Latitude 32º 20" 00' and 33º 15" 00' North, and Longitude 84º 30" 00' and 85º 15" 00' West (Figure 4.1). This area is situated within the Piedmont Physiographic Province of west-central Georgia, and elevations range from approximately 50 m near the Coastal Plain at the Fall Line in southern Muscogee County to 425 m atop Dowdell Knob along the Pine Mountain Ridge in northwestern Harris County. This area is characterized by gently rolling hills, deeply weathered bedrock, and isolated occurrences of granitic plutons (University of Georgia, 2007). The topography generally reflects folding and faulting of sediment layers eroded from the Appalachians during the Paleozoic era, which produced such features as the Pine Mountain Ridge near Warm Springs, GA (University of Georgia, 2007).

4.3.3 Land-cover & Land-use History

The study region contains urban, agricultural (pasture land), and forested ecosystems typical of the Southern Piedmont. The entire region was originally Creek Indian territory, which was ceded by the Creek people in the mid-1820s and subsequently taken over by the State of Georgia (Mitchell, 1900). Much of the land in Georgia was agrarian from the early 1700s until the first World War, but has since regenerated back to forest following abandonment of fields during the 1930s (Brown *et al.*, 2005). The resulting mosaic of forested land in West Georgia ranges from intensely managed pine plantations to oak-dominated hardwood stands, and includes a variety of intermediate successional stages. Pine-oak forest communities (see Chapter 2, Table 2.2 for a detailed species list) dominate the landscape and are generally located on relatively dry, exposed slopes and ridges, while tree species such as sweetgum (*Liquidambar styraciflua* L.), water oak (*Quercus nigra* L.), American hornbeam (*Carpinus caroliniana* Walt.), box elder (*Acer negundo* L.), yellow poplar (*Liriodendron tulipifera* L.), and eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Koch.) dominate moist stream-sides (Burton *et al.*, 2005).

4.3.4 Land-cover Classifications

Land-cover class percentages for the West Georgia area were documented and used as landscape indicators of forest ecosystem health. A Landsat 5 Thematic Mapper (TM) image (U.S. Geological Survey, 2005a) from September 2005 and two images from 2004 (August and December) were used as a stacked image layer to produce a land-cover classification for the West Georgia region for the year 2005 (Figure 4.2). Since no other cloud-free summer or winter imagery of the West Georgia area was available for 2005, the leaf-on (August) and leaf-off (December) images from 2004 were included to supplement the September 2005 image in order to improve class assignments and distinguish between deciduous and coniferous forests. These moderate-resolution images (30-meter) were selected because they were readily available, low cost, and already in a usable digital format (U.S. Geological Survey, 2005a, b). Moreover, moderate-resolution imagery, such as Landsat TM, is more applicable to landscape and regional assessments since there are usually fewer classification errors associated with general land-cover classifications (Smith *et al.*, 2003). Each image was radiometrically and geometrically corrected by the USGS to account for errors due to topographic relief and atmospheric interference (U.S. Geological Survey, 2005a, b). Pre-classification processing included the registration of each image to the September 2005 image to ensure they were in the same coordinate system (UTM Zone 16N; datum NAD 83; spheroid WGS 84) and aligned properly for classification and overlay analysis using the image geometric correction tool in ERDAS IMAGINE® 9.0 (Leica Geosystems, 2005). The initial classification scheme (Anderson *et al.*, 1976) developed for the entire four-county scene contained the following five land-cover characterization classes: water/wetlands, deciduous forest, evergreen forest, pasture, and bare ground (the latter contains cutover pine plantations, cultivated agricultural lands, and land under development). This was accomplished using a hybrid classification method (Jensen, 2005). Unsupervised classification was run first, using the ISODATA method, which produced fifty classes (Jensen, 2005). Each of the fifty spectral classes were assigned to their proper thematic classes through a comparison of the classified image with the multispecctral TM imagery, high resolution aerial photography, and observations taken during field work. The resulting classification was then supplemented by supervised classification (Jensen, 2005), which included the addition of signatures of places that were initially classified in error.

A separate classification scheme (Anderson *et al.*, 1976) for 2005 was developed for the urban areas in West Georgia (as delineated by the U.S. Census Bureau 2000 Decennial Census) to increase the accuracy of the classification. This was done to avoid grouping urban and residential vegetation with forest and pasture classes in rural areas which had similar spectral characteristics. Urban areas were first subset and masked from the stacked TM image using Census 2000 urban area delineations, and were then grouped into four classes using an unsupervised classification that originally produced twenty classes (Jensen, 2005). The resulting image contained the following four classes: water/wetlands, urban vegetation (includes all photosynthetically active plants with similar spectral characteristics as deciduous and/or evergreen tree species), urban lawn (includes all grassy areas), and urban/built-up (includes land-covered by structures and impervious surfaces). The urban area classification was compared to the initial four-county classification to examine any discrepancies between classes prior to overlaying and recoding procedures. Once the urban areas were classified, the image was overlaid with the initial classification to produce an eight-class final image. The final image contained the following eight land-cover characterization classes: urban/built-up, bare ground, pasture, urban lawn, urban vegetation, deciduous forest, evergreen forest, and water/wetlands (Anderson *et al.*, 1976; Jensen, 2005). Once a final land-cover classification for the entire area had been produced, an accuracy assessment was conducted and high-resolution 1-meter color Digital Ortho Quarter Quads (DOQQs) were used as reference material (date of imagery February 1999; accessed USGS Seamless Data Server June 13, 2006), along with the Landsat TM images, to verify the classification of thirty randomly generated points (Jensen, 2005).

A second land-cover classification was constructed for 2001 (Figure 4.3) to 1) assess changes across West Georgia between 2001 and 2005 for use in separate studies, and 2) compare results of this classification method to those of others constructed for the West Georgia region (Lockaby *et al.*, 2005). The same methods as described above for 2005 were used to classify the region and urban areas for 2001. Images from January 2003 (Landsat 5 TM) and March 2001 (Landsat 7 Enhanced Thematic Mapper Plus) were included to supplement the October 2001 (Landsat 7 ETM +) image to improve class assignments (U.S. Geological Survey, 2005a, b). The same classes used for the 2005 image were used for the 2001 map, so that changes between images could be directly compared. An accuracy assessment was also conducted for the 2001 image, using the Landsat TM and DOQQ imagery to verify the class placement of thirty random pixels (Jensen, 2005).

4.3.5 Post-Classification Change Detection Analysis

Change detection analysis was performed with post-classification comparisons using a GIS analysis matrix tool in ERDAS IMAGINE® 9.0 (Leica Geosystems, 2005). With this tool, the user is able to analyze how much of each class remained the same or changed to another class (e.g., forest to urban). For the purposes of this study, I was mainly interested in the overall percent changes of each class from 2001 to 2005. However, urban change was also analyzed to spatially examine where urban development is occurring across West Georgia, as well as to locate any places that may have been classified in error (e.g., transitions from urban/built-up to another land-cover type typically does not occur).

4.3.6 Landscape Indicators of Forest Ecosystem Health

Landscape pattern metrics for the West Georgia area were also collected and used as landscape indicators of forest ecosystem health. Landscape pattern data were obtained using the 2005 land-cover classification as input into Fragstats with the patch neighbor rule set to 8-cells (McGarigal *et al.*, 2002). Fragstats is a spatial pattern analysis software program designed to compute a multitude of landscape metrics for categorical maps (McGarigal *et al.*, 2002). The 8-cell rule considers all eight adjacent cells – the four orthogonal and four diagonal neighbors. With the 8-cell rule set, two cells of the same class that are diagonally contiguous will be considered part of the same patch, *vs.* the 4-cell rule where only the four orthogonal neighbors are considered and thus, the same two cells would be considered separate patches. The West Georgia study area was delineated by the census tracts containing each the 12 study sites, resulting in 10 sub-units for analysis (three of the developing sites were located within the same census tract due to the large tract size typical of rural counties of the area). Although many ecological studies use watersheds as the unit for summarizing data (Matson, 1990; Basnyat *et al.*, 2000; Groffman *et al.*, 2003; Holland *et al.*, 2004; Kremen and Ostfeld, 2005), for this analysis the census tract was used as the unit of delineation since this is the sampling unit used by the U.S. Census Bureau to compile socio-economic data. This allows combination of land-cover data with census demographic and Topologically Integrated Geographic Encoding and Referencing (TIGER®) GIS layers (U.S. Census Bureau, 2005). Further, these units are more appropriate for airshed studies since the greatest emission sources are generally located in more populated areas (Dai and Rocke, 2000). Only census tracts containing the location of the field plots were used in this analysis. For the purposes of the overall study, five main land-cover types of interest were analyzed: forest (urban vegetation + deciduous forest + evergreen forest), grass (pasture + urban lawn), water/wetlands, bare ground, and urban/built-up. These categories were recoded from the original classification to reflect a more general cover type. However, since the focus of this chapter is terrestrial forest ecosystem health, only the forest land-cover class (urban vegetation + deciduous forest + evergreen forest) was used in calculating the landscape indicator metrics. Although a multitude of landscape metrics can be calculated using Fragstats (McGarigal *et al.*, 2002), the goal was to select simple yet pertinent metrics as relative landscape-scale descriptors of forest ecosystem health in West Georgia. The following metrics were calculated using the forest land-cover class:

patch density (FORPD), edge density (FORED), and perimeter-area fractal dimension (FORPAFRAC), while Landscape Shannon’s Diversity Index (SHDI) and Landscape Shannon's Evenness Index (SHEI) were calculated at the landscape level and includes each of the five land-cover types listed above.

The FORPD metric expresses the number of patches per 100 ha within each of the sampling units (e.g., census tract, census county subdivision, watershed). However, no information is conveyed about the sizes or spatial distribution of the patches. The FORED metric reports the length of edge (in m/ha) within each of the sampling units. Again, this information is important but vague, since it is the total amount of edge per unit area, and no information about patch size is reported. The FORPAFRAC reflects patch shape complexity and is appealing because it can be used across a range of spatial scales. Fractal dimension ranges from 1 to 2, or from shapes with very simple perimeters to those with very complex perimeters, respectively. The SHDI metric expresses the proportion of the landscape occupied by a patch type of a particular class (McGarigal *et al.*, 2002). Landscape diversity is 0 where there is only one patch, and increases to infinity as the number of different patch types increases and/or the areal distribution among patch types becomes more even. Similarly, the SHEI metric represents the evenness of areal distribution among patch types (McGarigal *et al.*, 2002). Landscape evenness is 0 where the areal distribution among patch types is uneven, or where there is dominance of only one patch type, and increases toward 1, where there is perfect evenness among distribution of area among patch types. Since small experimental units (i.e., census tracts *vs.* watersheds) were used to calculate the metrics, the spatial distribution shortcomings of some of these were not a substantial problem.

4.3.7 Plot-level Biological Indicators of Forest Health

Forest stand structure and condition data from 36 field plots (12 urban, 12 developing, 12 rural) were included as biological variables in this assessment. These variables were selected because 1) they have been proven useful as forest health indicators in previous studies (McCune *et al.*, 1997; McIntyre, 2000; McKinney, 2002; Wear and Greis, 2002; Geiser and Neitlich, 2007), and 2) they were collected to characterize the differences in forest stand structure and condition across land-use types in West Georgia. For biological and urbanization variable definitions see Table 4.1; for more information about measurements, methods, and analysis, the reader is referred to Chapter 2.

4.3.8 Correlation Matrix

A total of 47 variables were obtained to represent a mix of biological, land-cover, and landscape pattern variables suitable to describe the current condition of ecosystem health in West Georgia: 30 biological variables from field-based measurements (see Chapter 2), and 17 urbanization variables from: census data (5), land-cover classification data (5), landscape pattern analysis data (5), and pollution datasets (2). A multivariate correlation matrix (Spearman's Rho) was constructed using JMP IN® 5.1.2 (SAS Institute Inc., 2003) to determine which of the urban and biological variables were highly correlated. Spearman's Rho is a correlation coefficient computed on the ranks of the data values (instead of using the values), using the formula for the Pearson's product-moment correlation, which measures the strength of the linear relationship between two variables (SAS Institute Inc., 2003). If there is an exact linear relationship between two variables, the correlation is 1 or –1, depending on whether the variables are positively or negatively related. If there is no linear relationship, the correlation is zero (SAS Institute Inc., 2003).

4.4 Results & Discussion

4.4.1 Land-cover Classification

Land-cover characterizations of the four-county area in West Georgia for 2001 and 2005, as classified and interpreted from Landsat (TM) imagery, include urban/built-up, bare ground (areas under development, cultivated areas, and harvested timberlands), pasture, urban lawn (lawns, grassy lots, and gold courses), urban vegetation (trees and large shrubs), deciduous forest, evergreen forest, and water/wetlands (Table 4.2). Forty-one percent of forest cover in West Georgia in 2005 was evergreen, which includes many areas of extensively-managed pine plantations. Urban census tracts were characterized by high percent cover of urban/built-up land (42-56%) and low percent cover of forest land (37-51%). By contrast, rural and developing sites had very low percent cover of urban/built-up land (0-1% and 2-11%, respectively) and very high percent cover of forest land (71-85% and 78-82%, respectively). Actual land-cover class percentages are presented in Table 4.2 and are further discussed below in the land-cover change detection analysis section. The overall classification accuracy for both of the West Georgia land-cover classifications was 93%, while Kappa values were 0.9116 and 0.9080 for 2001 and 2005, respectively (Table 4.3).

4.4.2 Land-cover Change Detection Analysis

Columbus, GA is a moderately-sized city, but urban development is occurring at a rapid pace (U.S. Census Bureau, 2006). Urban/built-up land accounted for only 2% of the total land-cover in 2001 across the four-county West Georgia region but increased to 4% in 2005 (Table 4.2). Although these percentages are nominal overall, urban/built-up land in the region has doubled in just 4 years. Most of these changes have occurred in Harris County, where census population growth data (U.S. Census Bureau, 2006) also reflect these rapid changes (56% from 1990-2005). There were no changes in deciduous forest (31%), urban vegetation (1%), or in the amount of water/wetlands (4%). A majority of the total forest cover in West Georgia is extensively-managed pine plantations, which is typical of this area of the South (Brown *et al.*, 2005). In 2005, the amount of evergreen forest land-cover was 41%, increasing from 35% in 2001. This is possibly a reflection of timber harvest and planting cycles, since the amount of bare ground decreased from 16% to 12% over the four-year period. The remaining portion of bare ground in 2001 could be an indication of areas undergoing development at that time as noted by the increase in urban/built-up land in 2005. Total grass cover, including both pasture and urban lawn, also decreased slightly from 9% and 2% in 2001 to 6% and 1% in 2005, respectively, which could also possibly be a sign of conversion from rural to urban/built-up land in the area.

4.4.3 Landscape Pattern Analysis

Since a majority of the land in West Georgia is forested (73% in 2005), the goal of the landscape pattern analysis was to gain more detailed information about how forested land patches were patterned across the landscape and if there were differences between land-use types (Table 4.4). Forest patch density was greatest in urban sites (10-22 patches/100 ha) *vs.* rural and developing sites (0.66-2.26 and 1.73-2.23 patches/100 ha, respectively). This suggests more patchiness among urban forests in West Georgia, possibly resulting from forest fragmentation due to land development. Similarly, forest edge density was also greatest in urban sites (122-162m/100 ha) *vs.* rural and developing sites (54-69m and 68-76m/100 ha, respectively), and is consistent with research by Zipperer (1993), who reported increased deforestation and higher perimeter-to-area ratios in forested patches in urban areas of Maryland.

Perimeter-area fractal dimension tells us something about the shape of forest patches. Typically, urban and managed forests have more regular, simple perimeter shapes (values near 1) while unmanaged, natural forests have more irregular, complex perimeter shapes (values near 2). Urban sites in West Georgia have PAFRAC values ranging from 1.46-1.56, *vs.* rural (1.41-1.45) and developing (1.45) sites which have slightly lower values, although these values were not significantly different between land-use types. The similarity in values across sites could possibly be attributed to the large amount of managed pine plantations located in rural areas of the West Georgia region sampled, which is evident from the high percentages of evergreen forest and bare ground land-cover in rural (41-50% and 8-18%, respectively) and developing (42-47% and 1-12%, respectively) areas of West Georgia.

To gain further insight into the diversity and evenness of land-cover types across land-use areas, landscape Shannon's diversity and evenness indices were calculated for the West Georgia region (Table 4.4). Results suggest that urban areas are the most diverse, with SHDI values ranging from 0.91-0.98, meaning that urban areas have a greater number of different patch types (i.e., land-cover class types) and/or the areal distribution among patch types is more even. The lower SHDI value ranges for rural and developing sites (0.59-0.82 and 0.67-0.76, respectively) suggest that either there are a fewer number of land-cover class types present (e.g., no urban/built-up land-cover present) or that one or more land-cover class types dominate the landscape (i.e., forest land-cover). This finding is supported by other studies in West Georgia (Burton *et al.*, 2005), but is contradicted in examinations of larger urban areas elsewhere (McKinney, 2006). One suggestion is that as areas begin to become urbanized and heterogeneous, SHDI increases (Zipperer *et al.*, 2000), until a point where the landscape is highly urbanized and intensely homogenous (McKinney, 2006). The SHEI index provides a similar scenario, indicating that distribution of area among land-cover types is most even, or less dominated by one land-cover type, in the urban (0.66-0.71) *vs.* rural (0.37-0.59) and developing (0.41-0.47) areas of West Georgia.

4.4.4 Correlation Matrix

4.4.4.1 The Urbanization Variables: Land-cover and Landscape Pattern vs. Census Data

The ultimate goal of the multivariate correlation matrix was to determine which urban and biological variables were well correlated. However, to validate how well the satellite-derived "urbanization" variables represent truly "urban" areas in West Georgia, correlations were first compared between land-cover/landscape pattern data and U.S. Census Bureau 2000 Decennial Census data (i.e., population, housing, road densities), calculated at the tract level for each of the tracts containing field plot locations. With the exception of % grass, all of the satellite-derived metrics had significant ($p \leq 0.10$) correlations of Rho ≥ |0.65| with the three census datasets, thus validating the use of these "urbanization" variables in this correlation analysis (Table 4.5).

4.4.4.2 Urbanization Variables **vs.** *Biological Variables*

Many of the biological variables measured from field plot locations were significantly ($p \leq 0.10$) correlated with each of the 10 "urbanization" variables derived from the land-cover classification and subsequent fragmentation analyses (Table 4.6 or Appendix 1). The main purpose of this analysis was to demonstrate the utility of these data correlations as a land management and planning tool. As such, some examples of these are briefly discussed below.

The percentage of forest land-cover in West Georgia was inversely correlated with population (Rho = -0.88; p = 0.03), housing (Rho = -0.87; p = 0.03), and road (Rho = -0.93; p = 0.04) densities (Figure 4.4). These correlations seem obvious, but they are nonetheless important. Cordell and Macie (2002) reported that Harris and Meriwether counties are ranked among the greatest in the country for 2020 projected population pressures on forested land and wildlife habitat. These data are also supported by my land-cover and census population data analyses, that reveal that Harris County had the most forested land area in the West Georgia region (81% of land was forested in 2005) yet also had the greatest population growth rate in the region from 1990-2005 (56%), which is nearly three times greater than the national average (19%).

The percentage of urban land *vs.* the combined injury to trees resulting from pest, disease, and mechanical injury were positively correlated (Rho = 0.64; p = 0.05; Figure 4.5). As the amount or urban land increased, so did the amount of injury. Typically, urban forests experience greater disturbance than rural areas, often rendering them more susceptible to other forms of environmental stress (Zipperer, 2002a). Findings from several previous studies have also suggested that urban systems have a higher incidence of pests and diseases (McLaughlin and Percy, 1999; McIntyre, 2000; McKinney, 2006). In West Georgia, however, mechanical injury scores were greatest, and could possibly be linked to hurricane and ice storm damage in the region prior to sampling. Even though limb breakage from these events was evident in all of the plots measured (urban, developing, and rural), the scores were greatest in urban areas.

The percentage of urban land *vs.* number of lichen species, or lichen species richness, were negatively correlated (Rho = -0.52; p = 0.06; Figure 4.6). Gombert (2004) reported that lichen diversity in France was influenced by “environmental artificiality” and air pollution exposure, resulting in lower lichen diversity in urban *vs.* rural areas. Lichen diversity also varies due to exposure to air pollutants such as SO_2 and NO_2 (McCune *et al.*, 1997; van Dobben *et al.*, 2001; Gombert *et al.*, 2004; Frati *et al.*, 2006; Fenn *et al.*, 2007; Geiser and Neitlich, 2007). Further, edge effects resulting from forest fragmentation due to urban land development can have major impacts on lichen species diversity (Renhorn *et al.*, 1997; Esseen and Renhorn, 1998).

The number of tree species per site, or tree species richness, and forest patch density were negatively correlated (Rho = -0.62; p = 0.01; Figure 4.7). As the number of forest patches increased the number of tree species decreased. A high number of forest patches in a given area typically indicates many small, fragmented forest patches, whereas a low number indicates fewer, larger forested patches (Zipperer, 1993, 2002b). Since urban forests are usually small due to encroaching residential and commercial land development, these areas typically have a higher number of forest patches per unit area, or high forest patch density (Zipperer, 2002b). In many of these urban forests, tree species richness is generally lower than in surrounding rural forests (McKinney, 2002; Miller and Hobbs, 2002; Burton *et al.*, 2005).

The percentage of mechanical injury and landscape Shannon’s diversity were positively correlated (Rho = 0.83; p <0.001; Figure 4.8). As noted earlier, mechanical injury was observed across the West Georgia region, possibly resulting from large, infrequent disturbances. Nevertheless, injury scores were greatest in urban areas. Urban areas also had the greatest SHDI values, indicating a variety of land-cover patch types in these areas. As land became fragmented and diversified from urban development, the likelihood for the potential of mechanically-injured trees also increased (Pickett *et al.*, 2001).

4.5 Conclusions

Results from this study suggest that this land-cover classification is adequate for selecting landscape indicators of ecosystem health in West Georgia. These indicators correlated well with many field-measured biological responses of ecosystem health, validating its utility as land management and planning tool. The percentage of forest land-cover had correlations to several of the urbanization variables, and was strongly inversely correlated with population, housing, and road densities. Previous analyses have reported that lichens are good bioindicators of forest ecosystem health (Nash and Gries, 1986; McCune *et al.*, 1997; Esseen and Renhorn, 1998; Gombert *et al.*, 2004; Kalwij *et al.*, 2005; Frati *et al.*, 2006; Geiser and Neitlich, 2007) and these results support those findings. Lichen incidence, abundance, and species richness were among several variables significantly correlated with landscape variables including % urban, forest, and pasture land-covers, forest patch and edge densities, forest perimeter-area fractal dimension, housing, population, and road densities, and distance to road. These correlations could be used to develop predictive models to discern what factors are related to ecosystem health, and to identify the areas that warrant further ground-based studies. Such a tool could prove useful to land managers by providing a quick and simple method to assess broad areas of land in a single analysis, enabling funds to be reserved for more in-depth analyses in areas identified as “impaired” through the use of this tool.

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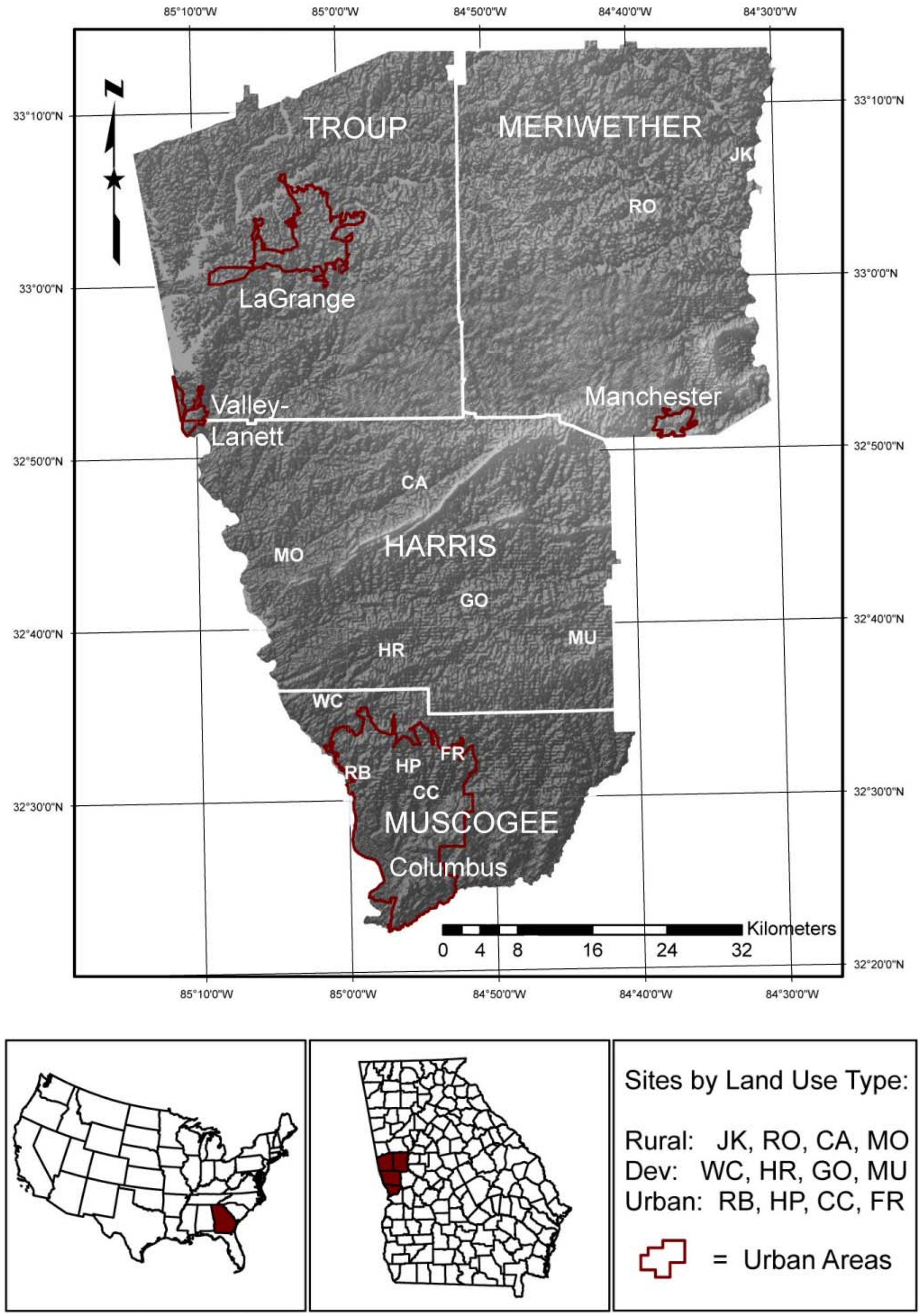

Figure 4.1 Map of West Georgia study area. Urban Sites: RB=Roaring Branch; HP=Heath Park; CC=Cooper Creek; FR=Flat Rock; Developing Sites: WC=Whiskey Creek; HR=Hunter Road; GO=Goolsby; MU=Mulberry Creek; Rural Sites: MO=Mountain Oak; CA=Callaway; RO=Red Oak: JK=Joe Kurz WMA. Source: Diane M. Styers, 2008.

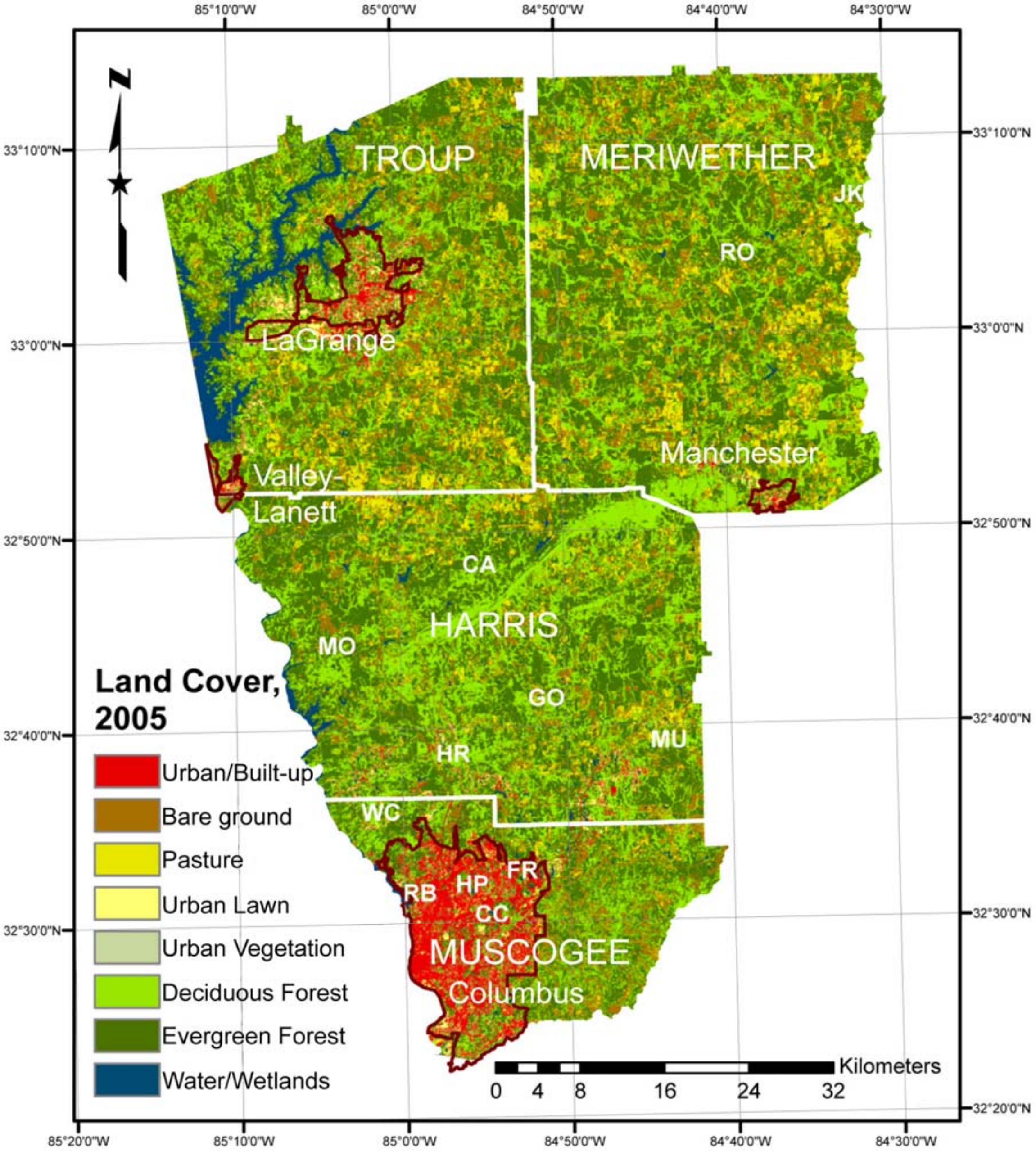

Figure 4.2 Land-cover classification of West Georgia for 2005 showing locations of the study sites. Source: Diane M. Styers, 2008.

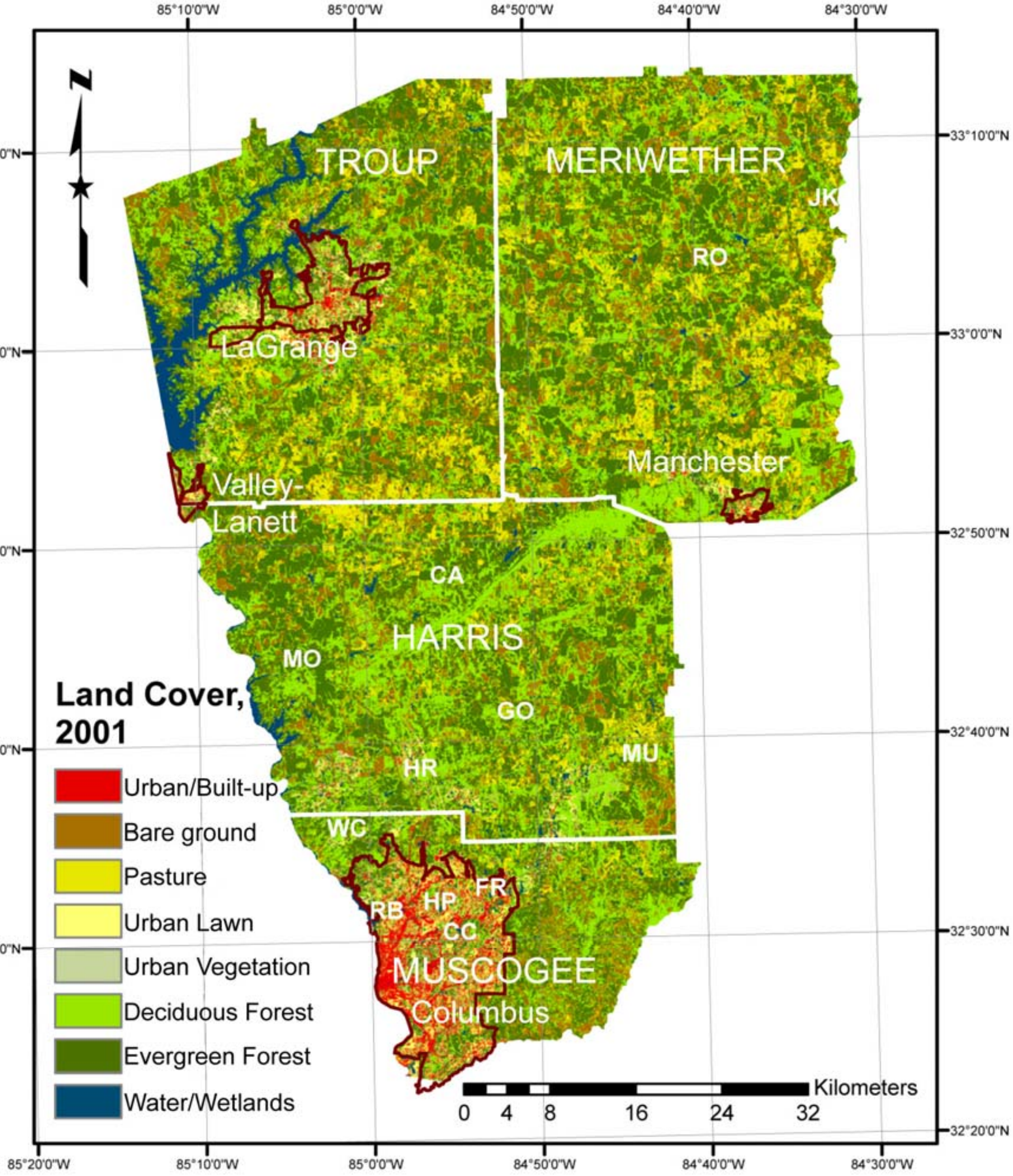

Figure 4.3 Land-cover classification of West Georgia for 2001 showing locations of the study sites. Source: Diane M. Styers, 2008.

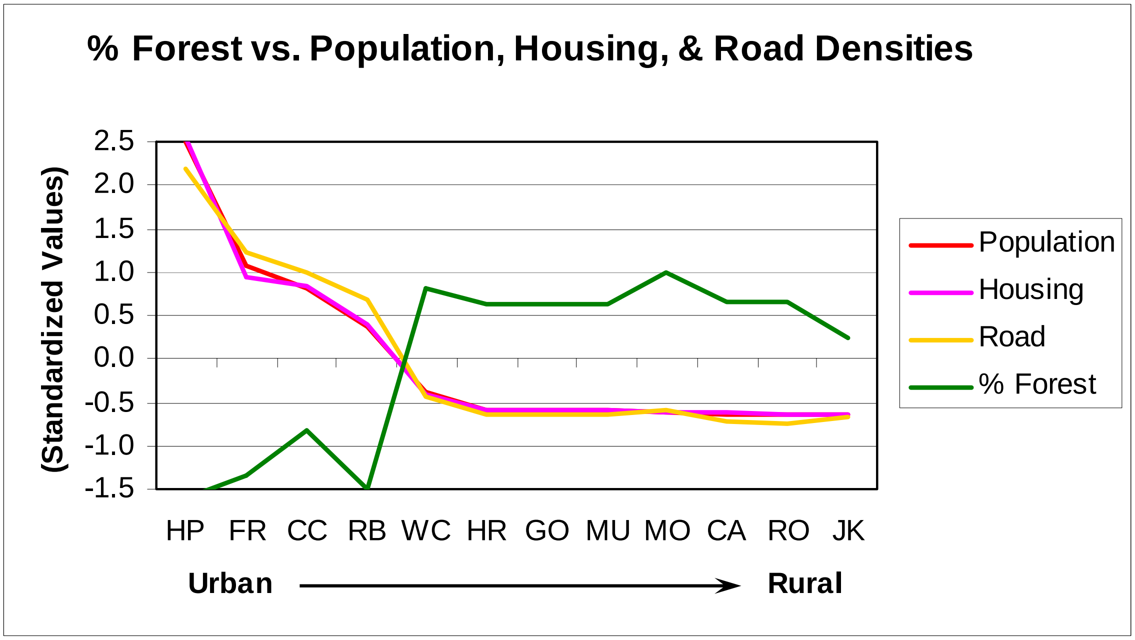

Figure 4.4 Percent forest land-cover *vs*. population, housing, and road densities in West Georgia. Source: Diane M. Styers, 2008.

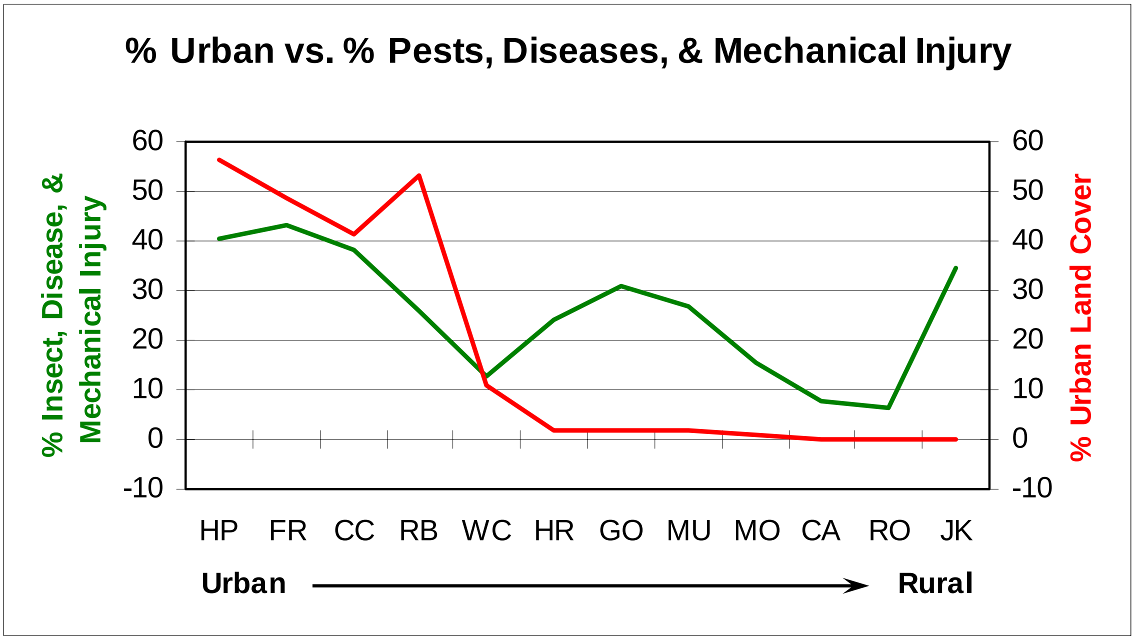

Figure 4.5 Percent urban land-cover *vs.* percent total injury to trees from pests, diseases, and mechanical injury in West Georgia. Source: Diane M. Styers, 2008.

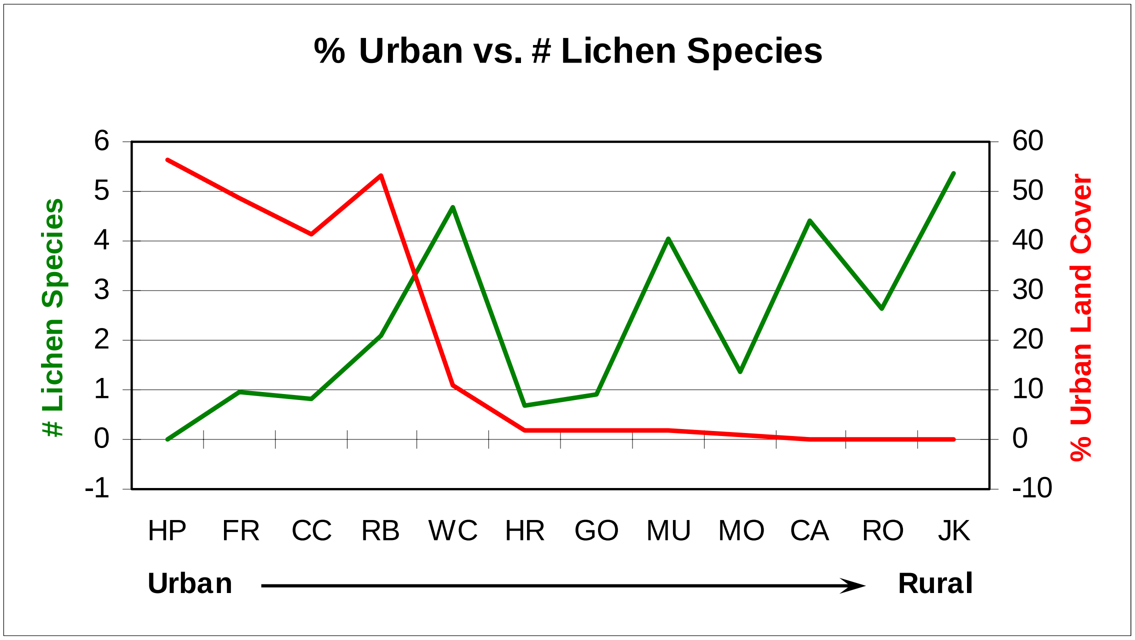

Figure 4.6 Percent urban land-cover *vs.* lichen species richness in West Georgia. Source: Diane M. Styers, 2008.

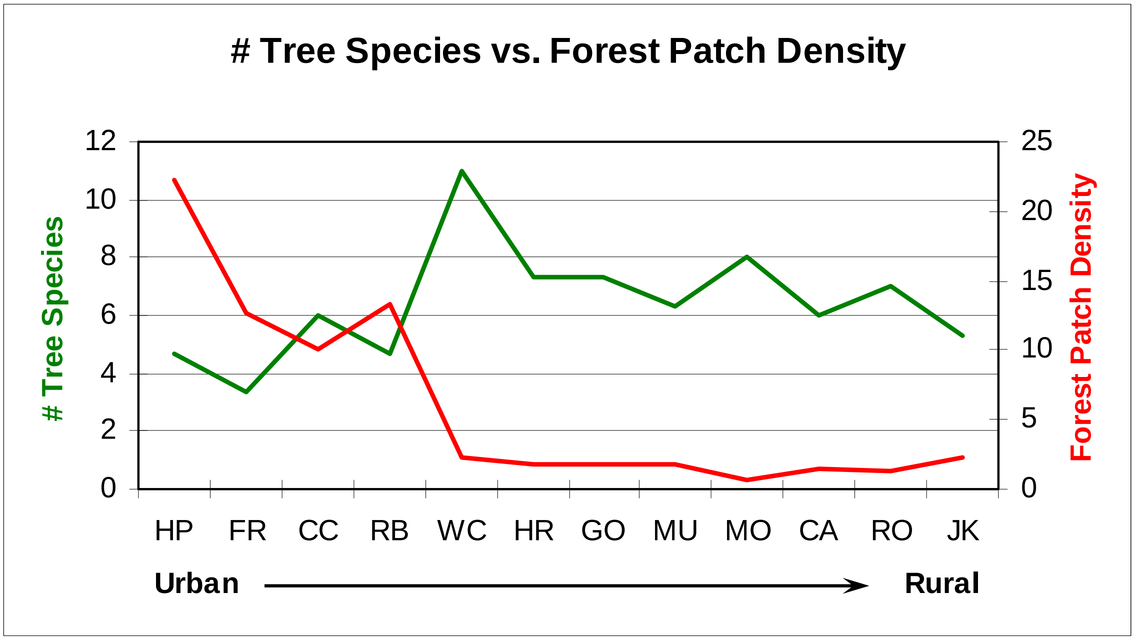

Figure 4.7 Tree species richness *vs.* forest patch density in West Georgia. Source: Diane M. Styers, 2008.

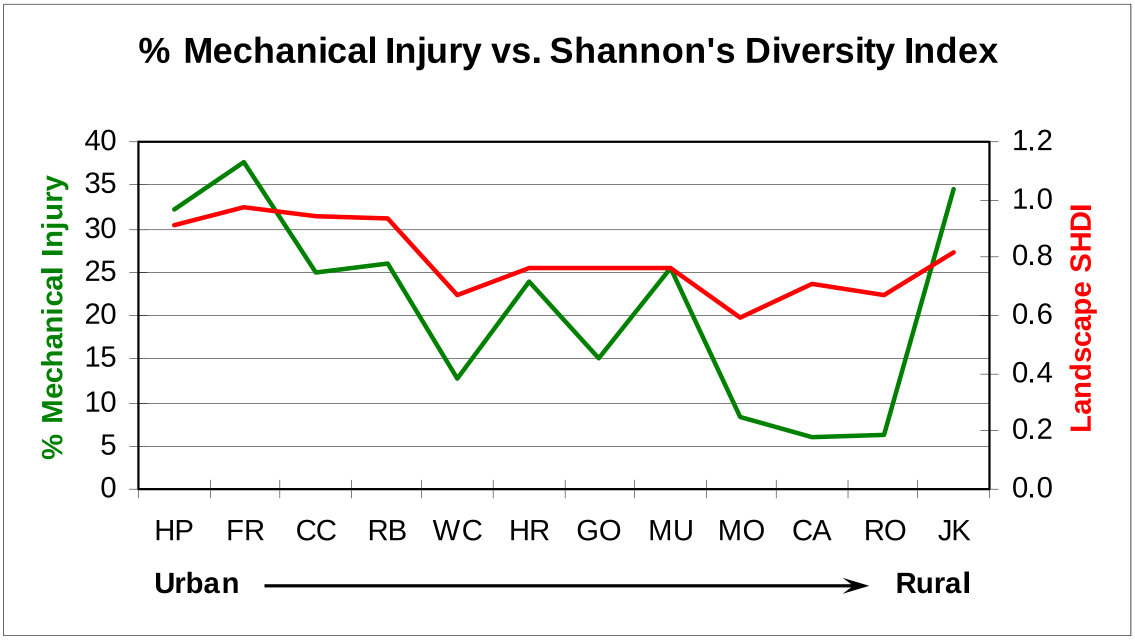

Figure 4.8 Percent mechanical injury *vs.* landscape Shannon's diversity index in West Georgia. Source: Diane M. Styers, 2008.

Table 4.1 Definitions for each of the biological and urbanization variables measured in West Georgia.

Biological Variables	**Definitions**
Total number of trees >10cm dbh /ha	Total number of mature trees (>10cm dbh) per hectare (ha)
Total number of hardwoods /ha	Total number of mature hardwoods (>10cm dbh) per ha
Total number of pines /ha	Total number of mature pines (>10cm dbh) per ha
Hardwood:Pine ratio	Ratio of hardwood to pine trees per ha
Total number of tree species	Total number of different tree species measured at each site
Mean dbh (cm) of all mature trees	Mean dbh (in cm) of all mature trees (>10cm) measured
Basal Area (m^2/ha)	Basal area (m^2/ha)
Median age of stand	Median age of forest stand as measured by six dominant pines at each site
% Peak canopy cover	Peak canopy cover percentage at each site (measured in mid-June)
Mean upper canopy height (m)	Mean height of upper canopy at each site (measured by six dominant trees in main canopy)
Mean subcanopy height (m)	Mean height of subcanopy at each site (measured by six average trees in secondary canopy)
Total number of trees 2.5-10cm dbh/ha	Total number of trees (2.5-10cm dbh) per ha
Mean number of saplings & shrubs 0.635-2.5cm/ha	Mean number of saplings & shrubs (0.635-2.5cm diameter & at least 1m in height) per ha
Mean number of seedlings <0.635cm /ha	Mean number of seedlings (<0.635cm diameter and <1m in height) per ha
% Woody stems /ha	Percentage of groundcover occupied by small woody stems (<0.635cm diameter) per ha
% Herbaceous plants /ha	Percentage of groundcover occupied by herbaceous plants per ha
% Leaf litter /ha	Percentage of groundcover occupied by leaf litter per ha
% Bare ground /ha	Percentage of groundcover occupied by bare ground (or dirt) per ha
% Trees with insect injury	Percentage of trees with evidence of insect injury
% Trees with disease injury	Percentage of trees with evidence of disease injury
% Trees with mechanical damage injury	Percentage of trees with evidence of mechanical injury
% Insect + Disease + Mech damage for all trees	Percentage of trees with evidence of insect, disease, &/or mechanical injury
% Trees with lichens	Percentage of trees with lichen incidence (presence *vs.* absence)
Mean number of lichen species per tree	Mean number of lichen species per tree
Mean lichen abundance rank for all hardwoods	Mean lichen abundance rank for all hardwoods (percentage of cover: 1=0%; 2=1-20%; 3=21-40%; 4=41-60%; 5=61-80%; 6=81-100%)

Table 4.1 con't. Definitions for each of the biological and urbanization variables measured in West Georgia.

Biological Variables con't	**Definitions**
Mean number of crustose lichen species on water oaks	Mean number of crustose lichen species per tree
Mean number of foliose lichen species on water oaks	Mean number of foliose lichen species per tree
Crustose:Foliose ratio (on water oaks)	Ratio of crustose to foliose lichen species per tree
Mean lichen abundance rank for water oaks	Mean lichen abundance rank for water oaks (percentage of cover: 1=0%; 2=1-20%; 3=21-40%; 4=41-60%; 5=61-80%; 6=81-100%)
Mean dominance of crustose over foliose (on water oaks)	Mean dominance of crustose over foliose lichens (1= crustose; 2= foliose)

Urbanization Variables	**Definitions**
Population density	Population density (number of people/km^2) for census tract containing site
Housing density	Housing density (number of houses/km^2) for census tract containing site
Road density	Road density (length of road in km/km^2) for census tract containing site
Plot distance to any road (m)	Measure of distance (in m) from each plot to the nearest road
Plot distance to major road (m)	Measure of distance (in m) from each plot to the nearest paved road
% Forest	Percentage of forest cover for census tract containing site
% Pasture	Percentage of pasture cover for census tract containing site
% Grasses (pasture + lawn)	Percentage of grass cover (pasture & urban lawn) for census tract containing site
% Urban	Percentage of urban/built-up land cover for census tract containing site
% Non-vegetated land (urban + bare ground)	Percentage of urban/built-up land & bare ground (dirt) cover for census tract containing site
Forest patch density	Number of forest patches per 100 ha within census tract containing site
Forest edge density	Total length of forest edge (in m/ha) within census tract containing site
Forest perimeter-area fractal shape	Forest patch shape complexity, ranging from simple (1) to complex (2) perimeter shapes
Shannon's landscape diversity index	Proportion of landscape occupied by a patch type of a particular class, where 0=only one patch type, increasing as the number of different patch types increases
Shannon's landscape evenness index	Evenness of areal distribution among patch types, where 0=uneven areal distribution or dominance of only one patch type, increasing toward 1, where there is perfect evenness
Maximum seasonal ozone concentration	Maximum ozone concentration measured at site from May - Sept, 2006
Maximum seasonal NO_x concentration	Maximum NO_x concentration measured at site from May - Sept, 2006

Table 4.2 Area and percentages of land-cover types in West Georgia for 2001 and 2005, and percentages of land-cover change between the two time periods.

Land Cover	**2001**		**2005**		
Class	**Area (ha)**	**Cover**	**Area (ha)**	**Cover**	**% Change**
Urban	10099	2%	16618	4%	100%
Bareground	71201	16%	59240	12%	-25%
Pasture	38943	9%	26192	6%	-33%
Urban Grass	8532	2%	5729	1%	-50%
Urban Vegetation	5813	1%	3266	1%	0%
Deciduous	140458	31%	140318	31%	0%
Evergreen	158867	35%	186182	41%	17%
Water	20748	4%	17117	4%	0%
Total	454662	100%	454662	100%	

Table 4.3 Classification accuracy error matrices and Kappa coefficients for 2001 and 2005 West Georgia land-cover classifications.

2001	Urban	Bare Ground	Pasture	Lawn	Urban Veg	Deciduous	Evergreen	Water	Row Total	Producer's Accuracy	User's Accuracy	Kappa
Urban	1	0	0	0	0	0	0	0	1	100%	100%	1.00
Bare Ground	0	4	0	0	0	1	0	0	5	100%	80%	0.77
Pasture	0	0	3	0	0	0	0	0	3	100%	100%	1.00
Lawn	0	0	0	1	0	0	0	0	1	100%	100%	1.00
Urban Veg	0	0	0	0	0	0	0	0	0	----	----	0.00
Deciduous	0	0	0	0	0	9	0	0	9	82%	100%	1.00
Evergreen	0	0	0	0	0	1	9	0	10	100%	90%	0.86
Water	0	0	0	0	0	0	0	1	1	100%	100%	1.00
Column Total	1	4	3	1	0	11	9	1	30			
2005												
Urban	1	0	0	0	0	0	0	0	1	100%	100%	1.00
Bare Ground	0	4	0	0	0	0	0	0	4	100%	100%	1.00
Pasture	0	0	2	0	0	0	0	0	2	100%	100%	1.00
Lawn	0	0	0	1	0	0	0	0	1	100%	100%	1.00
Urban Veg	0	0	0	0	0	0	0	0	0	----	----	0.00
Deciduous	0	0	0	0	0	8	1	0	9	89%	89%	0.84
Evergreen	0	0	0	0	0	1	11	0	12	92%	92%	0.86
Water	0	0	0	0	0	0	0	1	1	100%	100%	1.00
Column Total	1	4	2	1	0	9	12	1	30			

Note:

[1] Overall classification accuracy and Kappa for 2001 are 93.33% and 0.9116, respectively; for 2005 they are 93.33% and 0.9080, respectively.

Table 4.4 Landscape pattern metrics by site, based on 2005 West Georgia land-cover classification.

Site	Area (ha)	% of Landscape	FORPD (100 ha^{-1})	FORED (m/ha)	FORPAFRAC	SHDI	SHEI
HP	193	37.07	22.24	162.32	1.56	0.91	0.66
FR	305	41.86	12.62	135.51	1.47	0.98	0.71
CC	552	51.40	10.05	131.27	1.48	0.94	0.68
RB	500	38.78	13.26	121.56	1.46	0.94	0.68
WC	2716	81.87	2.23	75.81	1.45	0.67	0.41
HR, GO, MU	27274	78.22	1.73	68.20	1.45	0.76	0.47
MO	32288	85.29	0.66	54.17	1.45	0.59	0.37
CA	26414	79.00	1.46	56.32	1.41	0.71	0.44
RO	23058	78.75	1.24	59.71	1.44	0.67	0.48
JK	19547	71.00	2.26	69.29	1.44	0.82	0.59

Table 4.5 Ten urbanization metrics calculated using 2005 West Georgia land-cover classification, and corresponding Spearman's Rho correlation coefficients and p-values to population, housing, and road densities in West Georgia.

Spearman's Rho Correlations	**Population Density**		**Housing Density**		**Road Density**	
	Rho	**p**	**Rho**	**p**	**Rho**	**p**
% Forest	-0.88	0.03	-0.87	0.03	-0.93	0.04
% Pasture	-0.66	<0.01	-0.65	<0.01	-0.70	<0.01
% Grassland	-0.16	0.73	-0.18	0.73	-0.13	0.60
% Urban	0.90	<0.01	0.90	<0.01	0.95	<0.01
% Urban+Bareground	0.90	0.07	0.89	0.07	0.94	0.10
FORPD	0.97	<0.01	0.97	<0.01	0.98	<0.01
FORED	0.96	<0.01	0.96	<0.01	0.99	<0.01
FORPAFRAC	0.92	<0.01	0.93	<0.01	0.88	<0.01
SHDI	0.73	0.03	0.72	0.03	0.80	0.05
SHEI	0.75	0.08	0.74	0.08	0.81	0.10

Table 4.6 Significant Spearman's Rho correlation coefficients and p-values between land-cover classes and other variables.

% Forest	**Rho**	**p**
#TreeSpp	0.75	<0.01
#Stems2.5-10	0.68	<0.01
#Stems>10	0.57	0.01
DistAnyRoad	0.54	0.02
%urban+bg	-1.00	<0.01
%urban	-0.97	0.02
max_nox	-0.96	0.01
fored	-0.95	<0.01
forpd	-0.95	<0.01
shei	-0.94	<0.01
RoadDens	-0.93	0.04
shdi	-0.92	<0.01
PopDens	-0.88	0.03
HousDens	-0.87	0.03
MeanDBH	-0.77	<0.01
pafrac	-0.71	0.02
%I+D+M	-0.71	<0.01
%Mech	-0.70	<0.01
%HerbMean	-0.57	0.01

% Pasture	**Rho**	**p**
LicAbdMeanHW	0.57	0.06
#LicSppHW	0.57	0.06
DOMCru/Fol	0.50	0.07
max_nox	-0.95	0.04
%urban	-0.74	<0.01
RoadDens	-0.70	<0.01
fored	-0.68	0.01
PopDens	-0.66	<0.01
HousDens	-0.65	<0.01
forpd	-0.63	0.04
pafrac	-0.57	<0.01

% Grass	**Rho**	**p**
DOMCru/Fol	0.74	0.02
%HerbMean	0.54	0.08
%Mech	0.52	0.04
#Stems<0.635	-0.68	0.02
%WoodyMean	-0.62	0.01
#TreeSpp	-0.54	0.06
max_o3	-0.50	0.05

% Urban/BU	**Rho**	**p**
%urban+bg	0.98	0.05
fored	0.97	<0.01
max_nox	0.97	0.07
RoadDens	0.95	<0.01
forpd	0.95	<0.01
PopDens	0.90	<0.01
HousDens	0.90	<0.01
shei	0.86	0.09
shdi	0.84	0.03
pafrac	0.73	<0.01
%I+D+M	0.64	0.05
%Mech	0.60	0.07
%forest	-0.97	0.02
%pasture	-0.74	<0.01
LicAbdMeanHW	-0.57	0.05
#LicSppHW	-0.52	0.06
DistAnyRoad	-0.50	0.01

% Urban/BU + BG	**Rho**	**p**
%urban	0.98	0.05
max_nox	0.97	0.01
fored	0.96	<0.01
forpd	0.96	<0.01
RoadDens	0.94	0.10
shei	0.92	<0.01
shdi	0.90	<0.01
PopDens	0.90	0.07
HousDens	0.89	0.07
MeanDBH	0.76	<0.01
pafrac	0.73	0.05
%I+D+M	0.68	0.02
%Mech	0.67	0.01
%HerbMean	0.54	0.01
%forest	-1.00	<0.01
#Hardwoods	-0.77	0.06
#TreeSpp	-0.71	<0.01
#Stems2.5-10	-0.66	<0.01
#Stems>10	-0.56	<0.01
DistAnyRoad	-0.52	0.05

Table 4.7 Significant Spearman's Rho correlation coefficients and p-values between landscape pattern metrics and other variables.

FORPD	**Rho**	**p**	**FORED**	**Rho**	**p**	**FORPAFRAC**	**Rho**	**p**	**LS SHDI**	**Rho**	**p**	**LS SHEI**	**Rho**	**p**
RoadDens	0.98	<0.01	RoadDens	0.99	<0.01	HousDens	0.93	<0.01	shei	0.97	<0.01	max_nox	0.98	0.01
HousDens	0.97	<0.01	max_nox	0.97	0.01	PopDens	0.92	<0.01	max_nox	0.93	0.07	shdi	0.97	<0.01
PopDens	0.97	<0.01	%urban	0.97	<0.01	max_nox	0.89	0.04	%urban+bg	0.90	<0.01	%urban+bg	0.92	<0.01
fored	0.97	<0.01	forpd	0.97	<0.01	RoadDens	0.88	<0.01	fored	0.87	<0.01	fored	0.87	<0.01
max_nox	0.96	0.07	%urban+bg	0.96	<0.01	forpd	0.87	0.02	%urban	0.84	0.03	%urban	0.86	0.09
%urban+bg	0.96	<0.01	PopDens	0.96	<0.01	fored	0.84	0.01	%I+D+M	0.83	<0.01	forpd	0.81	<0.01
%urban	0.95	<0.01	HousDens	0.96	<0.01	%urban+bg	0.73	0.05	%Mech	0.83	<0.01	%Mech	0.79	0.01
pafrac	0.87	0.02	shei	0.87	<0.01	%urban	0.73	<0.01	RoadDens	0.80	0.05	%I+D+M	0.78	0.01
shei	0.81	<0.01	shdi	0.87	<0.01	%I+D+M	0.65	0.01	forpd	0.79	<0.01	PopDens	0.75	0.08
shdi	0.79	<0.01	pafrac	0.84	0.01	MeanDBH	0.58	0.09	PopDens	0.73	0.03	MeanDBH	0.75	<0.01
MeanDBH	0.72	0.02	%I+D+M	0.74	<0.01	shei	0.57	0.06	HousDens	0.72	0.03	HousDens	0.74	0.08
%I+D+M	0.66	0.01	MeanDBH	0.70	0.02	shdi	0.55	0.03	%HerbMean	0.69	<0.01	%HerbMean	0.70	<0.01
%Mech	0.62	<0.01	%Mech	0.68	<0.01	%Mech	0.54	0.05	MeanDBH	0.68	0.01	pafrac	0.57	0.06
%HerbMean	0.52	0.03	%HerbMean	0.58	0.01	%HWwLic	-0.86	0.06	pafrac	0.55	0.03	%forest	-0.94	<0.01
%forest	-0.95	<0.01	%forest	-0.95	<0.01	%forest	-0.71	0.02	%forest	-0.92	<0.01	#TreeSpp	-0.79	<0.01
%pasture	-0.63	0.04	%pasture	-0.68	0.01	LicAbdMeanHW	-0.61	<0.01	#TreeSpp	-0.78	<0.01	#Stems2.5-10	-0.71	0.01
#TreeSpp	-0.62	0.01	#TreeSpp	-0.59	0.03	#LicSppHW	-0.61	0.01	#Stems<0.635	-0.70	0.02	#Stems<0.635	-0.61	0.07
#Stems2.5-10	-0.59	0.04	#Stems2.5-10	-0.53	0.09	%pasture	-0.57	<0.01	#Stems2.5-10	-0.67	0.01	%WoodyMean	-0.57	0.07
#Stems>10	-0.54	0.07							%WoodyMean	-0.63	0.02	#Stems>10	-0.53	0.02
									DistAnyRoad	-0.55	0.01			

4.8 Appendix

Appendix 4.1. Correlation Matrix: Variables.

Col	Row	Variable
A	1	% Woody stems /ha
B	2	% Herbaceous plants /ha
C	3	% Leaf litter /ha
D	4	% Bare ground /ha
E	5	Mean number of seedlings <0.635cm /ha
F	6	Mean number of saplings & shrubs 0.635-2.5cm /ha
G	7	Total number of trees 2.5-10cm dbh / ha
H	8	Total number of trees >10cm dbh /ha
I	9	Total number of hardwoods /ha
J	10	Total number of pines /ha
K	11	Hardwood:Pine ratio
L	12	Total number of tree species
M	13	Median age of stand
N	14	Mean dbh (cm) of all mature trees
O	15	Basal Area (m^2/ha)
P	16	Mean number of crustose lichen species on water oaks
Q	17	Mean number of foliose lichen species on water oaks
R	18	Crustose:Foliose ratio (on water oaks)
S	19	Mean lichen abundance rank for water oaks
T	20	Mean dominance of crustose over foliose (on water oaks)
U	21	% Trees with lichens
V	22	Mean number of lichen species per tree
W	23	Mean lichen abundance rank for all hardwoods
X	24	% Trees with insect injury
Y	25	% Trees with disease injury
Z	26	% Trees with mechanical damage injury
AA	27	% Insect + Disease + Mech damage for all trees
AB	28	% Peak canopy cover
AC	29	Mean upper canopy height (m)
AD	30	Mean subcanopy height (m)
AE	31	Population density
AF	32	Housing density
AG	33	Road density
AH	34	Plot distance to any road (m)
AI	35	Plot distance to major road (m)
AJ	36	% Forest
AK	37	% Pasture
AL	38	% Grasses (pasture + lawn)
AM	39	% Urban
AN	40	% Non-vegetated land (urban + bare ground)
AO	41	Forest patch density (FORPD)
AP	42	Forest edge density (FORED)
AQ	43	Forest perimeter-area fractal shape (FORPAFRAC)
AR	44	Shannon's landscape diversity index (SHDI)
AS	45	Shannon's landscape evenness index (SHEI)
AT	46	Maximum seasonal ozone concentration
AU	47	Maximum seasonal NO_x concentration

Appendix 4.2. Correlation Matrix: Correlation coefficients.

Variable	A	B	C	D	E	F	G	H
1	1.00	-0.28	0.18	-0.09	0.92	0.33	0.58	0.28
2	-0.28	1.00	-0.66	0.15	-0.34	0.23	-0.61	-0.42
3	0.18	-0.66	1.00	-0.83	0.12	0.14	0.52	0.39
4	-0.09	0.15	-0.83	1.00	0.05	-0.38	-0.27	-0.19
5	0.92	-0.34	0.12	0.05	1.00	0.20	0.48	0.14
6	0.33	0.23	0.14	-0.38	0.20	1.00	0.13	0.31
7	0.58	-0.61	0.52	-0.27	0.48	0.13	1.00	0.78
8	0.28	-0.42	0.39	-0.19	0.14	0.31	0.78	1.00
9	0.18	-0.38	0.16	0.08	0.21	0.02	0.76	0.74
10	0.21	-0.19	0.39	-0.37	-0.03	0.43	0.29	0.64
11	-0.42	0.13	-0.53	0.59	-0.24	-0.30	-0.17	-0.16
12	0.62	-0.68	0.42	-0.06	0.63	-0.03	0.89	0.53
13	0.34	-0.07	0.44	-0.53	0.17	0.48	0.28	0.47
14	-0.18	0.67	-0.35	-0.07	-0.20	-0.09	-0.71	-0.82
15	0.17	0.49	0.01	-0.41	0.05	0.11	0.01	-0.08
16	0.15	0.32	-0.25	0.10	0.02	0.22	0.27	0.61
17	0.03	0.56	-0.21	-0.22	-0.10	0.57	-0.17	0.03
18	-0.15	-0.13	-0.25	0.48	-0.04	-0.52	-0.05	-0.23
19	-0.04	0.72	-0.38	-0.05	-0.15	0.49	-0.07	0.22
20	-0.16	0.52	-0.20	-0.19	-0.21	0.46	-0.42	-0.22
21	-0.15	-0.29	0.23	-0.14	-0.12	0.26	0.17	0.28
22	-0.04	-0.13	-0.05	0.10	-0.08	0.11	0.25	0.39
23	-0.04	-0.23	0.00	0.12	-0.05	-0.08	0.31	0.39
24	-0.10	0.06	0.08	-0.07	0.00	0.19	0.09	0.38
25	0.15	0.16	0.04	-0.07	0.07	0.27	-0.12	-0.09
26	-0.56	0.85	-0.62	0.20	-0.55	-0.18	-0.64	-0.58
27	-0.45	0.82	-0.51	0.14	-0.46	-0.02	-0.59	-0.47
28	-0.15	-0.70	0.51	-0.18	-0.03	-0.21	0.50	0.45
29	0.11	0.45	0.05	-0.43	0.02	0.16	0.00	-0.22
30	0.28	0.28	0.15	-0.43	0.12	0.26	0.00	-0.21
31	-0.06	0.56	-0.37	0.12	-0.13	-0.27	-0.49	-0.43
32	-0.07	0.54	-0.36	0.13	-0.14	-0.30	-0.48	-0.42
33	-0.14	0.55	-0.32	0.06	-0.20	-0.26	-0.51	-0.44
34	0.30	-0.31	-0.07	0.33	0.40	-0.14	0.25	0.09
35	0.33	0.17	-0.16	0.13	0.37	0.03	-0.15	-0.14
36	0.41	-0.57	0.25	0.05	0.46	0.26	0.68	0.57
37	-0.23	0.01	-0.01	-0.04	-0.20	0.25	-0.02	0.13
38	-0.62	0.54	-0.20	-0.16	-0.68	0.22	-0.49	-0.30
39	-0.26	0.46	-0.19	-0.05	-0.31	-0.29	-0.53	-0.48
40	-0.36	0.54	-0.24	-0.04	-0.41	-0.29	-0.66	-0.56
41	-0.19	0.52	-0.32	0.08	-0.25	-0.35	-0.59	-0.54
42	-0.24	0.58	-0.30	0.03	-0.31	-0.29	-0.53	-0.46
43	0.04	0.49	-0.45	0.28	0.05	-0.38	-0.43	-0.49
44	-0.63	0.69	-0.30	-0.05	-0.70	-0.19	-0.67	-0.48
45	-0.57	0.70	-0.25	-0.13	-0.61	-0.16	-0.71	-0.53
46	-0.16	0.06	0.21	-0.76	-0.10	0.11	-0.16	0.46
47	-0.48	0.85	-0.69	0.03	-0.32	0.11	-0.62	-0.32

Appendix 4.2. Correlation Matrix: Correlation coefficients con't.

Variable	I	J	K	L	M	N	O	P
1	0.18	0.21	-0.42	0.62	0.34	-0.18	0.17	0.15
2	-0.38	-0.19	0.13	-0.68	-0.07	0.67	0.49	0.32
3	0.16	0.39	-0.53	0.42	0.44	-0.35	0.01	-0.25
4	0.08	-0.37	0.59	-0.06	-0.53	-0.07	-0.41	0.10
5	0.21	-0.03	-0.24	0.63	0.17	-0.20	0.05	0.02
6	0.02	0.43	-0.30	-0.03	0.48	-0.09	0.11	0.22
7	0.76	0.29	-0.17	0.89	0.28	-0.71	0.01	0.27
8	0.74	0.64	-0.16	0.53	0.47	-0.82	-0.08	0.61
9	1.00	-0.05	0.39	0.74	-0.02	-0.81	-0.20	0.44
10	-0.05	1.00	-0.68	-0.06	0.71	-0.29	0.10	0.40
11	0.39	-0.68	1.00	0.00	-0.54	-0.12	-0.27	-0.04
12	0.74	-0.06	0.00	1.00	-0.05	-0.69	-0.24	0.05
13	-0.02	0.71	-0.54	-0.05	1.00	-0.06	0.54	0.25
14	-0.81	-0.29	-0.12	-0.69	-0.06	1.00	0.55	-0.28
15	-0.20	0.10	-0.27	-0.24	0.54	0.55	1.00	0.27
16	0.44	0.40	-0.04	0.05	0.25	-0.28	0.27	1.00
17	-0.09	0.16	-0.02	-0.32	0.14	0.30	0.32	0.46
18	0.00	-0.34	0.29	0.07	-0.28	-0.07	-0.17	-0.35
19	0.12	0.18	0.04	-0.29	0.17	0.18	0.46	0.74
20	-0.21	-0.09	0.20	-0.47	0.14	0.43	0.27	0.10
21	0.34	0.02	0.27	0.21	-0.19	-0.36	-0.47	-0.02
22	0.55	-0.05	0.41	0.29	-0.29	-0.45	-0.38	0.40
23	0.63	-0.13	0.53	0.33	-0.14	-0.42	-0.22	0.31
24	0.15	0.39	-0.24	-0.08	0.33	-0.21	0.14	0.37
25	-0.24	0.14	-0.41	-0.08	0.19	0.03	-0.02	-0.13
26	-0.41	-0.39	0.25	-0.66	-0.40	0.68	0.36	0.09
27	-0.42	-0.21	0.02	-0.63	-0.21	0.57	0.33	0.09
28	0.63	-0.05	0.30	0.53	-0.18	-0.70	-0.45	-0.03
29	-0.17	-0.13	-0.17	-0.14	0.26	0.43	0.73	0.05
30	-0.43	0.17	-0.46	-0.17	0.46	0.60	0.69	-0.21
31	-0.63	0.09	-0.41	-0.54	0.06	0.67	0.49	0.17
32	-0.62	0.08	-0.41	-0.54	0.06	0.65	0.48	0.16
33	-0.67	0.10	-0.44	-0.58	0.04	0.69	0.47	0.12
34	0.49	-0.42	0.45	0.52	-0.24	-0.30	-0.32	-0.06
35	-0.04	-0.17	0.02	-0.02	0.26	0.25	0.27	0.07
36	0.77	-0.04	0.35	0.75	0.08	-0.77	-0.37	0.05
37	0.37	-0.23	0.60	0.00	-0.01	-0.27	-0.18	0.05
38	-0.16	-0.27	0.42	-0.54	-0.19	0.35	0.07	-0.06
39	-0.72	0.11	-0.47	-0.59	-0.06	0.69	0.35	-0.03
40	-0.77	0.04	-0.38	-0.71	-0.07	0.76	0.36	-0.06
41	-0.73	0.04	-0.39	-0.62	-0.05	0.72	0.39	0.03
42	-0.64	0.04	-0.38	-0.59	-0.03	0.70	0.45	0.08
43	-0.50	-0.16	-0.24	-0.38	-0.08	0.58	0.41	0.10
44	-0.60	-0.02	-0.14	-0.78	-0.11	0.68	0.34	0.00
45	-0.63	-0.06	-0.18	-0.79	-0.07	0.75	0.42	0.02
46	0.17	0.47	-0.62	-0.24	0.65	-0.22	-0.05	0.69
47	-0.45	-0.07	-0.22	-0.73	-0.12	0.66	0.76	0.31

Appendix 4.2. Correlation Matrix: Correlation coefficients con't.

Variable	Q	R	S	T	U	V	W	X
1	0.03	-0.15	-0.04	-0.16	-0.15	-0.04	-0.04	-0.10
2	0.56	-0.13	0.72	0.52	-0.29	-0.13	-0.23	0.06
3	-0.21	-0.25	-0.38	-0.20	0.23	-0.05	0.00	0.08
4	-0.22	0.48	-0.05	-0.19	-0.14	0.10	0.12	-0.07
5	-0.10	-0.04	-0.15	-0.21	-0.12	-0.08	-0.05	0.00
6	0.57	-0.52	0.49	0.46	0.26	0.11	-0.08	0.19
7	-0.17	-0.05	-0.07	-0.42	0.17	0.25	0.31	0.09
8	0.03	-0.23	0.22	-0.22	0.28	0.39	0.39	0.38
9	-0.09	0.00	0.12	-0.21	0.34	0.55	0.63	0.15
10	0.16	-0.34	0.18	-0.09	0.02	-0.05	-0.13	0.39
11	-0.02	0.29	0.04	0.20	0.27	0.41	0.53	-0.24
12	-0.32	0.07	-0.29	-0.47	0.21	0.29	0.33	-0.08
13	0.14	-0.28	0.17	0.14	-0.19	-0.29	-0.14	0.33
14	0.30	-0.07	0.18	0.43	-0.36	-0.45	-0.42	-0.21
15	0.32	-0.17	0.46	0.27	-0.47	-0.38	-0.22	0.14
16	0.46	-0.35	0.74	0.10	-0.02	0.40	0.31	0.37
17	1.00	-0.83	0.81	0.85	0.43	0.50	0.36	-0.08
18	-0.83	1.00	-0.57	-0.70	-0.62	-0.51	-0.42	-0.10
19	0.81	-0.57	1.00	0.56	0.14	0.30	0.19	0.35
20	0.85	-0.70	0.56	1.00	0.45	0.38	0.38	-0.20
21	0.43	-0.62	0.14	0.45	1.00	0.77	0.71	-0.09
22	0.50	-0.51	0.30	0.38	0.77	1.00	0.89	-0.30
23	0.36	-0.42	0.19	0.38	0.71	0.89	1.00	-0.27
24	-0.08	-0.10	0.35	-0.20	-0.09	-0.30	-0.27	1.00
25	-0.36	0.41	-0.18	-0.35	-0.61	-0.56	-0.71	0.08
26	0.26	0.14	0.46	0.24	-0.32	-0.20	-0.30	0.01
27	0.08	0.26	0.40	0.04	-0.53	-0.45	-0.58	0.23
28	-0.19	-0.09	-0.30	-0.18	0.60	0.56	0.58	-0.01
29	0.11	0.16	0.20	0.07	-0.58	-0.40	-0.43	-0.15
30	0.21	-0.19	0.18	0.23	-0.23	-0.50	-0.36	0.00
31	0.00	0.14	0.20	-0.11	-0.72	-0.57	-0.58	0.17
32	-0.03	0.16	0.17	-0.13	-0.73	-0.57	-0.58	0.17
33	0.01	0.10	0.21	-0.09	-0.65	-0.58	-0.61	0.24
34	0.00	-0.16	-0.13	0.17	0.46	0.50	0.70	-0.26
35	0.17	-0.26	0.14	0.38	-0.07	-0.04	0.21	0.01
36	-0.11	0.02	-0.18	-0.09	0.43	0.47	0.53	-0.14
37	0.29	-0.14	0.08	0.50	0.42	0.57	0.57	-0.38
38	0.57	-0.30	0.38	0.74	0.37	0.36	0.28	-0.35
39	0.02	0.00	0.14	-0.07	-0.46	-0.52	-0.57	0.22
40	0.07	0.00	0.14	0.04	-0.46	-0.50	-0.55	0.15
41	-0.01	0.12	0.10	-0.08	-0.63	-0.53	-0.58	0.08
42	0.02	0.09	0.22	-0.07	-0.59	-0.54	-0.57	0.22
43	-0.20	0.38	0.04	-0.26	-0.86	-0.61	-0.61	0.09
44	0.15	0.03	0.31	0.16	-0.33	-0.38	-0.43	0.17
45	0.24	-0.12	0.35	0.28	-0.30	-0.35	-0.39	0.18
46	0.27	-0.65	0.46	0.17	0.38	0.30	0.25	0.73
47	0.39	-0.27	0.80	0.25	-0.30	-0.56	-0.46	0.70

Appendix 4.2. Correlation Matrix: Correlation coefficients con't.

Variable	Y	Z	AA	AB	AC	AD	AE	AF
1	0.15	-0.56	-0.45	-0.15	0.11	0.28	-0.06	-0.07
2	0.16	0.85	0.82	-0.70	0.45	0.28	0.56	0.54
3	0.04	-0.62	-0.51	0.51	0.05	0.15	-0.37	-0.36
4	-0.07	0.20	0.14	-0.18	-0.43	-0.43	0.12	0.13
5	0.07	-0.55	-0.46	-0.03	0.02	0.12	-0.13	-0.14
6	0.27	-0.18	-0.02	-0.21	0.16	0.26	-0.27	-0.30
7	-0.12	-0.64	-0.59	0.50	0.00	0.00	-0.49	-0.48
8	-0.09	-0.58	-0.47	0.45	-0.22	-0.21	-0.43	-0.42
9	-0.24	-0.41	-0.42	0.63	-0.17	-0.43	-0.63	-0.62
10	0.14	-0.39	-0.21	-0.05	-0.13	0.17	0.09	0.08
11	-0.41	0.25	0.02	0.30	-0.17	-0.46	-0.41	-0.41
12	-0.08	-0.66	-0.63	0.53	-0.14	-0.17	-0.54	-0.54
13	0.19	-0.40	-0.21	-0.18	0.26	0.46	0.06	0.06
14	0.03	0.68	0.57	-0.70	0.43	0.60	0.67	0.65
15	-0.02	0.36	0.33	-0.45	0.73	0.69	0.49	0.48
16	-0.13	0.09	0.09	-0.03	0.05	-0.21	0.17	0.16
17	-0.36	0.26	0.08	-0.19	0.11	0.21	0.00	-0.03
18	0.41	0.14	0.26	-0.09	0.16	-0.19	0.14	0.16
19	-0.18	0.46	0.40	-0.30	0.20	0.18	0.20	0.17
20	-0.35	0.24	0.04	-0.18	0.07	0.23	-0.11	-0.13
21	-0.61	-0.32	-0.53	0.60	-0.58	-0.23	-0.72	-0.73
22	-0.56	-0.20	-0.45	0.56	-0.40	-0.50	-0.57	-0.57
23	-0.71	-0.30	-0.58	0.58	-0.43	-0.36	-0.58	-0.58
24	0.08	0.01	0.23	-0.01	-0.15	0.00	0.17	0.17
25	1.00	0.05	0.44	-0.50	0.35	0.09	0.31	0.32
26	0.05	1.00	0.90	-0.50	0.41	0.16	0.58	0.57
27	0.44	0.90	1.00	-0.63	0.47	0.18	0.66	0.66
28	-0.50	-0.50	-0.63	1.00	-0.34	-0.58	-0.75	-0.73
29	0.35	0.41	0.47	-0.34	1.00	0.41	0.30	0.30
30	0.09	0.16	0.18	-0.58	0.41	1.00	0.36	0.33
31	0.31	0.58	0.66	-0.75	0.30	0.36	1.00	1.00
32	0.32	0.57	0.66	-0.73	0.30	0.33	1.00	1.00
33	0.29	0.61	0.69	-0.72	0.26	0.38	0.99	0.98
34	-0.36	-0.42	-0.56	0.28	-0.50	-0.19	-0.46	-0.46
35	-0.01	-0.14	-0.12	-0.37	-0.12	0.26	0.20	0.20
36	-0.17	-0.70	-0.71	0.60	-0.21	-0.35	-0.88	-0.87
37	-0.20	-0.13	-0.26	0.43	0.08	-0.43	-0.66	-0.65
38	-0.18	0.52	0.32	-0.02	0.22	0.01	-0.16	-0.18
39	0.18	0.60	0.64	-0.60	0.14	0.40	0.90	0.90
40	0.18	0.67	0.68	-0.61	0.19	0.36	0.90	0.89
41	0.26	0.62	0.66	-0.68	0.25	0.31	0.97	0.97
42	0.27	0.68	0.74	-0.68	0.26	0.38	0.96	0.96
43	0.41	0.54	0.65	-0.69	0.38	0.19	0.92	0.93
44	0.19	0.83	0.83	-0.54	0.25	0.31	0.73	0.72
45	0.13	0.79	0.78	-0.53	0.27	0.32	0.75	0.74
46	-0.06	-0.17	-0.02	0.04	-0.77	-0.30	0.42	0.45
47	-0.09	0.86	0.79	-0.64	0.25	0.65	0.97	0.96

Appendix 4.2. Correlation Matrix: Correlation coefficients con't.

Variable	AG	AH	AI	AJ	AK	AL	AM	AN
1	-0.14	0.30	0.33	0.41	-0.23	-0.62	-0.26	-0.36
2	0.55	-0.31	0.17	-0.57	0.01	0.54	0.46	0.54
3	-0.32	-0.07	-0.16	0.25	-0.01	-0.20	-0.19	-0.24
4	0.06	0.33	0.13	0.05	-0.04	-0.16	-0.05	-0.04
5	-0.20	0.40	0.37	0.46	-0.20	-0.68	-0.31	-0.41
6	-0.26	-0.14	0.03	0.26	0.25	0.22	-0.29	-0.29
7	-0.51	0.25	-0.15	0.68	-0.02	-0.49	-0.53	-0.66
8	-0.44	0.09	-0.14	0.57	0.13	-0.30	-0.48	-0.56
9	-0.67	0.49	-0.04	0.77	0.37	-0.16	-0.72	-0.77
10	0.10	-0.42	-0.17	-0.04	-0.23	-0.27	0.11	0.04
11	-0.44	0.45	0.02	0.35	0.60	0.42	-0.47	-0.38
12	-0.58	0.52	-0.02	0.75	0.00	-0.54	-0.59	-0.71
13	0.04	-0.24	0.26	0.08	-0.01	-0.19	-0.06	-0.07
14	0.69	-0.30	0.25	-0.77	-0.27	0.35	0.69	0.76
15	0.47	-0.32	0.27	-0.37	-0.18	0.07	0.35	0.36
16	0.12	-0.06	0.07	0.05	0.05	-0.06	-0.03	-0.06
17	0.01	0.00	0.17	-0.11	0.29	0.57	0.02	0.07
18	0.10	-0.16	-0.26	0.02	-0.14	-0.30	0.00	0.00
19	0.21	-0.13	0.14	-0.18	0.08	0.38	0.14	0.14
20	-0.09	0.17	0.38	-0.09	0.50	0.74	-0.07	0.04
21	-0.65	0.46	-0.07	0.43	0.42	0.37	-0.46	-0.46
22	-0.58	0.50	-0.04	0.47	0.57	0.36	-0.52	-0.50
23	-0.61	0.70	0.21	0.53	0.57	0.28	-0.57	-0.55
24	0.24	-0.26	0.01	-0.14	-0.38	-0.35	0.22	0.15
25	0.29	-0.36	-0.01	-0.17	-0.20	-0.18	0.18	0.18
26	0.61	-0.42	-0.14	-0.70	-0.13	0.52	0.60	0.67
27	0.69	-0.56	-0.12	-0.71	-0.26	0.32	0.64	0.68
28	-0.72	0.28	-0.37	0.60	0.43	-0.02	-0.60	-0.61
29	0.26	-0.50	-0.12	-0.21	0.08	0.22	0.14	0.19
30	0.38	-0.19	0.26	-0.35	-0.43	0.01	0.40	0.36
31	0.99	-0.46	0.20	-0.88	-0.66	-0.16	0.90	0.90
32	0.98	-0.46	0.20	-0.87	-0.65	-0.18	0.90	0.89
33	1.00	-0.50	0.14	-0.93	-0.70	-0.13	0.95	0.94
34	-0.50	1.00	0.61	0.54	0.26	-0.10	-0.50	-0.52
35	0.14	0.61	1.00	-0.03	-0.02	-0.12	0.03	0.06
36	-0.93	0.54	-0.03	1.00	0.55	-0.16	-0.97	-1.00
37	-0.70	0.26	-0.02	0.55	1.00	0.62	-0.74	-0.60
38	-0.13	-0.10	-0.12	-0.16	0.62	1.00	-0.05	0.09
39	0.95	-0.50	0.03	-0.97	-0.74	-0.05	1.00	0.98
40	0.94	-0.52	0.06	-1.00	-0.60	0.09	0.98	1.00
41	0.98	-0.49	0.10	-0.95	-0.63	-0.06	0.95	0.96
42	0.99	-0.49	0.11	-0.95	-0.68	-0.03	0.97	0.96
43	0.88	-0.34	0.22	-0.71	-0.57	-0.28	0.73	0.73
44	0.80	-0.55	-0.07	-0.92	-0.36	0.41	0.84	0.90
45	0.81	-0.48	0.08	-0.94	-0.33	0.41	0.86	0.92
46	0.41	0.17	0.49	-0.37	-0.36	-0.50	0.41	0.40
47	0.97	-0.34	0.15	-0.96	-0.95	0.19	0.97	0.97

Appendix 4.2. Correlation Matrix: Correlation coefficients con't.

Variable	AO	AP	AQ	AR	AS	AT	AU
1	-0.19	-0.24	0.04	-0.63	-0.57	-0.16	-0.48
2	0.52	0.58	0.49	0.69	0.70	0.06	0.85
3	-0.32	-0.30	-0.45	-0.30	-0.25	0.21	-0.69
4	0.08	0.03	0.28	-0.05	-0.13	-0.76	0.03
5	-0.25	-0.31	0.05	-0.70	-0.61	-0.10	-0.32
6	-0.35	-0.29	-0.38	-0.19	-0.16	0.11	0.11
7	-0.59	-0.53	-0.43	-0.67	-0.71	-0.16	-0.62
8	-0.54	-0.46	-0.49	-0.48	-0.53	0.46	-0.32
9	-0.73	-0.64	-0.50	-0.60	-0.63	0.17	-0.45
10	0.04	0.04	-0.16	-0.02	-0.06	0.47	-0.07
11	-0.39	-0.38	-0.24	-0.14	-0.18	-0.62	-0.22
12	-0.62	-0.59	-0.38	-0.78	-0.79	-0.24	-0.73
13	-0.05	-0.03	-0.08	-0.11	-0.07	0.65	-0.12
14	0.72	0.70	0.58	0.68	0.75	-0.22	0.66
15	0.39	0.45	0.41	0.34	0.42	-0.05	0.76
16	0.03	0.08	0.10	0.00	0.02	0.69	0.31
17	-0.01	0.02	-0.20	0.15	0.24	0.27	0.39
18	0.12	0.09	0.38	0.03	-0.12	-0.65	-0.27
19	0.10	0.22	0.04	0.31	0.35	0.46	0.80
20	-0.08	-0.07	-0.26	0.16	0.28	0.17	0.25
21	-0.63	-0.59	-0.86	-0.33	-0.30	0.38	-0.30
22	-0.53	-0.54	-0.61	-0.38	-0.35	0.30	-0.56
23	-0.58	-0.57	-0.61	-0.43	-0.39	0.25	-0.46
24	0.08	0.22	0.09	0.17	0.18	0.73	0.70
25	0.26	0.27	0.41	0.19	0.13	-0.06	-0.09
26	0.62	0.68	0.54	0.83	0.79	-0.17	0.86
27	0.66	0.74	0.65	0.83	0.78	-0.02	0.79
28	-0.68	-0.68	-0.69	-0.54	-0.53	0.04	-0.64
29	0.25	0.26	0.38	0.25	0.27	-0.77	0.25
30	0.31	0.38	0.19	0.31	0.32	-0.30	0.65
31	0.97	0.96	0.92	0.73	0.75	0.42	0.97
32	0.97	0.96	0.93	0.72	0.74	0.45	0.96
33	0.98	0.99	0.88	0.80	0.81	0.41	0.97
34	-0.49	-0.49	-0.34	-0.55	-0.48	0.17	-0.34
35	0.10	0.11	0.22	-0.07	0.08	0.49	0.15
36	-0.95	-0.95	-0.71	-0.92	-0.94	-0.37	-0.96
37	-0.63	-0.68	-0.57	-0.36	-0.33	-0.36	-0.95
38	-0.06	-0.03	-0.28	0.41	0.41	-0.50	0.19
39	0.95	0.97	0.73	0.84	0.86	0.41	0.97
40	0.96	0.96	0.73	0.90	0.92	0.40	0.97
41	1.00	0.97	0.87	0.79	0.81	0.38	0.96
42	0.97	1.00	0.84	0.87	0.87	0.38	0.97
43	0.87	0.84	1.00	0.55	0.57	0.19	0.89
44	0.79	0.87	0.55	1.00	0.97	0.25	0.93
45	0.81	0.87	0.57	0.97	1.00	0.42	0.98
46	0.38	0.38	0.19	0.25	0.42	1.00	0.31
47	0.96	0.97	0.89	0.93	0.98	0.31	1.00

Appendix 4.3. Correlation Matrix: Correlation p-values.

Variable	A	B	C	D	E	F	G	H
1		0.21	0.93	0.27	0.00	0.30	0.12	0.34
2	0.21		0.11	0.90	0.30	0.93	0.06	0.11
3	0.93	0.11		0.00	0.63	0.85	0.60	0.62
4	0.27	0.90	0.00		0.11	0.78	0.83	0.95
5	0.00	0.30	0.63	0.11		0.46	0.19	0.60
6	0.30	0.93	0.85	0.78	0.46		0.62	0.26
7	0.12	0.06	0.60	0.83	0.19	0.62		0.00
8	0.34	0.11	0.62	0.95	0.60	0.26	0.00	
9	0.99	0.76	0.44	0.52	0.97	0.80	0.03	0.02
10	0.41	0.40	0.33	0.44	0.83	0.11	0.41	0.09
11	0.96	0.78	0.39	0.38	0.59	0.48	0.69	0.75
12	0.06	0.03	0.55	0.65	0.03	0.65	0.00	0.03
13	0.37	0.62	0.37	0.41	0.66	0.16	0.24	0.17
14	0.41	0.02	0.74	0.65	0.55	0.48	0.00	0.00
15	0.64	0.11	0.43	0.88	0.70	0.98	0.87	0.66
16	0.78	0.66	0.31	0.73	0.72	0.59	0.40	0.10
17	0.60	0.93	0.63	0.90	0.99	0.11	0.60	0.94
18	0.96	0.75	0.58	0.23	0.60	0.06	0.56	0.95
19	0.93	0.12	0.08	0.58	0.66	0.31	0.97	0.46
20	0.32	0.33	0.80	0.63	0.22	0.28	0.10	0.25
21	0.23	0.54	0.72	0.59	0.14	0.75	0.47	0.95
22	0.97	0.39	0.89	0.88	0.70	0.42	0.75	0.44
23	0.68	0.46	0.92	0.91	0.54	0.78	0.36	0.36
24	0.73	0.92	0.39	0.64	0.79	0.29	0.89	0.30
25	0.50	0.39	0.89	0.96	0.62	0.32	0.76	0.76
26	0.08	0.00	0.10	0.75	0.16	0.51	0.01	0.02
27	0.22	0.00	0.13	0.82	0.31	0.93	0.05	0.18
28	0.20	0.19	0.50	0.51	0.15	0.47	0.40	0.49
29	0.81	0.07	0.36	0.84	0.77	0.88	0.70	0.81
30	0.28	0.57	0.67	0.78	0.31	0.98	0.77	0.59
31	0.83	0.24	0.58	0.72	0.90	0.26	0.28	0.32
32	0.83	0.24	0.58	0.72	0.90	0.26	0.28	0.32
33	0.94	0.27	0.39	0.60	0.97	0.40	0.29	0.34
34	0.43	0.37	0.82	0.85	0.32	0.76	0.23	0.38
35	0.31	0.09	0.38	0.68	0.34	0.88	0.41	0.50
36	0.05	0.01	0.65	0.56	0.07	0.18	0.00	0.01
37	0.60	0.60	0.64	0.65	0.55	0.27	0.69	0.65
38	0.01	0.08	0.94	0.40	0.02	0.68	0.07	0.13
39	0.64	0.35	0.72	0.81	0.71	0.15	0.19	0.21
40	0.11	0.01	0.88	0.38	0.12	0.20	0.00	0.00
41	0.19	0.03	0.59	0.72	0.15	0.16	0.04	0.07
42	0.40	0.01	0.48	0.83	0.37	0.24	0.09	0.12
43	0.59	0.18	0.41	0.72	0.84	0.34	0.16	0.18
44	0.02	0.00	0.69	0.38	0.02	0.54	0.01	0.08
45	0.07	0.00	0.97	0.21	0.07	0.55	0.01	0.02
46	0.91	0.96	0.57	0.12	0.54	0.87	0.62	0.62
47	0.35	0.04	0.16	0.74	0.70	0.96	0.47	0.21

Appendix 4.3. Correlation Matrix: Correlation p-values con't.

Variable	I	J	K	L	M	N	O	P
1	0.99	0.41	0.96	0.06	0.37	0.41	0.64	0.78
2	0.76	0.40	0.78	0.03	0.62	0.02	0.11	0.66
3	0.44	0.33	0.39	0.55	0.37	0.74	0.43	0.31
4	0.52	0.44	0.38	0.65	0.41	0.65	0.88	0.73
5	0.97	0.83	0.59	0.03	0.66	0.55	0.70	0.72
6	0.80	0.11	0.48	0.65	0.16	0.48	0.98	0.59
7	0.03	0.41	0.69	0.00	0.24	0.00	0.87	0.40
8	0.02	0.09	0.75	0.03	0.17	0.00	0.66	0.10
9		0.60	0.12	0.07	0.73	0.02	0.69	0.13
10	0.60		0.00	0.94	0.01	0.38	0.73	0.21
11	0.12	0.00		0.15	0.04	0.78	0.53	0.35
12	0.07	0.94	0.15		0.92	0.01	0.38	0.61
13	0.73	0.01	0.04	0.92		0.71	0.12	0.25
14	0.02	0.38	0.78	0.01	0.71		0.08	0.34
15	0.69	0.73	0.53	0.38	0.12	0.08		0.37
16	0.13	0.21	0.35	0.61	0.25	0.34	0.37	
17	0.79	0.59	0.48	0.32	0.71	0.85	0.74	0.10
18	0.70	0.46	0.39	0.30	0.40	0.63	0.65	0.22
19	0.20	0.48	0.60	0.34	0.54	0.95	0.19	0.00
20	0.48	0.57	0.96	0.06	0.91	0.27	0.83	0.61
21	0.63	0.55	0.74	0.55	0.43	0.53	0.08	0.64
22	0.19	0.58	0.39	0.67	0.44	0.17	0.14	0.30
23	0.03	0.26	0.17	0.51	0.81	0.21	0.59	0.32
24	0.59	0.07	0.18	0.79	0.16	0.46	0.96	0.25
25	0.28	0.03	0.05	0.57	0.20	0.76	0.54	0.66
26	0.45	0.30	0.91	0.01	0.11	0.01	0.37	0.95
27	0.49	0.97	0.57	0.03	0.56	0.05	0.27	0.74
28	0.28	0.43	0.44	0.66	0.35	0.27	0.27	0.76
29	0.93	0.76	0.73	0.78	0.81	0.22	0.01	0.66
30	0.37	0.65	0.48	0.92	0.21	0.14	0.00	0.62
31	0.37	0.44	0.13	0.20	0.78	0.17	0.32	0.84
32	0.37	0.44	0.13	0.20	0.78	0.17	0.32	0.84
33	0.39	0.38	0.14	0.22	0.68	0.18	0.34	0.94
34	0.05	0.10	0.00	0.02	0.46	0.12	0.17	0.74
35	0.95	0.97	0.97	0.50	0.48	0.28	0.18	0.46
36	0.11	0.61	0.47	0.00	0.43	0.00	0.32	0.74
37	0.68	0.33	0.20	0.64	0.90	0.41	0.38	0.93
38	0.43	0.24	0.68	0.06	0.34	0.14	0.98	0.48
39	0.28	0.59	0.16	0.17	0.47	0.16	0.55	0.63
40	0.06	0.61	0.44	0.00	0.66	0.00	0.22	0.77
41	0.37	0.86	0.38	0.01	0.26	0.02	0.33	0.80
42	0.51	0.97	0.40	0.03	0.44	0.02	0.15	0.70
43	0.24	0.56	0.24	0.18	0.78	0.09	0.40	0.65
44	0.25	0.93	0.26	0.00	0.81	0.01	0.24	0.96
45	0.14	0.93	0.33	0.00	0.95	0.00	0.14	0.94
46	0.66	0.27	0.47	0.28	0.07	0.96	0.87	0.16
47	0.91	0.79	0.87	0.38	0.79	0.07	0.02	0.96

Appendix 4.3. Correlation Matrix: Correlation p-values con’t.

Variable	Q	R	S	T	U	V	W	X
1	0.60	0.96	0.93	0.32	0.23	0.97	0.68	0.73
2	0.93	0.75	0.12	0.33	0.54	0.39	0.46	0.92
3	0.63	0.58	0.08	0.80	0.72	0.89	0.92	0.39
4	0.90	0.23	0.58	0.63	0.59	0.88	0.91	0.64
5	0.99	0.60	0.66	0.22	0.14	0.70	0.54	0.79
6	0.11	0.06	0.31	0.28	0.75	0.42	0.78	0.29
7	0.60	0.56	0.97	0.10	0.47	0.75	0.36	0.89
8	0.94	0.95	0.46	0.25	0.95	0.44	0.36	0.30
9	0.79	0.70	0.20	0.48	0.63	0.19	0.03	0.59
10	0.59	0.46	0.48	0.57	0.55	0.58	0.26	0.07
11	0.48	0.39	0.60	0.96	0.74	0.39	0.17	0.18
12	0.32	0.30	0.34	0.06	0.55	0.67	0.51	0.79
13	0.71	0.40	0.54	0.91	0.43	0.44	0.81	0.16
14	0.85	0.63	0.95	0.27	0.53	0.17	0.21	0.46
15	0.74	0.65	0.19	0.83	0.08	0.14	0.59	0.96
16	0.10	0.22	0.00	0.61	0.64	0.30	0.32	0.25
17		0.00	0.03	0.01	0.05	0.02	0.24	0.76
18	0.00		0.07	0.00	0.05	0.04	0.24	0.79
19	0.03	0.07		0.21	0.56	0.31	0.41	0.13
20	0.01	0.00	0.21		0.01	0.07	0.15	1.00
21	0.05	0.05	0.56	0.01		0.00	0.01	0.95
22	0.02	0.04	0.31	0.07	0.00		0.00	0.74
23	0.24	0.24	0.41	0.15	0.01	0.00		0.70
24	0.76	0.79	0.13	1.00	0.95	0.74	0.70	
25	0.46	0.55	0.83	0.25	0.03	0.03	0.00	0.28
26	0.78	0.85	0.29	0.39	0.89	0.53	0.33	0.96
27	0.78	0.83	0.22	0.94	0.27	0.13	0.05	0.50
28	0.70	0.80	0.75	0.71	0.07	0.07	0.05	0.43
29	0.72	0.75	0.48	0.65	0.03	0.16	0.27	0.42
30	0.92	0.78	0.97	0.80	0.07	0.12	0.49	0.54
31	0.44	0.40	0.78	0.24	0.11	0.03	0.04	0.61
32	0.44	0.40	0.78	0.24	0.11	0.03	0.04	0.61
33	0.70	0.54	0.57	0.24	0.12	0.06	0.02	0.42
34	0.99	0.93	0.71	0.86	0.28	0.05	0.03	0.42
35	0.66	0.54	0.20	0.61	0.52	0.65	0.87	0.74
36	0.66	0.86	0.84	0.63	0.59	0.13	0.16	0.73
37	0.47	0.39	0.74	0.07	0.07	0.06	0.06	0.48
38	0.55	0.30	0.79	0.02	0.20	0.58	0.74	0.52
39	0.42	0.36	0.94	0.25	0.20	0.06	0.05	0.87
40	0.94	0.76	0.84	0.39	0.73	0.20	0.26	0.64
41	0.97	0.93	0.45	0.94	0.65	0.36	0.26	0.64
42	0.99	0.90	0.28	0.94	0.40	0.26	0.24	0.83
43	0.26	0.24	0.98	0.21	0.06	0.01	0.00	0.28
44	0.87	0.76	0.40	0.46	0.74	0.20	0.23	0.66
45	0.88	0.41	0.45	0.25	0.84	0.26	0.35	0.83
46	0.40	0.33	0.27	0.69	0.21	0.47	0.50	0.23
47	0.79	0.62	0.21	0.69	0.54	0.33	0.46	0.29

Appendix 4.3. Correlation Matrix: Correlation p-values con't.

Variable	Y	Z	AA	AB	AC	AD	AE	AF
1	0.50	0.08	0.22	0.20	0.81	0.28	0.83	0.83
2	0.39	0.00	0.00	0.19	0.07	0.57	0.24	0.24
3	0.89	0.10	0.13	0.50	0.36	0.67	0.58	0.58
4	0.96	0.75	0.82	0.51	0.84	0.78	0.72	0.72
5	0.62	0.16	0.31	0.15	0.77	0.31	0.90	0.90
6	0.32	0.51	0.93	0.47	0.88	0.98	0.26	0.26
7	0.76	0.01	0.05	0.40	0.70	0.77	0.28	0.28
8	0.76	0.02	0.18	0.49	0.81	0.59	0.32	0.32
9	0.28	0.45	0.49	0.28	0.93	0.37	0.37	0.37
10	0.03	0.30	0.97	0.43	0.76	0.65	0.44	0.44
11	0.05	0.91	0.57	0.44	0.73	0.48	0.13	0.13
12	0.57	0.01	0.03	0.66	0.78	0.92	0.20	0.20
13	0.20	0.11	0.56	0.35	0.81	0.21	0.78	0.78
14	0.76	0.01	0.05	0.27	0.22	0.14	0.17	0.17
15	0.54	0.37	0.27	0.27	0.01	0.00	0.32	0.32
16	0.66	0.95	0.74	0.76	0.66	0.62	0.84	0.84
17	0.46	0.78	0.78	0.70	0.72	0.92	0.44	0.44
18	0.55	0.85	0.83	0.80	0.75	0.78	0.40	0.40
19	0.83	0.29	0.22	0.75	0.48	0.97	0.78	0.78
20	0.25	0.39	0.94	0.71	0.65	0.80	0.24	0.24
21	0.03	0.89	0.27	0.07	0.03	0.07	0.11	0.11
22	0.03	0.53	0.13	0.07	0.16	0.12	0.03	0.03
23	0.00	0.33	0.05	0.05	0.27	0.49	0.04	0.04
24	0.28	0.96	0.50	0.43	0.42	0.54	0.61	0.61
25		0.78	0.07	0.02	0.38	0.71	0.13	0.13
26	0.78		0.00	0.69	0.18	0.90	0.09	0.09
27	0.07	0.00		0.17	0.10	0.83	0.03	0.03
28	0.02	0.69	0.17		0.70	0.13	0.09	0.09
29	0.38	0.18	0.10	0.70		0.14	0.63	0.63
30	0.71	0.90	0.83	0.13	0.14		0.16	0.16
31	0.13	0.09	0.03	0.09	0.63	0.16		0.00
32	0.13	0.09	0.03	0.09	0.63	0.16	0.00	
33	0.12	0.05	0.02	0.18	0.50	0.34	0.00	0.00
34	0.08	0.12	0.05	0.50	0.38	0.35	0.01	0.01
35	0.34	0.65	0.35	0.00	0.83	0.24	0.39	0.39
36	0.40	0.00	0.00	0.47	0.33	0.60	0.03	0.03
37	0.16	0.32	0.13	0.12	0.73	0.21	0.00	0.00
38	0.46	0.04	0.23	0.48	0.58	0.83	0.73	0.73
39	0.24	0.07	0.05	0.24	0.77	0.27	0.00	0.00
40	0.53	0.01	0.02	0.39	0.44	0.43	0.07	0.07
41	0.53	0.00	0.01	0.68	0.32	0.50	0.00	0.00
42	0.40	0.00	0.00	0.32	0.23	0.23	0.00	0.00
43	0.06	0.05	0.01	0.12	0.48	0.52	0.00	0.00
44	0.34	0.00	0.00	0.48	0.34	0.55	0.03	0.03
45	0.50	0.01	0.01	0.33	0.44	0.32	0.08	0.08
46	0.87	0.87	0.87	1.00	0.11	0.62	0.83	0.83
47	0.91	0.00	0.11	0.42	0.21	0.04	0.07	0.07

Appendix 4.3. Correlation Matrix: Correlation p-values con't.

Variable	AG	AH	AI	AJ	AK	AL	AM	AN
1	0.94	0.43	0.31	0.05	0.60	0.01	0.64	0.11
2	0.27	0.37	0.09	0.01	0.60	0.08	0.35	0.01
3	0.39	0.82	0.38	0.65	0.64	0.94	0.72	0.88
4	0.60	0.85	0.68	0.56	0.65	0.40	0.81	0.38
5	0.97	0.32	0.34	0.07	0.55	0.02	0.71	0.12
6	0.40	0.76	0.88	0.18	0.27	0.68	0.15	0.20
7	0.29	0.23	0.41	0.00	0.69	0.07	0.19	0.00
8	0.34	0.38	0.50	0.01	0.65	0.13	0.21	0.00
9	0.39	0.05	0.95	0.11	0.68	0.43	0.28	0.06
10	0.38	0.10	0.97	0.61	0.33	0.24	0.59	0.61
11	0.14	0.00	0.97	0.47	0.20	0.68	0.16	0.44
12	0.22	0.02	0.50	0.00	0.64	0.06	0.17	0.00
13	0.68	0.46	0.48	0.43	0.90	0.34	0.47	0.66
14	0.18	0.12	0.28	0.00	0.41	0.14	0.16	0.00
15	0.34	0.17	0.18	0.32	0.38	0.98	0.55	0.22
16	0.94	0.74	0.46	0.74	0.93	0.48	0.63	0.77
17	0.70	0.99	0.66	0.66	0.47	0.55	0.42	0.94
18	0.54	0.93	0.54	0.86	0.39	0.30	0.36	0.76
19	0.57	0.71	0.20	0.84	0.74	0.79	0.94	0.84
20	0.24	0.86	0.61	0.63	0.07	0.02	0.25	0.39
21	0.12	0.28	0.52	0.59	0.07	0.20	0.20	0.73
22	0.06	0.05	0.65	0.13	0.06	0.58	0.06	0.20
23	0.02	0.03	0.87	0.16	0.06	0.74	0.05	0.26
24	0.42	0.42	0.74	0.73	0.48	0.52	0.87	0.64
25	0.12	0.08	0.34	0.40	0.16	0.46	0.24	0.53
26	0.05	0.12	0.65	0.00	0.32	0.04	0.07	0.01
27	0.02	0.05	0.35	0.00	0.13	0.23	0.05	0.02
28	0.18	0.50	0.00	0.47	0.12	0.48	0.24	0.39
29	0.50	0.38	0.83	0.33	0.73	0.58	0.77	0.44
30	0.34	0.35	0.24	0.60	0.21	0.83	0.27	0.43
31	0.00	0.01	0.39	0.03	0.00	0.73	0.00	0.07
32	0.00	0.01	0.39	0.03	0.00	0.73	0.00	0.07
33		0.01	0.57	0.04	0.00	0.60	0.00	0.10
34	0.01		0.80	0.02	0.07	0.68	0.01	0.05
35	0.57	0.80		0.51	0.35	0.52	0.69	0.26
36	0.04	0.02	0.51		0.19	0.11	0.02	0.00
37	0.00	0.07	0.35	0.19		0.15	0.00	0.25
38	0.60	0.68	0.52	0.11	0.15		0.87	0.18
39	0.00	0.01	0.69	0.02	0.00	0.87		0.05
40	0.10	0.05	0.26	0.00	0.25	0.18	0.05	
41	0.00	0.02	0.58	0.00	0.04	0.32	0.00	0.00
42	0.00	0.04	0.24	0.00	0.01	0.54	0.00	0.00
43	0.00	0.01	0.60	0.02	0.00	0.74	0.00	0.05
44	0.05	0.01	0.57	0.00	0.24	0.05	0.03	0.00
45	0.11	0.06	0.22	0.00	0.29	0.10	0.09	0.00
46	0.83	0.79	0.21	0.91	0.83	0.05	0.83	0.50
47	0.07	0.21	0.47	0.01	0.04	0.70	0.07	0.01

Appendix 4.3. Correlation Matrix: Correlation p-values con't.

Variable	AO	AP	AQ	AR	AS	AT	AU
1	0.19	0.40	0.59	0.02	0.07	0.91	0.35
2	0.03	0.01	0.18	0.00	0.00	0.96	0.04
3	0.59	0.48	0.41	0.69	0.97	0.57	0.16
4	0.72	0.83	0.72	0.38	0.21	0.12	0.74
5	0.15	0.37	0.84	0.02	0.07	0.54	0.70
6	0.16	0.24	0.34	0.54	0.55	0.87	0.96
7	0.04	0.09	0.16	0.01	0.01	0.62	0.47
8	0.07	0.12	0.18	0.08	0.02	0.62	0.21
9	0.37	0.51	0.24	0.25	0.14	0.66	0.91
10	0.86	0.97	0.56	0.93	0.93	0.27	0.79
11	0.38	0.40	0.24	0.26	0.33	0.47	0.87
12	0.01	0.03	0.18	0.00	0.00	0.28	0.38
13	0.26	0.44	0.78	0.81	0.95	0.07	0.79
14	0.02	0.02	0.09	0.01	0.00	0.96	0.07
15	0.33	0.15	0.40	0.24	0.14	0.87	0.02
16	0.80	0.70	0.65	0.96	0.94	0.16	0.96
17	0.97	0.99	0.26	0.87	0.88	0.40	0.79
18	0.93	0.90	0.24	0.76	0.41	0.33	0.62
19	0.45	0.28	0.98	0.40	0.45	0.27	0.21
20	0.94	0.94	0.21	0.46	0.25	0.69	0.69
21	0.65	0.40	0.06	0.74	0.84	0.21	0.54
22	0.36	0.26	0.01	0.20	0.26	0.47	0.33
23	0.26	0.24	0.00	0.23	0.35	0.50	0.46
24	0.64	0.83	0.28	0.66	0.83	0.23	0.29
25	0.53	0.40	0.06	0.34	0.50	0.87	0.91
26	0.00	0.00	0.05	0.00	0.01	0.87	0.00
27	0.01	0.00	0.01	0.00	0.01	0.87	0.11
28	0.68	0.32	0.12	0.48	0.33	1.00	0.42
29	0.32	0.23	0.48	0.34	0.44	0.11	0.21
30	0.50	0.23	0.52	0.55	0.32	0.62	0.04
31	0.00	0.00	0.00	0.03	0.08	0.83	0.07
32	0.00	0.00	0.00	0.03	0.08	0.83	0.07
33	0.00	0.00	0.00	0.05	0.11	0.83	0.07
34	0.02	0.04	0.01	0.01	0.06	0.79	0.21
35	0.58	0.24	0.60	0.57	0.22	0.21	0.47
36	0.00	0.00	0.02	0.00	0.00	0.91	0.01
37	0.04	0.01	0.00	0.24	0.29	0.83	0.04
38	0.32	0.54	0.74	0.05	0.10	0.05	0.70
39	0.00	0.00	0.00	0.03	0.09	0.83	0.07
40	0.00	0.00	0.05	0.00	0.00	0.50	0.01
41		0.00	0.02	0.00	0.00	0.83	0.07
42	0.00		0.01	0.00	0.00	0.91	0.01
43	0.02	0.01		0.03	0.06	0.83	0.04
44	0.00	0.00	0.03		0.00	0.83	0.07
45	0.00	0.00	0.06	0.00		0.50	0.01
46	0.83	0.91	0.83	0.83	0.50		0.87
47	0.07	0.01	0.04	0.07	0.01	0.87	

5. LANDSCAPE INDICATORS OF ECOSYSTEM HEALTH IN THE WEST GEORGIA PIEDMONT: A REGIONAL APPROACH

5.1 Abstract

Ecological data obtained from field plots can provide detailed information about ecosystem structure and function. However, this information typically reflects processes that occur over small spatial areas. Accordingly, it is difficult to extrapolate these data to patterns and processes that take place at regional scales. Satellite imagery can provide a means to explore environmental variables at broad scales. The main objective of this study was to examine the utility of a regional ecological assessment tool using landscape indicators of ecosystem health in a rapidly-developing area of West Georgia. Indicator variables included in the assessment were: population density and change, road density, percent forest land-cover, forest patch density, Landscape Shannon's Diversity Index, proportion of stream that has roads within 30 meters, proportion of area that has agriculture on slopes >3%, proportion of stream with adjacent agriculture, and proportion of stream with adjacent forest cover. Cluster analysis was used to combine indicator variables into different groups, and cluster means were used to rank regional areas according to environmental impact. Results suggest the landscape indicators were related to field-based measurements, and areas of adverse environmental impact were identified.

Keywords: ecological assessment, ecosystem health, Georgia, landscape indicator, remote-sensing, urbanization

5.2 Introduction

Urbanization effects on natural resources extend well beyond the boundaries of built-up areas into surrounding wildland environments (Macie and Hermansen, 2002). As urban/built-up forms and infrastructure continue to encroach into natural areas at a rapid pace, the importance of effective ecological monitoring in a time- and cost-efficient manner becomes more imperative. Traditional ecological research has used ground-based observations over small spatial areas and short time scales (Pettorelli *et al.*, 2005). It is difficult to extrapolate these data to broader spatial and temporal scales in an accurate manner (Kerr and Ostrovsky, 2003). Landscape indicators have thus become key assets in current ecological research, as information about various environmental resources can be easily obtained (Sepp and Bastian, 2007). A landscape indicator is a characteristic of the environment measured at the ecosystem level that provides evidence of the condition of one or more ecological resources (Jones *et al.*, 1997). Landscape ecological assessments using satellite-derived data can provide information about a landscape and ecological processes that may not be detectable at the field plot level.

Remotely-sensed imagery can be utilized for a variety of ecosystem monitoring and management goals. Habitat suitability analyses, such as GAP projects, provide information at regional scales for biodiversity and conservation assessments for native wildlife species within their natural land-cover types (Hogland, 2005). Water quality assessments, such as those conducted by Basnyat *et al.* (2000) and Holland *et al.* (2004) were accomplished using various satellite-derived basin characteristics as model predictors of non-point source pollution (erosion, sedimentation, nutrient runoff). Bradley and Mustard (2005) used remote-sensing technologies to distinguish land-cover change from land-cover variability regarding native *vs.* non-native invasive plant species cover. Predictive models for drought (Tadesse *et al.*, 2005) and fuel-load (Jia *et al.*, 2006) have also been developed using remotely-sensed data for aid in agricultural planning and decision-making and wildfire management plans. Chen *et al.* (1999) modeled canopy photosynthesis to gain information concerning regional plant growth and carbon budget estimations. Remote assessments (i.e., using photogrammetry, satellite, radar, LIDAR, and other technologies) have also been conducted to estimate biogenic emissions for ozone production (Diem and Comrie, 2000; Xu *et al.*, 2002) and to document ozone-induced foliar injury (Diem, 2002). These broad-scale environmental assessments can be used to enhance our understanding of information from field-based ecological research.

Field-based studies remain an important component of many research fields for several reasons. When conducted prior to broader scale assessments, field studies can provide information to the researcher about how the ecological process under study varies over space. Variation across space is important when extrapolating data from forest stands to broader, more regional scales, as the resolution of satellite-derived data may be inadequate for some fine-scale ecological processes. When conducted after broad-scale assessments, field studies can be used to verify and validate model predictions resulting from remotely-sensed image analyses, such as land-cover classifications, temporal changes in normalized difference vegetation index (NDVI), and fuel-load or drought assessments. Used in conjunction, however, fine- and broad-scale ecological assessments incorporate the strengths of both methods and result in more robust datasets and predictive capabilities.

As evident from the examples above, much work has been accomplished through the integration of remotely-sensed imagery and smaller-scale biological datasets. Of particular interest is the work of Jones *et al.* (1997). These authors conducted an extensive ecological assessment of the U.S. Mid-Atlantic region using a combination of regional- and local-scale information such as census, air and water quality, soils, and forest pattern data. The methods developed by the authors were simple and concise, used largely public-available datasets and ecologically relevant indicators of ecosystem health at broad spatial scales. The authors (Jones *et al*., 1997) using these analyses were able to provide an understanding of changing conditions across the region and illustrate how patterns of ecological conditions measured at the regional scale can be used as a context for community-level functions. This work is important and has paved the way for the development and implementation of a highly predictive landscape-scale ecological tool.

Other researchers (discussed below) have conducted similar broad-scale ecological assessments integrating field and satellite data, producing interesting results. The journal Landscape and Urban Planning published a special issue (2007, Vol 79, Issue 2) entitled “Studying landscape change: indicators, assessment and application” which was derived from the 6th World Congress of the International Association for Landscape Ecology (IALE) held in Darwin (Australia) July 13–17, 2006. In this issue, Olsen *et al.* (2007) analyzed landscape indicators of ecological change on intensely and lightly used lands in

Georgia (USA). Lathrop *et al.* (2007) modeled potential future impacts of land-use change in the forested New York-New Jersey Highlands (USA). Smith and Wyatt (2007) integrated field surveys and satellite-derived land-cover maps to create a unified product for "Countryside Surveys" in the United Kingdom. Syrbe *et al.* (2007) utilized landscape indicator measurements for the monitoring of ecosystem services in Germany. For more information on these and other studies in this special issue the reader is referred to the issue's introduction (Sepp and Bastian, 2007).

The main objectives of this study were to develop a predictive ecological assessment tool utilizing census, land-cover, and forest fragmentation data in a GIS overlay analysis to determine landscape indicators of overall ecosystem health and assess a rapidly developing area of West Georgia (the Columbus metropolitan and surrounding area). Such information provides a baseline inventory of landscape ecological indicators for the West Georgia region that can be tracked into the future to observe changes in ecosystem health as urban development continues. The objectives of this project were to test the utility of a landscape ecological assessment tool for West Georgia by: 1) determining which landscape indicators can be measured at this regional scale, 2) deciding if the methods developed by Jones *et al.* (1997) work at this smaller, multi-county scale, and 3) determining which areas of West Georgia display environmental impacts typically associated with urban development.

5.3 Methods & Materials

5.3.1 Study Area

The study area (hereafter referred to as 'West Georgia'; Figure 5.1) comprises Muscogee (location of Columbus urbanized area), Harris, Meriwether, and Troup counties in the west-central Georgia Piedmont. The study region extends from Latitude 32º 20" 00' and 33º 15" 00' North, to Longitude 84º 30" 00' and 85º 15" 00' West (Figure 5.1). This area is located within the Piedmont Physiographic Province of west-central Georgia, and is characterized by gently rolling hills with elevations ranging from approximately 50-425 m (University of Georgia, 2007). The four-county area varies substantially in terms of land development, consisting of highly-modified land-uses in the urbanized core of Columbus and in several smaller urban clusters within the region, and pasture/grazing lands, managed timber plantation forests, and mixed pine-hardwood post-primary forests that have established since abandonment of cultivated lands in the 1930s in rural parts of the region (Brown *et al.*, 2005). Urban growth around the Columbus area is constrained by Fort Benning (a large U.S. military base) to the south and by the Chattahoochee River to the west, such that new development mainly occurs to the north and east of Columbus.

For the purposes of this study, the U.S. Census Bureau's Census 2000 geographic definitions of urban and rural were used (U.S. Census Bureau, 2001). The U.S. Census Bureau (2006) recognizes four urban areas in the region: one urbanized area (UZA), defined by a population >50,000 people and a population density of at least 386 people/km^2, and three urban clusters (UCs), characterized by a population between 2,500-49,999 people and a population density of at least 386 people/km^2. The UZA is Columbus (Muscogee County), and the UCs are LaGrange (Troup County), Manchester (Meriwether County), and portions of Valley-Lanett (Harris and Troup Counties), shown in Figure 5.1. According to these definitions, all other land areas in the West Georgia study area are classified as rural (U.S. Census Bureau, 2006). “Developing” areas were defined by a population growth between 1990-2005 greater than the national average (19%).

5.3.2 Delineation of Experimental Units

Census county subdivisions (CCSs) were used as the unit of delineation since this is the sampling unit utilized to compile socio-economic data. These data are necessary to combine land-cover and fragmentation data with census demographic and topologically integrated geographic encoding and referencing system (TIGER®) data (U.S. Census Bureau, 2005). Further, these units were also used because there were a similar number of census county subdivisions in most of the counties (except Muscogee), which would help to prevent clustering resulting from an unbalanced mix of “urban” or “rural” units. Census county subdivisions are the same as census tracts in rural counties such as Harris (four CCSs) and Meriwether (six CCSs). In Troup County, the 13 census tracts were combined to form six census county subdivisions. Muscogee County was one entire census county subdivision, even though it is composed of 56 tracts. To make these data more uniform, the census tracts for Muscogee County were manually incorporated into county subdivisions. To accomplish this, population, housing, and road densities were first calculated for each of the tracts. Because these variables were consistent across space (i.e., tracts with high population density also had high housing and road densities) and highly correlated (population with housing density r = 1.00, and road density r = 0.99), only population density was used to group the tracts into eight evenly-distributed categories of density ranges. Eight was the maximum number of county subdivisions used since the goal was to maintain a similar number of county subdivisions in each county and to retain a relatively even balance of the number of urban *vs.* rural units across the four-county region. Next, ArcGIS (Environmental Systems Research Institute, 2005) was used to determine adjacency of county subdivisions within a single density category. Through a delicate balance of maintaining adjacency and population density, the 56 tracts were combined to form eight county subdivisions for Muscogee County.

5.3.3 Calculation of Landscape Indicators

As previously stated, the overall goal of this study was to determine and assess appropriate landscape indicators of overall ecosystem health for the West Georgia region. Based on field-study results for West Georgia, five general components of ecosystem health were targeted for assessment: forests, air, water, soil, and demographic/landscape changes. Thus, each of the indicator variables utilized in the development of this tool measure different aspects of environmental condition that are typically affected by urban development. The 10 landscape indicator variables included in the assessment were: population density and change, road density, percent forest land-cover, forest patch density, Landscape Shannon's Diversity Index, proportion of stream that has roads within 30 meters, proportion of area that has agriculture on slopes >3%, proportion of stream with adjacent agriculture, and proportion of stream with adjacent forest cover. Information regarding the specific data and methods used to calculate each of the 10 indicators is provided in more detail below.

5.3.3.1 Census Demographic and TIGER® Data

Population data and shapefiles for 2000 were obtained from the U.S. Census Bureau TIGER® website (U.S. Census Bureau, 2005) to determine the 'population density' metric. Population density for each of the census county subdivisions in West Georgia was calculated using the total land area for each unit for use as one of the landscape indicator variables (U.S. Census Bureau, 2005). Population data for 1990 were also gathered to calculate the 'population change from 1990-2000' metric for each census county subdivision in West Georgia (U.S. Census Bureau, 2006). Additional TIGER® data acquired included detailed road and stream GIS layers to calculate the 'road density' metric and for use in overlay analysis (U.S. Census Bureau, 2005). These layers are more accurate than can be achieved from a 30-meter Landsat image analysis, where roads and streams may be obstructed by trees or other objects. TIGER® layers are discussed in more detail below.

5.3.3.2 Land-cover Classification

Landsat 5 Thematic Mapper (TM) images (U.S. Geological Survey, 2005) from September 2005 and August and December 2004 were used as a stacked image layer to produce a land-cover classification for the West Georgia region for the year 2005 (Figure 5.2). Cloud-free summer and winter imagery was not available for 2005, and was thus supplemented by leaf-on (August) and leaf-off (December) images from 2004 to improve class assignments. These Landsat images (30-meter) were selected because they were readily available, low cost, and already in a usable digital format (U.S. Geological Survey, 2005). Pre-classification processing included the geocorrection of each image to ensure they were in the same coordinate system (UTM Zone 16N; datum NAD 83; spheroid WGS 84) and aligned properly for classification and GIS overlay analysis using the image geometric correction tool in ERDAS IMAGINE® 9.0 (Leica Geosystems, 2005). The final classification scheme for the entire four-county scene contained the following eight land-cover characterization classes: urban/built-up, bare ground, pasture, urban lawn, urban vegetation, deciduous forest, evergreen forest, and water/wetlands (Anderson *et al.*, 1976). For portions of the overall study, five generalized land-cover types were analyzed: forest (urban vegetation + deciduous forest + evergreen forest), grass (pasture + urban lawn), water/wetlands, bare ground, and urban/built-up (Anderson *et al.*, 1976). These categories were recoded from the original classification to reflect a more general cover type. The forest land-cover class (urban vegetation + deciduous forest + evergreen forest) was used to calculate the '% forest cover' metric, and the 'agriculture/bare ground' metric was created by combining the pasture, urban lawn, and bare ground land-cover classes. Both the forest and agriculture/bare ground (pasture + urban lawn + bare ground) land-cover classes were utilized to calculate other metrics described below. An accuracy assessment was conducted and high-resolution 1-meter color Digital Ortho Quarter Quads (DOQQs) were used as reference material (date of imagery February 1999; accessed USGS Seamless Data Server June 13, 2006), along with the Landsat TM images, to verify the classification of thirty randomly generated points (Jensen, 2005). For more information on the classification process, the reader is referred to Chapter 4.

5.3.3.3 Fragmentation Analysis

Once the 2005 land-cover classification for the West Georgia region was produced, it was used as input into Fragstats with the patch neighbor rule set to 8-cells (McGarigal *et al.*, 2002) to summarize landscape indicator values. Many landscape metrics can be calculated using Fragstats; however, the goal was to select simple yet pertinent metrics that could be used to describe relative landscape-scale indicators of ecosystem health in West Georgia. For this portion of the study only ‘forest patch density (FORPD)’ and ‘Landscape Shannon's Diversity Index (SHDI)’ metrics were calculated for each of the 24 census county subdivisions. The “patch types” in this analysis are the eight original land-cover class types – urban/built-up, bare ground, pasture, urban lawn, urban vegetation, deciduous forest, evergreen forest, and water/wetlands. For more information about these variables, the reader is referred to Chapter 4.

5.3.4 GIS Overlay Analysis

GIS overlay analysis was conducted to provide four additional landscape indicator variables, calculated using the TIGER® road and stream data (U.S. Census Bureau, 2005) and the forest, pasture, urban lawn, and bare ground land-cover classes. The total length of road within 30 m of a stream was calculated by rasterizing the vector road and stream layers and subsequently performing an intersection overlay analysis using ERDAS Imagine® 9.0 (Leica Geosystems, 2005) resulting in the 'proportion of roads crossing streams' metric. The percentage (road length/stream length) for each unit was extracted from the two layers. When roads are near streams, water quality declines from high rates of stormwater runoff to pollutant spills from leaked vehicle fluids, road and brake dust, and other dry and wet chemicals deposited on roadways (Sabin *et al.*, 2006). The amount of agriculture on slopes greater than 3% is considered by the USDA (Jones *et al.*, 1997) to be an indicator of potential soil erosion and pollutant runoff. Since a majority of the "agricultural" land in West Georgia is pasture, the pasture, urban lawn, and bare ground land-cover classes were combined and renamed 'agriculture/bare ground' for use in this analysis since each of those cover types have the potential to affect soil erosion and/or water quality. A digital elevation model (DEM) for West Georgia was obtained from the USGS (U.S. Geological Survey, 2004). Elevation values were converted to % slope and the image was recoded into 2 classes: 1 = 0-3% and 2 = >3% using the recode tool in ERDAS Imagine® 9.0 (Leica Geosystems, 2005). The agriculture/bare ground layer was overlaid onto the recoded DEM and the percentage of agriculture/bare ground on slopes greater than 3% per unit was extracted to obtain the '% agriculture/bare ground on slopes

>3%' metric. The amount of agriculture/bare ground *vs.* forest cover along streams is also an important indicator of water quality, as riparian zones provide a buffer against excess water and pollutant runoff (Jones *et al.*, 1997). The agriculture/bare ground and forest land-cover classes were separately overlaid on the TIGER® stream layer (U.S. Census Bureau, 2005) to extract the proportion of total streamlength with adjacent agriculture/bare ground and forest land-cover, producing the '% agriculture/bare ground adjacent to streams' and '% forest cover adjacent to streams' metrics.

5.3.5 Landscape Indicator Data Analysis

5.3.5.1 Data Standardization and Multicollinearity Analysis

Since cluster analysis is sensitive to broad ranges in data values, each of the landscape indicator variable values was standardized using the mean and standard deviation of the original value. As a result, all values ranged between -5 and +5 and the largest range within a single variable was |4.84|. The standardized variables were then placed into a correlation matrix to detect any multicollinearity among potential predictor variables.

5.3.5.2 Cluster Analysis

Cluster analysis was performed using JMP IN® 5.1.2 (SAS Institute Inc., 2003) to identify groups of census county subdivisions with similar ecological indicator characteristics. Several cluster combinations were examined and the combination that produced the most distinct separation of census county subdivisions was selected as the final output. The ten metrics described above (i.e., population density and change, road density, percent forest land-cover, forest patch density, Landscape Shannon's Diversity Index, proportion of stream that has roads within 30 meters, proportion of area that has agriculture/bare ground on slopes >3%, proportion of stream with adjacent agriculture/bare ground, and proportion of stream with adjacent forest cover) were used as landscape indicators in the cluster analysis. Spearman’s rank correlations suggest multicollinearity between some of the potential predictor variables but that was expected. For example, population *vs.* road density, road density *vs.* the proportion of roads crossing streams, % forest cover *vs.* forest cover adjacent to streams, and % forest cover *vs.* forest patch density are all highly correlated. All of the ten variables were included because they measured different aspects of the same environment, namely different characteristics of water, air, and soil quality (Jones *et al.*, 1997). However, since population and road densities were strongly correlated, population density values were excluded from impact score assignment since there was already a “population” metric within the set of variables.

5.3.5.3 Relative Cumulative Environmental Impact (RCEI)

Groups of census county subdivisions were then ranked in order of low to high relative cumulative environmental impact (RCEI) using variable means for census county subdivisions within each of the clusters. High values for two of the variables (‘% forest cover' and '% forest cover adjacent to streams') suggest a potential positive impact, while high values for the remaining eight variables ('population density', 'population change from 1990-2000', 'road density', 'FORPD', 'SHDI', 'proportion of roads crossing streams', '% agriculture/bare ground on slopes >3%', and '% agriculture/bare ground adjacent to streams') suggest a potential negative impact. The resulting rank scores were then totaled to determine which areas were more or less environmentally impacted relative to others in the West Georgia region. These areas were mapped and color-coded using ArcGIS (Environmental Systems Research Institute, 2005).

5.4 Results & Discussion

5.4.1 Landscape Indicators in Urban, Developing, and Rural Areas of West Georgia

Using the methods developed by Jones *et al.* (1997) as a guide, I selected the ten landscape ecological indicators described above to analyze the West Georgia region. Data for these ten variables were available for areas across the entire region and had ranges suitable for analysis. Some of the variables measured and included in the assessment by Jones *et al*. (1997) were not appropriate for inclusion here because either 1) they did not exist for the West Georgia region (e.g., stream impoundments), 2) there were spatial gaps in the data (e.g., nitrogen and phosphorus loadings to streams and potential soil loss data), 3) the data were not regionally distinct enough to be included in these analyses (e.g., NDVI and nitrate, sulfate, and ozone concentrations), or 4) the West Georgia study area was too small compared to the larger Mid-Atlantic region (e.g., number of dams on rivers and edge/interior habitat analyses at broad scales). Details for each of the 10 variables that were included in the analyses are discussed below.

5.4.1.1 Population Density, Population Change, and Road Density

Population density values from 2000 varied greatly in West Georgia from urban to rural areas (Table 5.1, Figure 5.2). Population density in urban census county subdivisions ranged from 659-2029 people/km^2. The majority of people live in the central portion of Columbus, with the least amount located along the northern suburbs and to the west along the Chattahoochee River. In areas of West Georgia considered to be "developing," population densities ranged from 6-293 people/km^2. Although this range appears wide, it is fairly typical of developing areas around Columbus, as some areas are more urban, while others are similar to rural areas. For example, just two of the eight census county subdivisions considered developing were at the high end of the density range. The largest of these includes the City of LaGrange, GA and the other spans the entire northern portion of Muscogee County, where development is rapidly expanding from the northern Columbus suburbs. Without these two subdivisions in the developing category, the range would be 6-42 people/km^2. By contrast, rural subdivisions had very low population densities, from 10-41 people/km^2, with the exception of the subdivision in this group that contains the entire Fort Benning military base in southeastern Muscogee County (179 people/km^2).

Population change between 1990-2000 was calculated for each of the census county subdivisions in West Georgia (Table 5.1, Figure 5.3). Changes in urban census county subdivisions ranged from -18 to 30% between 1990-2000. Interestingly, the values for each of the subdivisions except for one were negative, suggesting an exodus from urban areas during this time period. The one subdivision that exhibited population growth (30%), considerably above the national average of 13% (from 1990-2000), was in the older, north-central suburbs of Columbus. In the developing areas of West Georgia, population change between 1990-2000 ranged from -7 to 50%. This category includes the largest increase within the entire region (50%), measured for an area in Troup County to the north of LaGrange. It is possible that some of this growth could be due to the sprawling 28-county Atlanta metropolitan area (U.S. Census Bureau, 2006). According to the 2006 Census population estimates, metro Atlanta is currently the fastest growing metropolitan area in the United States (U.S. Census Bureau, 2006), and some commuters to Atlanta are moving into the northern West Georgia region. Further, all subdivisions in this group had increases in population during this period except for one. Oddly, the census county subdivision in extreme northern Muscogee County had a net change of -7% over the 10-year period but is one of the areas where much development is occurring. These values seem to suggest the opposite of the development trends observed from apparent new construction in the area. One possible explanation could be that a majority of growth in this area has occurred since the 2000 census statistics were gathered and compiled. However, without more recent data, this hypothesis cannot be confirmed. Rural subdivisions in West Georgia had mixed growth trends, ranging from -6 to 17% from 1990-2000. Six of these, mainly in Meriwether County, had decreased or no growth, while four had population increases that occurred during the time period in each of the rural counties (Figure 5.4). These values further suggest similarities between rural and developing areas in West Georgia.

Road density in West Georgia can be an indication of potential future growth, and has water and air quality implications as well, from vehicle emissions, fluid spills, brake and tire wear. Road densities in 2000 for the West Georgia area did not vary as much as the population density statistics suggest (Table 5.1; Figure 5.5). In urban census county subdivisions, road densities ranged from 7.83-15.5 km of road length per area of km^2. Developing census county subdivisions had road density values between 0.46-5.09 km/km^2, while rural subdivisions ranged between 1.27-3.19 km/km^2. There were few differences in road densities in rural and developing areas in West Georgia. This could possibly be due to the extensive network of federal, state, and county roads that have been in existence since the 1950s, all of which link rural areas of West Georgia with a major interstate connector (I-185).

5.4.1.2 Urban/Built-up, Bare ground, Grass, and Forest Land-cover

The generalized 2005 land-cover of the four-county area in West Georgia (Figure 5.6) includes urban/built-up, bare ground (areas under development, cultivation, and harvested timberlands), grass (pasture, urban lawns, grassy lots, and golf courses), forest cover (urban vegetation, deciduous forest, evergreen forest), and water/wetlands (Table 5.2). Urban census county subdivisions were characterized by high percent cover of urban/built-up land (52-76%) and low percent cover of forested land (18-39%). By contrast, rural and developing areas had very low percent cover of urban/built-up land (0-

3% and 0-12%, respectively) and very high percent cover of forested land (61-86% and 59-89%, respectively; see Figure 5.7). Bare ground and grass cover in urban areas of West Georgia were virtually nonexistent, with 0% bare ground and grass ranging from 0.48-2.22%. In contrast, bare ground in developing areas was 8-13% while in rural areas it increased in range from 12-21%. These values could possibly reflect harvest and planting cycles at the numerous timber plantations in West Georgia, or they could also be an indication of areas undergoing development at that time. Similarly, grass cover in rural subdivisions ranged from 6-15% excluding the Fort Benning subdivision (1.24%). Pasture cover in developing areas ranged from 2-8%, and was mostly a mixture of animal and feed pastures, cultivated lawns, and golf courses.

5.4.1.3 Forest Patch Density and Landscape Shannon's Diversity Index

Forest patch density (FORPD) is a measure of the number of patches per unit area (100 ha) within each unit measured. Patch density is generally a better metric than the raw number of patches since it allows comparison of areas of different sizes, such as with variably-sized census county subdivisions. In the urban census county subdivisions, FORPD ranged between 11.37 and 24.89/100 ha (Table 5.1; Figure 5.8). However, values in rural and developing areas were similar, ranging from 1.15-2.84/100 ha and 0.66-3.91/100 ha, respectively, and were much lower than urban FORPD values. This suggests more patchiness among urban forests in West Georgia, possibly resulting from forest fragmentation due to land development. These results are consistent with research by Zipperer (1993), who reported increased deforestation in forested patches in urban areas of Maryland.

Landscape Shannon's diversity index (SHDI) expresses the proportion of the landscape occupied by a patch type of a particular class (McGarigal *et al.*, 2002). Landscape diversity is 0 where there is only one patch type (land-cover class type) and increases to infinity as the number of different patch types increases and/or the areal distribution among patch types becomes more even. All eight original land-cover characterization classes were input into the analysis of this metric. In urban census county subdivisions, SHDI values were between 0.69 and 1.12 (Table 5.1; Figure 5.9). Surprisingly, SHDI values were similar in rural areas (0.67-0.96). Developing subdivisions had the least and greatest overall SHDI values (0.56-1.15), and this wide range again demonstrates the similarity of these areas to both rural and urban land-use types. It is understandable that rural landscapes would be more homogeneous than urban and developing areas, especially in the case of West Georgia where a majority of the land-cover is forest. Researchers have reported both high (Burton *et al.*, 2005) and low (McKinney, 2006) SHDI values for urban areas. One possible hypothesis for these mixed results is that, as areas begin to become urbanized and heterogeneous, SHDI increases (Zipperer *et al.*, 2000) until a point where the landscape is highly urbanized and intensely homogenous (McKinney, 2006). This could be the case in the developing areas of West Georgia, where forested and agricultural landscapes are becoming more urbanized.

5.4.1.4 Agriculture/Bare ground on Slopes >3% and Streamlength with Adjacent Roads, Agriculture/Bare ground, and Forest Cover

Agriculture/bare ground on slopes >3% is an indication of potential soil loss and sedimentation of nearby streams, as well as potential pollutant runoff (Jones *et al.*, 1997). Since there is not a large amount of cultivated cropland in West Georgia, the bare ground, urban lawn, and pasture land-cover classes were used to calculate this metric because the potential for sedimentation and chemical runoff to streams from these land-cover types is high (Table 5.1; Figure 5.10). In the urban census county subdivisions, this value ranged from 32-66%. The total amount of land-cover in these classes was fairly low (4-14%); however, the potential for runoff is possible from parcels of land under development or from steep lawns and golf courses where the use of fertilizers, pesticides, and herbicides is typically high. In developing subdivisions in West Georgia, the amount of agriculture/bare ground on slopes >3% was between 43-77%, which has the greatest value of any of the land-use types. These high values could possibly be linked to some combination of new construction, timber plantation rotations, lawns, golf courses, and animal and feed pastures, typical of these developing areas, comprising a mix of urban- and rural-like land-use types. The overall values for rural areas were not much lower than urban or developing areas (32-71%), but the range is greater than either of these areas. The larger total amount of bare ground and pasture land-cover in rural areas could possibly be the reason for these values.

Healthy streams are important components of ecosystems in any area, as they provide drinking water and other services to people living in these communities

(Schoonover and Lockaby, 2006). Roadways, on the other hand, are a major source of soluble and particulate pollutant runoff to streams (Sabin *et al.*, 2006), thereby diminishing their health and ability to provide ecosystem services. Roads that occur with 30 m of a stream have a greater potential to affect stream quality than those located outside of this distance (Jones *et al.*, 1997). For this metric the proportion of road length within 30 m of a stream to the total amount of streamlength in a given area was calculated (Table 5.1; Figure 5.11). In urban census county subdivisions, these values ranged between 1-57%. This is a wide range in values, and there is no clear trend since both the least and greatest values are located in census county subdivisions in the central portion of downtown Columbus. However, it is possible that the high values were a result of higher road densities in these areas. Rural and developing census county subdivisions had much lower values, ranging from 1-3% and 1-4%, respectively. In contrast, it is possible that these values could be attributed to the lower road densities in these areas.

Riparian zones are an important component of healthy stream ecosystems. Riparian zones buffer runoff from higher grounds, including sediment, fertilizers, pesticides, and herbicides. The presence of forested land along streams is a positive indicator of ecosystem health, while the absence of forest buffers when agricultural fields are present is a potentially negative indicator. The proportion of total streamlength with adjacent forest *vs.* agriculture/bare ground was assessed to examine stream ecosystem health in West Georgia (Table 5.1; Figures 5.12 and 5.13). In urban census county subdivisions, 0-1% of the total streamlength had adjacent agriculture/bare ground cover while 4-48% was forested. The low agriculture/bare ground cover was probably a reflection of the low overall percentage of bare ground and pasture cover in urban areas. Even though urban lawn cover is prevalent in Columbus, these data suggest that they are not adjacent to streams. The adjacent forest cover has a wide range of values for these urban areas, and all but two census county subdivisions had values greater than 28%, which is a good indicator of high water quality and biodiversity for the urban streams of Columbus (Burton *et al.*, 2005; Schoonover and Lockaby, 2006). In developing census county subdivisions, streams having adjacent agricultural lands occurred about 7-16% of the time, while 56-83% was forested. Overall, these values appear to be good, and suggest over half of the total streamlength in these areas have adequate riparian buffers. Areas with adjacent agriculture/bare ground, however, do have the potential for sedimentation and pollution resulting from runoff. The values for rural subdivisions are even higher, with 9-27% of adjacent agriculture/bare ground cover and 72-83% forest land-cover. As with the greater amount of agriculture/bare ground on slopes >3% in rural areas, these greater values could possibly be due to the greater total amount of bare ground and pasture land-cover in these areas. Further, over half of the census county subdivisions in this group had streams with less than 20% adjacent agriculture/bare ground cover. On the positive side, there appears to be a great amount of forested land-cover in rural subdivisions, which would hopefully help to mitigate those areas without riparian zones.

5.4.2 Cluster Ranks and Relative Cumulative Environmental Impact Scores

All of the 10 landscape indicator variables were input into JMP IN® 5.1.2 to perform a cluster analysis to examine which areas of West Georgia would separate out as distinct from one another. Several analyses were conducted and the best fit resulted in five clusters (Table 5.4, Figure 5.14). Any fewer than five resulted in not enough separation between subdivisions, while in all new clusters created after the fifth, only a single subdivision would separate itself as a single cluster. Since the goal was to determine which areas were most similar and to rank these areas based on their relative cumulative environmental impact scores, the five cluster solution was selected.

The five clusters were then analyzed by examining the original values for each indicator for all of the individual census county subdivisions. These values were then averaged resulting in a single value for each indicator within each cluster. The clusters were then ranked from low to high, based on whether the indicator was an ecologically positive or negative attribute. For example, a high value for % forest cover would be a positive attribute while a high value for agriculture on slopes >3% would be a negative attribute. The three highest scores for the negative indicators and the three lowest scores for the positive indicators were noted. Highlighted indicators for each cluster were then summed resulting in that cluster's relative cumulative environmental impact score (RCEI). The clusters were then ranked according to these scores, with the greatest RCEI (most environmentally impacted areas) receiving the lowest (poorest) rank (Table 5.4). Since population and road densities were strongly correlated, the population density values were excluded from RCEI score assignment. Similarly, since landscape SHDI is a relative measure of landscape homogeneity *vs.* heterogeneity, it is a subjective indicator and thus, these values were also excluded from RCEI score assignments.

Cluster 1 was ranked 1st and the ten census county subdivisions in this group were located in each of the four counties. All Meriwether County census subdivisions fell into this category, as did western Troup County, northern Harris County, and Fort Benning, located in southeastern Muscogee County. This cluster is characterized by low population and road densities, but had high population growth between 1990-2000. Cluster 1 had the highest value for streams with adjacent agricultural land, but also had the highest value for streams with adjacent forest land-cover. Percent forest cover was high in this cluster and forest patch density was low. The proportion of agriculture located on slopes >3% was also low and this cluster had the lowest value for the amount of roads near streams. SHDI was moderate in Cluster 1.

Cluster 4 was ranked 2nd, which included the remaining three subdivisions of Harris County along with two located in northwestern Troup County. This group had the lowest population and road densities of any cluster, but had the highest value for population growth between 1990-2000. Cluster 4 had a moderate value for streams with adjacent agricultural land, but had a high value for streams with adjacent forest land-cover. Overall forest cover was the highest of the clusters and forest patch density was the lowest measured. The proportion of agriculture located on slopes >3% was the highest, but the amount of roads near streams was low. SHDI was low in Cluster 4.

Cluster 2 was ranked 3rd, and encompasses the majority of Columbus except for the extreme interior subdivision, located in the central downtown area. Cluster 2 had high population and road densities, but moderate population growth between 1990-2000. This group had a low value for streams with adjacent agricultural land, but also had low adjacent forest land-cover as well. Forest cover in Columbus was low and forest patch density was high. The proportion of agriculture located on slopes >3% was the lowest, but the amount of roads near streams was high. SHDI was high in Cluster 2.

Cluster 3 was ranked 4th, and is a single subdivision located in central downtown Columbus. This cluster had the highest population and road densities of the subdivisions, but the lowest percentage of population growth between 1990-2000. Cluster 3 had the lowest value for streams with adjacent agricultural land, but also had the lowest amount of streams adjacent to forest. Forest cover in the central city was least of any measured and forest patch density was the greatest. The proportion of agriculture located on slopes >3% was moderate, but the amount of roads near streams was the greatest. SHDI was the lowest of all subdivisions in Cluster 3.

Cluster 5 was ranked 5th and last, and is composed of one subdivision located in extreme northern Muscogee County just outside the Columbus city limits and two subdivisions in central and western Troup County, which includes the City of LaGrange. Cluster 5 had moderate population and road densities, but had low population growth between 1990-2000 of any of the subdivisions. This group had a high value for streams with adjacent agricultural land, but had moderate riparian forest cover. Both forest cover and forest patch density were moderate in this cluster. The proportion of agriculture located on slopes >3% was high, and the amount of roads near streams was moderate. SHDI was the highest of all subdivisions in Cluster 5.

5.4.3 Regional Environmental Impact vs. Plot-level Forest Stand Condition

The results above suggest that this landscape-scale ecosystem assessment tool is capable of identifying areas of high relative cumulative environmental impact using only a few census- and satellite-derived metrics. However, how do these results compare to those obtained from ground-based plot-level forest health assessments? Do the two sets of results portray ecological health for the West Georgia region in the same manner? To assess the spatial accuracy of the landscape ecological tool, plot-level forest condition data collected from 2004-2006 (see Chapter 2) were used to compare areas of plot-level *vs.* landscape-level ecological health in West Georgia.

It is apparent from the results described above that, regionally, the most environmentally impacted areas in West Georgia were located on lands under development in northern Muscogee County and in central and western Troup County around the City of LaGrange, as well as in the highly urbanized, central portion of downtown Columbus (Figure 5.14). Since plot data were not collected in Troup County as part of the field study, only data from Muscogee County could be compared. According to the field-collected forest condition data, the urban areas of West Georgia were the most environmentally impacted; however, the developing areas, specifically those in northern Muscogee County, did not appear as “impacted” or “stressed” as the regional assessment suggests. Of the 13 forest condition variables collected (Table 5.5, from Chapter 2), seven were significantly different between land-use types. Plots located in developing areas had the least mean for only one variable, ‘number of foliose lichen species on water oaks (*Quercus nigra* L.)’, but had the greatest mean for ‘number of tree species’ (tree species richness). In all other significantly different variables, developing land-use types had the intermediate value between urban and rural land-use types, and in most cases, was not significantly different from either urban or rural areas. Urban plots had the greatest values for injury to trees from ‘pest’, ‘disease’, and ‘mechanical injury’, and the lowest means for ‘percentage of trees with lichens’,’ number lichen species per tree' (lichen species richness), and 'mean lichen abundance', making urban areas the most impacted, or having the poorest forest condition of the areas measured in West Georgia (Table 5.5).

The landscape ecological assessment tool suggests that rural areas were the least environmentally impacted (or most healthy) of all areas in West Georgia, thus supporting the results from the forest condition field study. Further, the landscape-level analysis revealed that urban areas surrounding Columbus are heavily impacted ecologically, which also supports the field study findings. The only differences in the two datasets lie within the developing areas of West Georgia. Trends in these areas have been the most difficult to determine in several research projects conducted in the West Georgia region as part of the overall project (Burton *et al.*, 2005; Schoonover and Lockaby, 2006). With some variables, the developing sites selected may have been more indicative of rural land-use types, given the values of several urbanization variables calculated (e.g., low road density, high percentage of forest cover). However, with others, developing areas appear more similar to urban land-use types, according to field data (e.g., low number of foliose lichen species) and environmental impact scores (e.g., low % forest cover adjacent to streams). It may be possible that the indicators selected for the broad-scale ecological assessment are appropriate for detecting early stress on an ecosystem, such that conditions favorable to high environmental impacts are noticeable prior to individual species or forest stand responses. However, additional research should be conducted to confirm this hypothesis. Selecting more sampling sites in developing areas that have more intermediate "urbanized" values might also alleviate some of these uncertainties and improve the predictability of this tool. Had this tool been used prior to field site selection in West Georgia, more plots would have been located in the "moderate to high impact" areas (Figure 5.15), which may have lead to more apparent trends in these areas. However, the tool appears to provide an adequate initial assessment and map of environmentally-impacted areas of West Georgia and supports the findings reported from the field study data.

5.5 Conclusions

Regional ecosystem assessments using satellite-derived imagery, such as the one described above, can be conducted prior to field sampling as quick diagnostic tests to detect early stress and identify which specific areas within a region warrant further ground-based analyses. They can also be utilized after field sampling to verify the context of environmental responses measured at plot-level scales to determine whether there is a localized issue or if the issue is part of a more regional problem. Such context-based analyses provide information about regional land-cover patterns that correlate plot-level data with adjacent land-uses and surrounding landscape characteristics. The ability to identify environmentally-impacted areas over broad scales using landscape indicators and field-based measurements with statistical and geographic information system modeling techniques provides a cost- and time-efficient means for monitoring forest ecosystem health.

As with any assessment tool, there are advantages and disadvantages associated with its use. This tool appears to be appropriate for broad generalizations about an entire landscape as a whole, but is not detailed enough for site-specific management goals due to its inherent coarse spatial scale (30-meter). Smaller experimental units would have resulted in more detailed information; however, maintaining an even balance of units between urban and rural areas is often difficult at a small scale of analysis but is necessary for use in cluster analysis. For the West Georgia region, it would be best to implement a tool such as this prior to field sampling so that more field plots can be placed into those areas that appear “moderate or highly impacted” to determine what the specific differences are between “impacted” *vs.* “reference” sites. Overall, this ecological assessment tool is a worthwhile investment for those needing a rapid diagnosis of ecosystem health in an inexpensive and timely manner.

5.6 Acknowledgements

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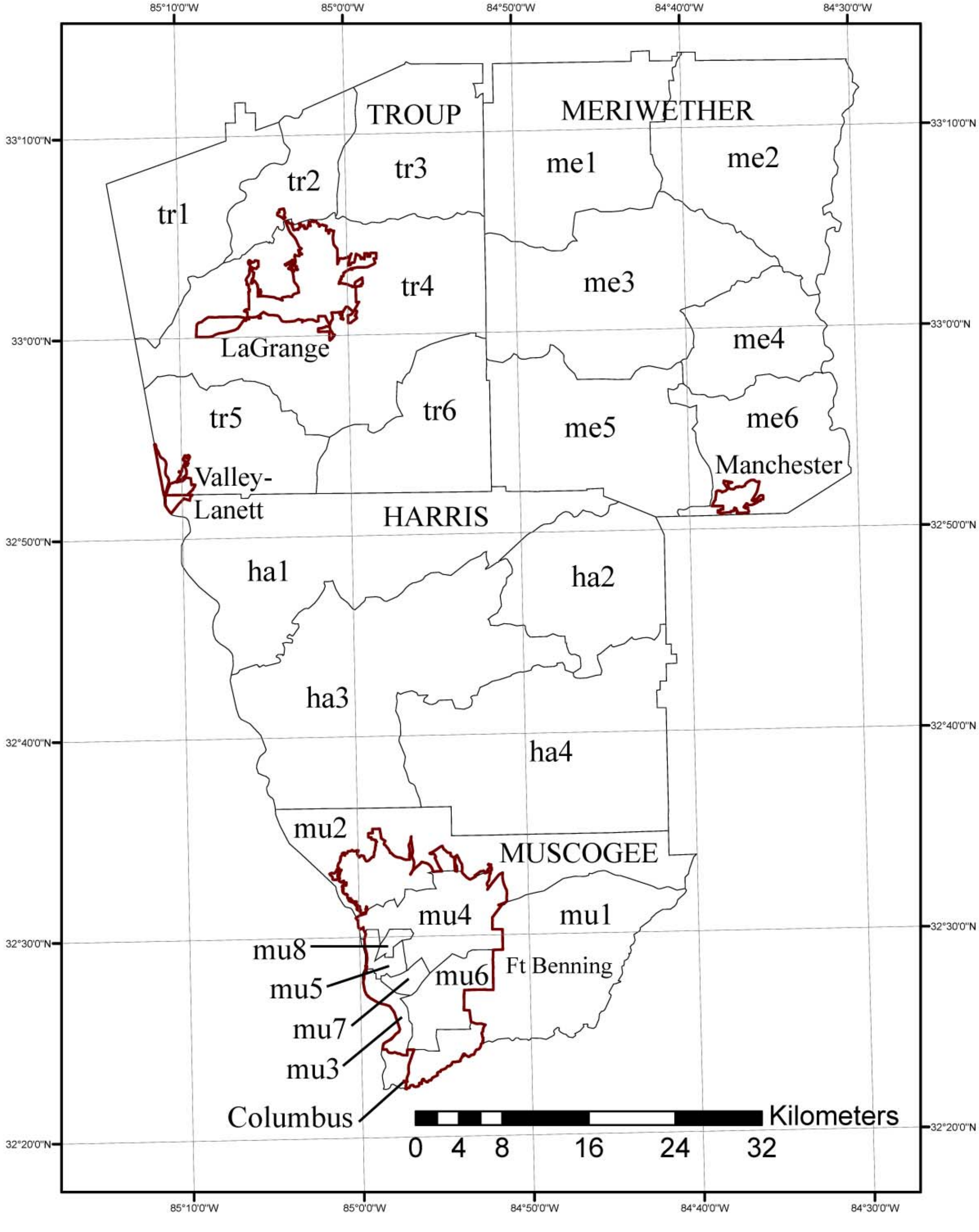

Figure 5.1 Map of study area showing cities, counties, and census county subdivisions in West Georgia. Codes explained in Table 5.1. Source: Diane M. Styers, 2008.

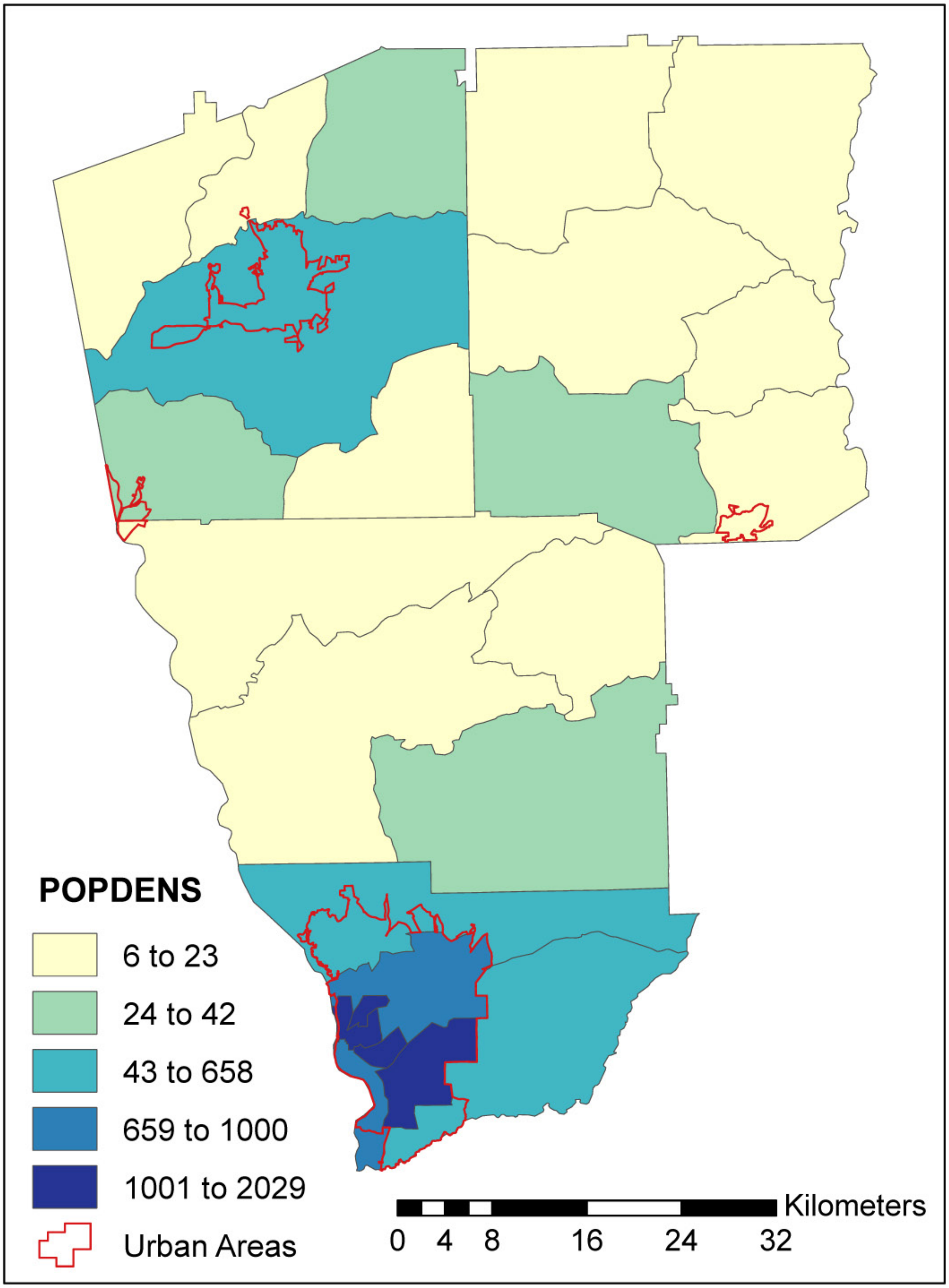

Figure 5.2 Population density (number of people/km^2 in 2000) in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

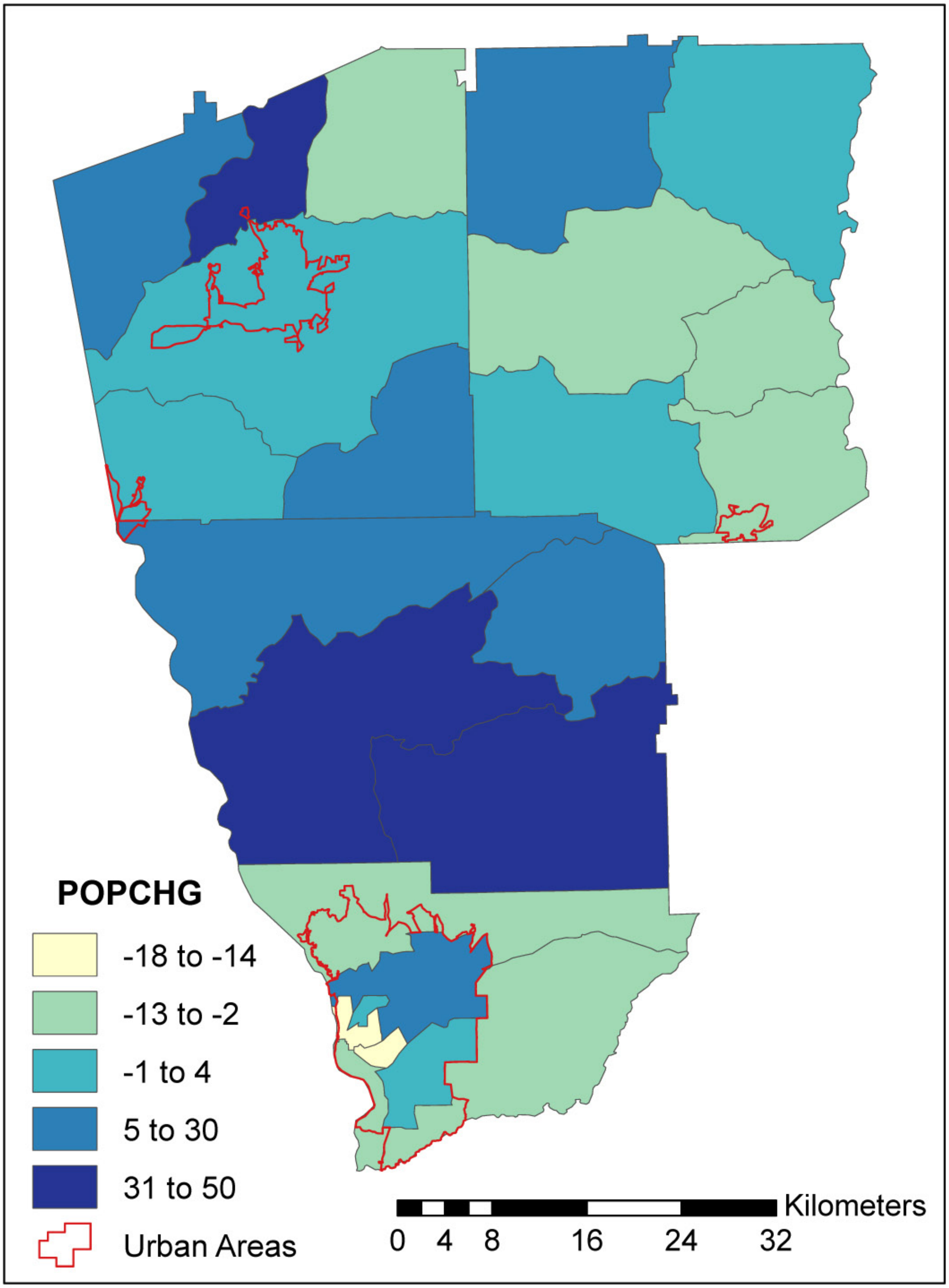

Figure 5.3 Population change (% change from 1990-2000) in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

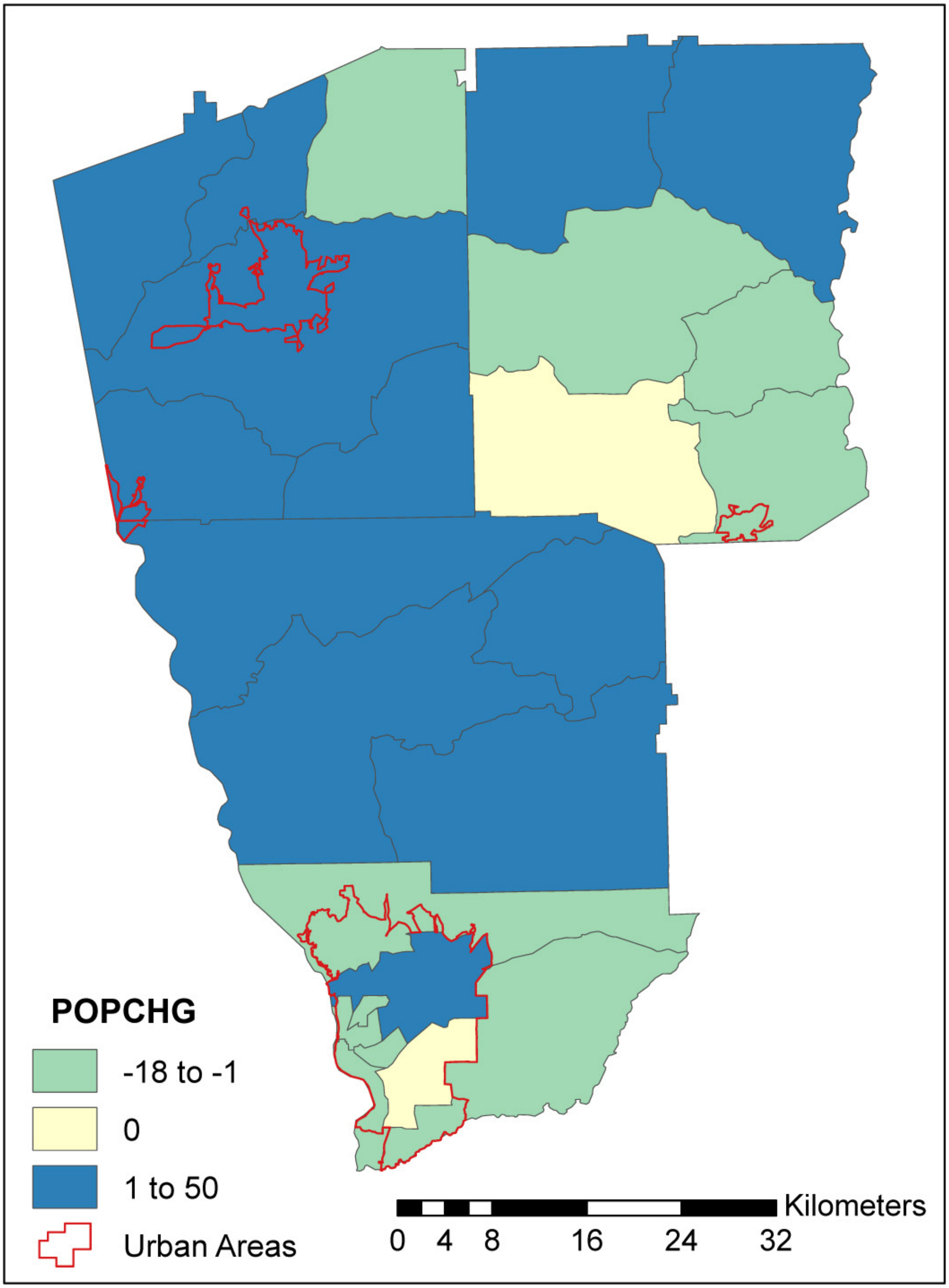

Figure 5.4 Negative *vs.* positive population growth (% growth between 1990-2000) in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

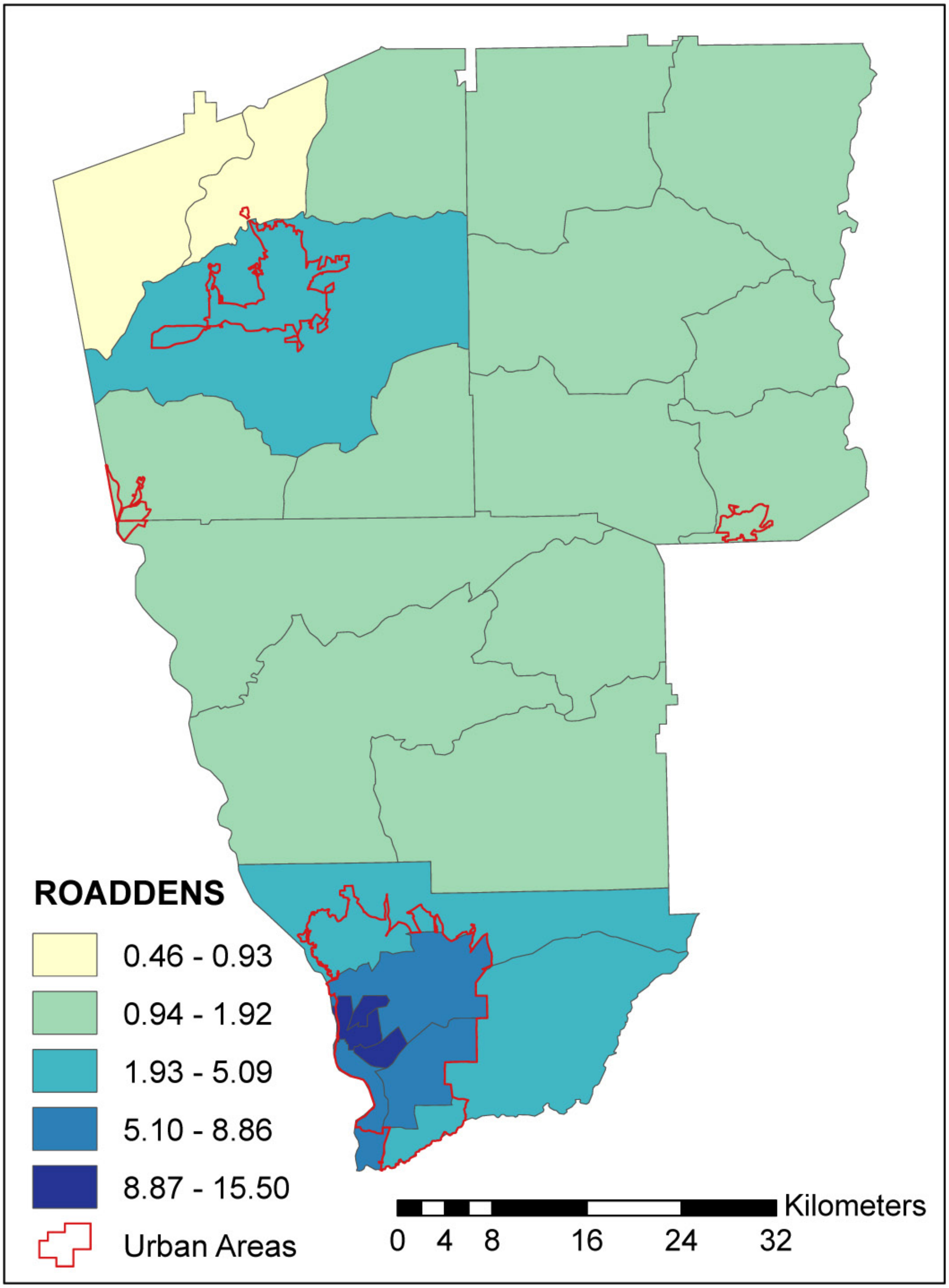

Figure 5.5 Road density (length of road in km/km^2) in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

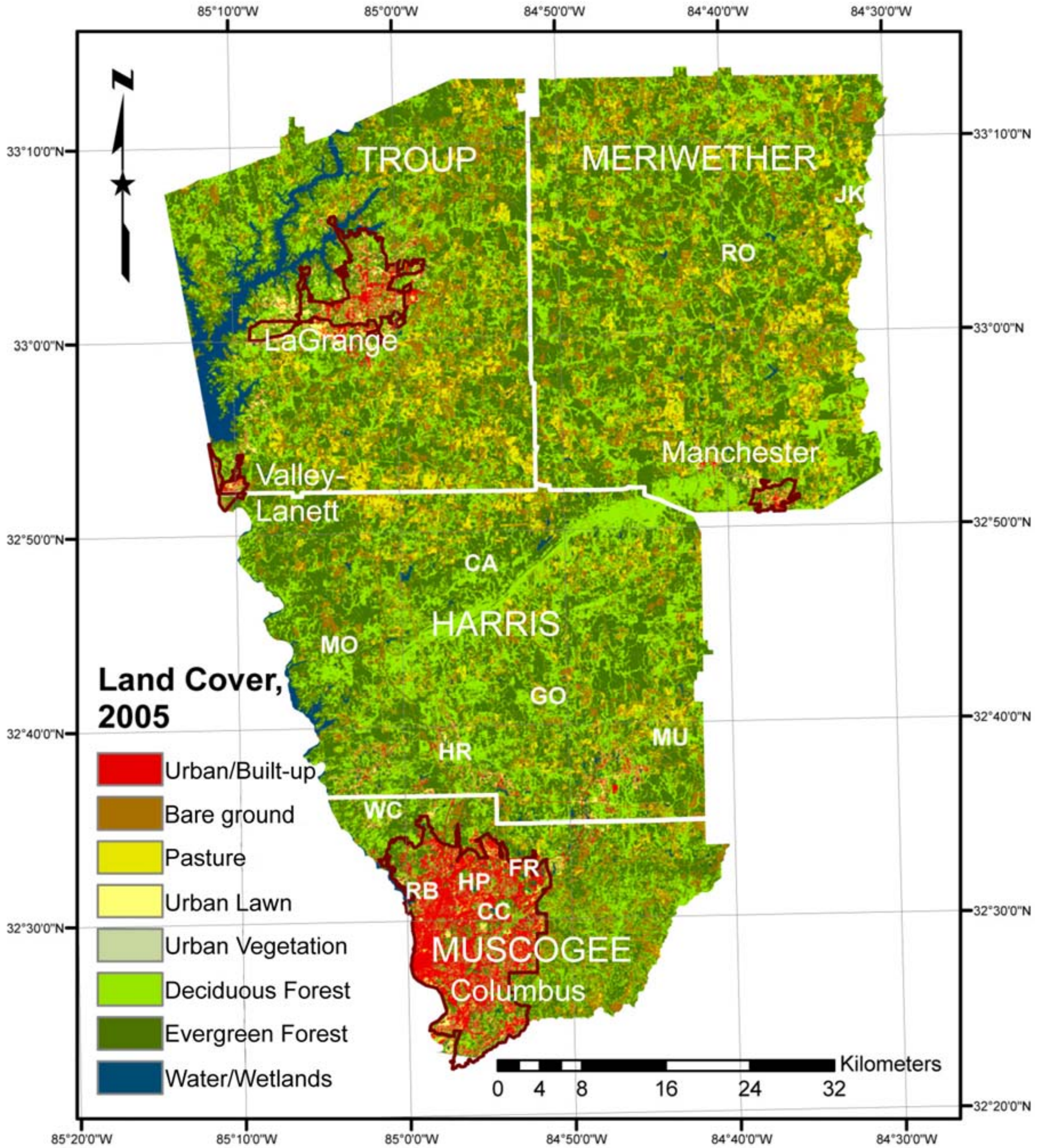

Figure 5.6 Land-cover classification of West Georgia for 2005 showing locations of the study sites. Source: Diane M. Styers, 2008.

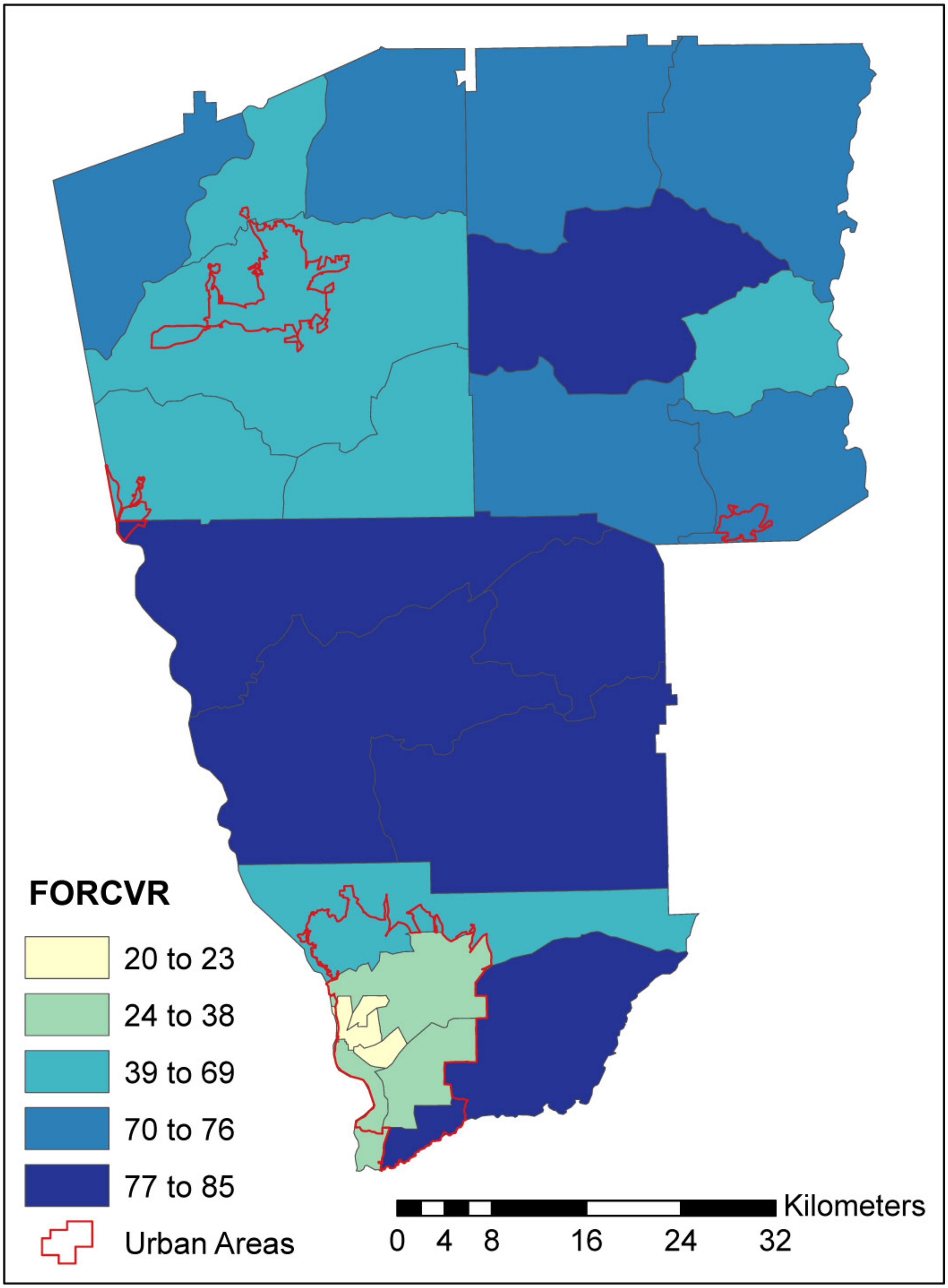

Figure 5.7 Percentage of forest land-cover in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

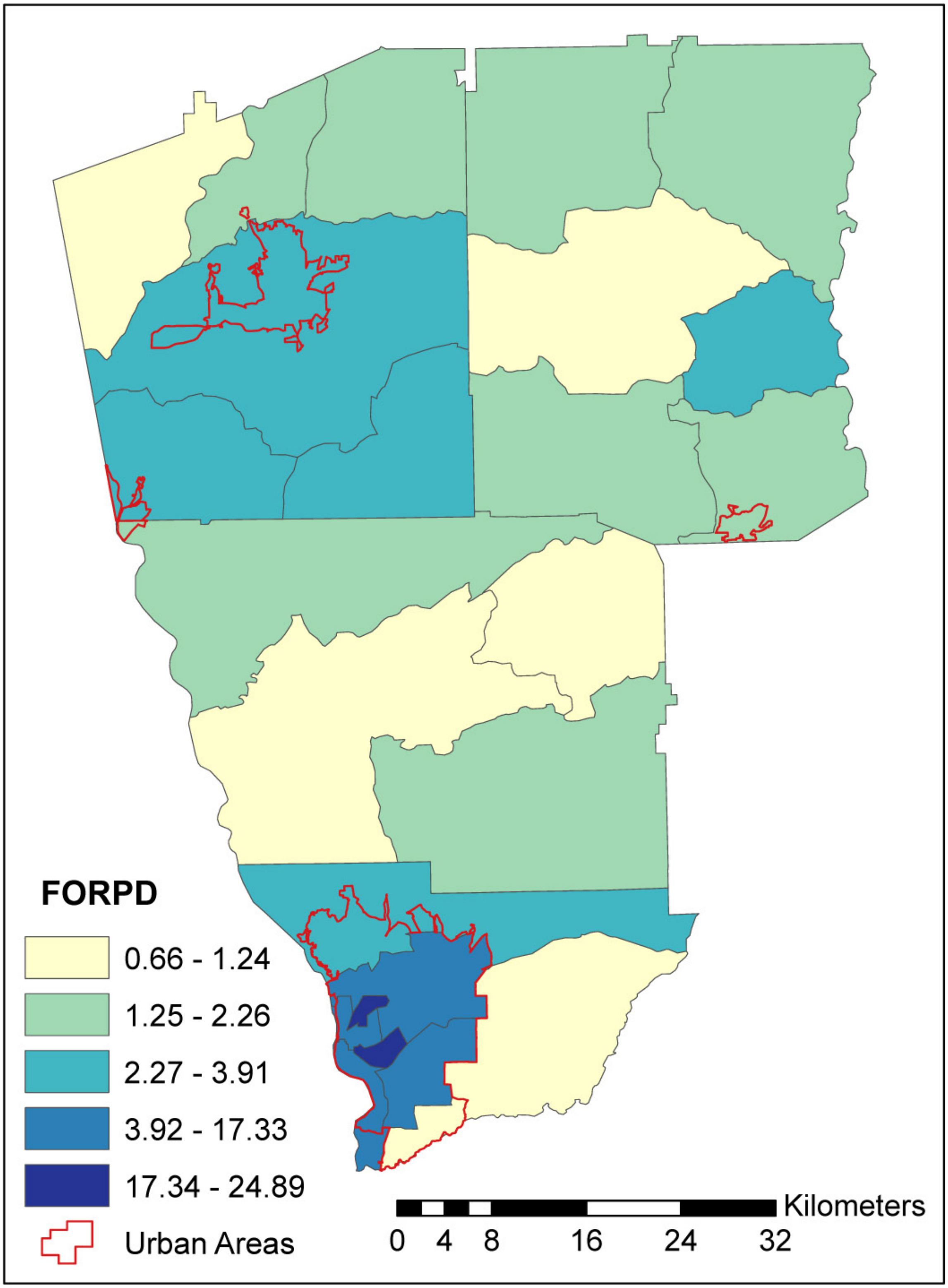

Figure 5.8 Forest patch density (number of forest patches/100 ha) in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

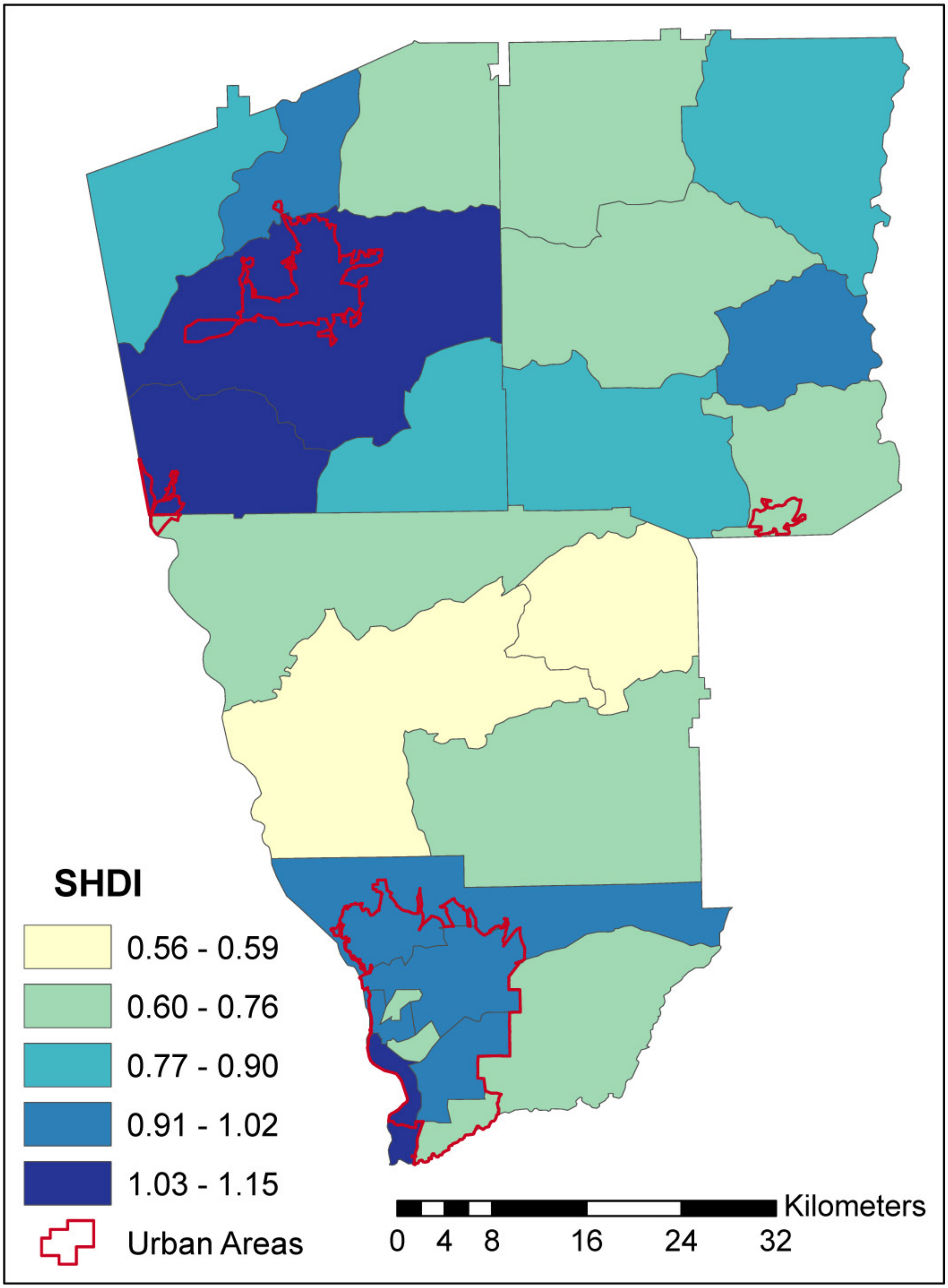

Figure 5.9 Landscape Shannon's diversity index (ranging from 0-1) in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

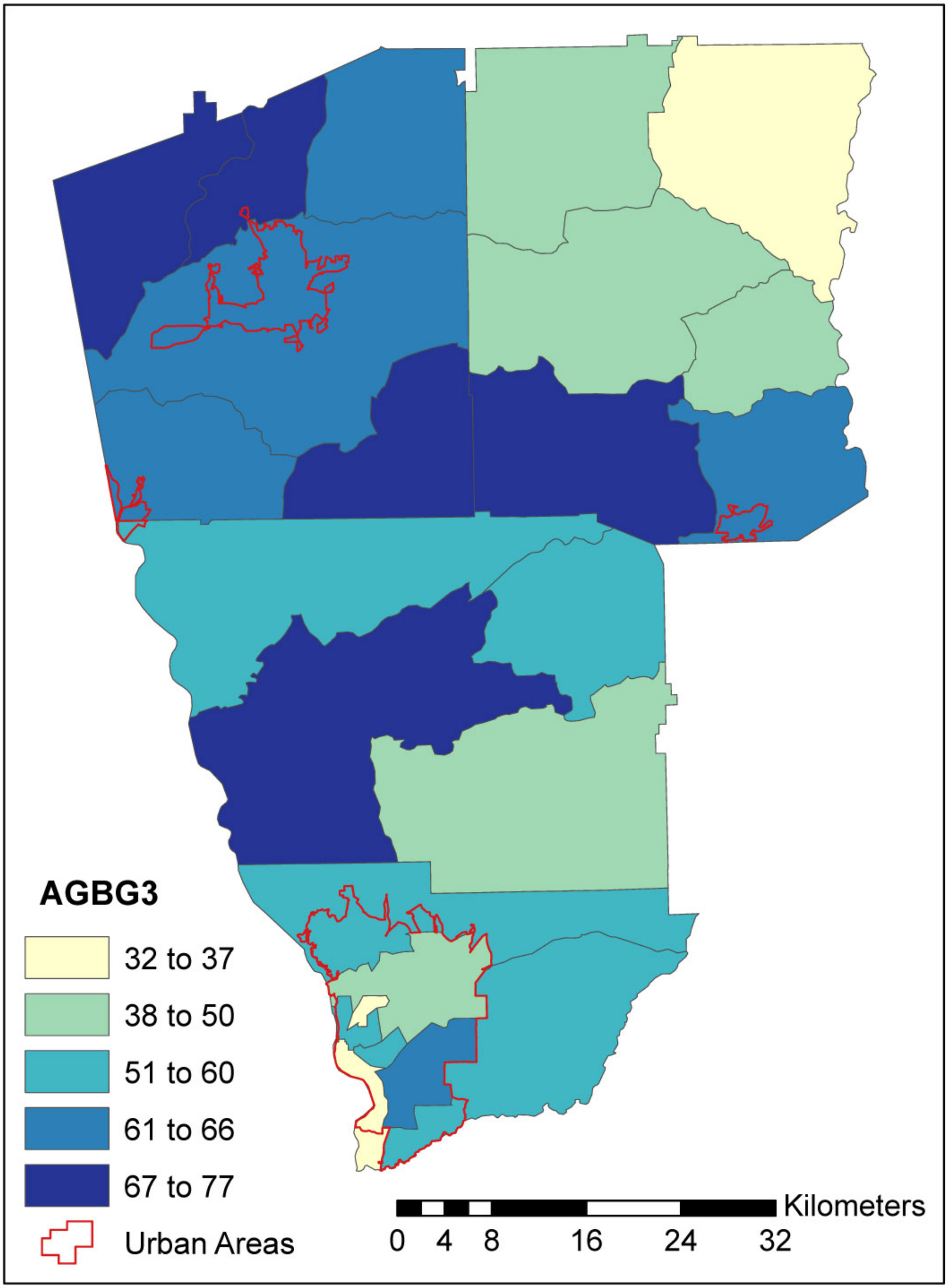

Figure 5.10 Percentage of agriculture/bare ground on slopes >3% in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

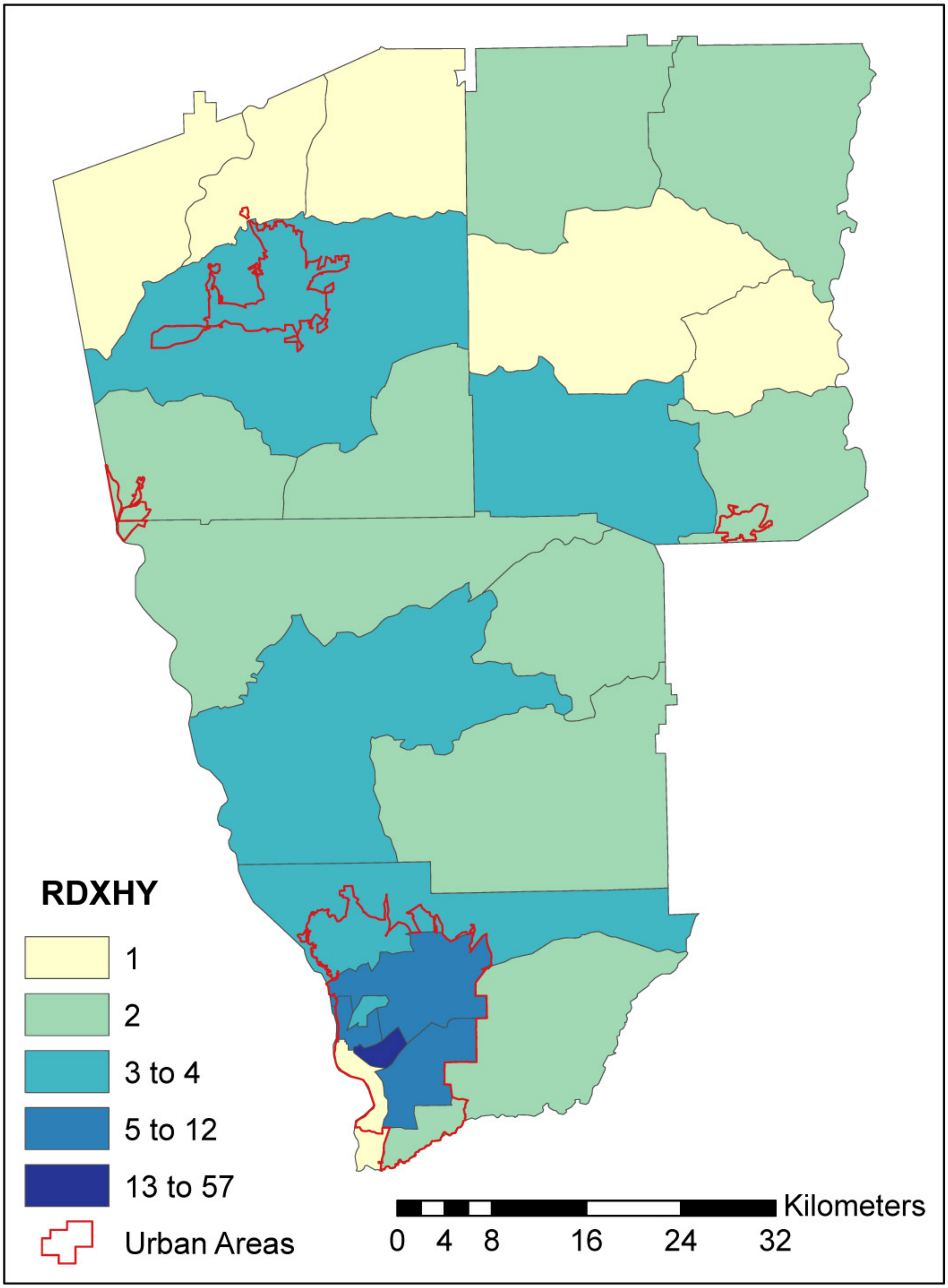

Figure 5.11 Percentage of streamlength within 30 m of a road (relative to total streamlength) in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

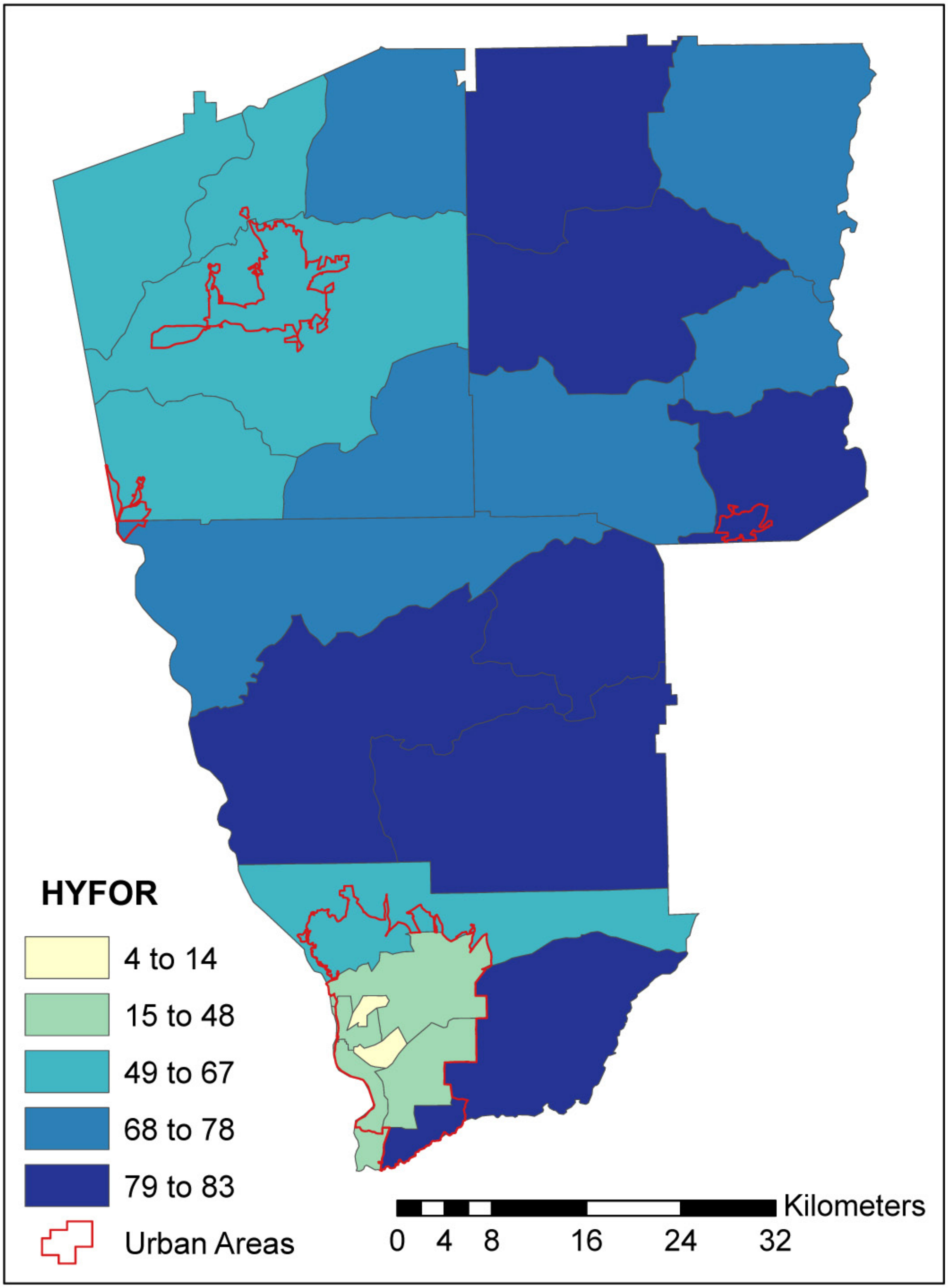

Figure 5.12 Percentage of streamlength with adjacent forest land-cover in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

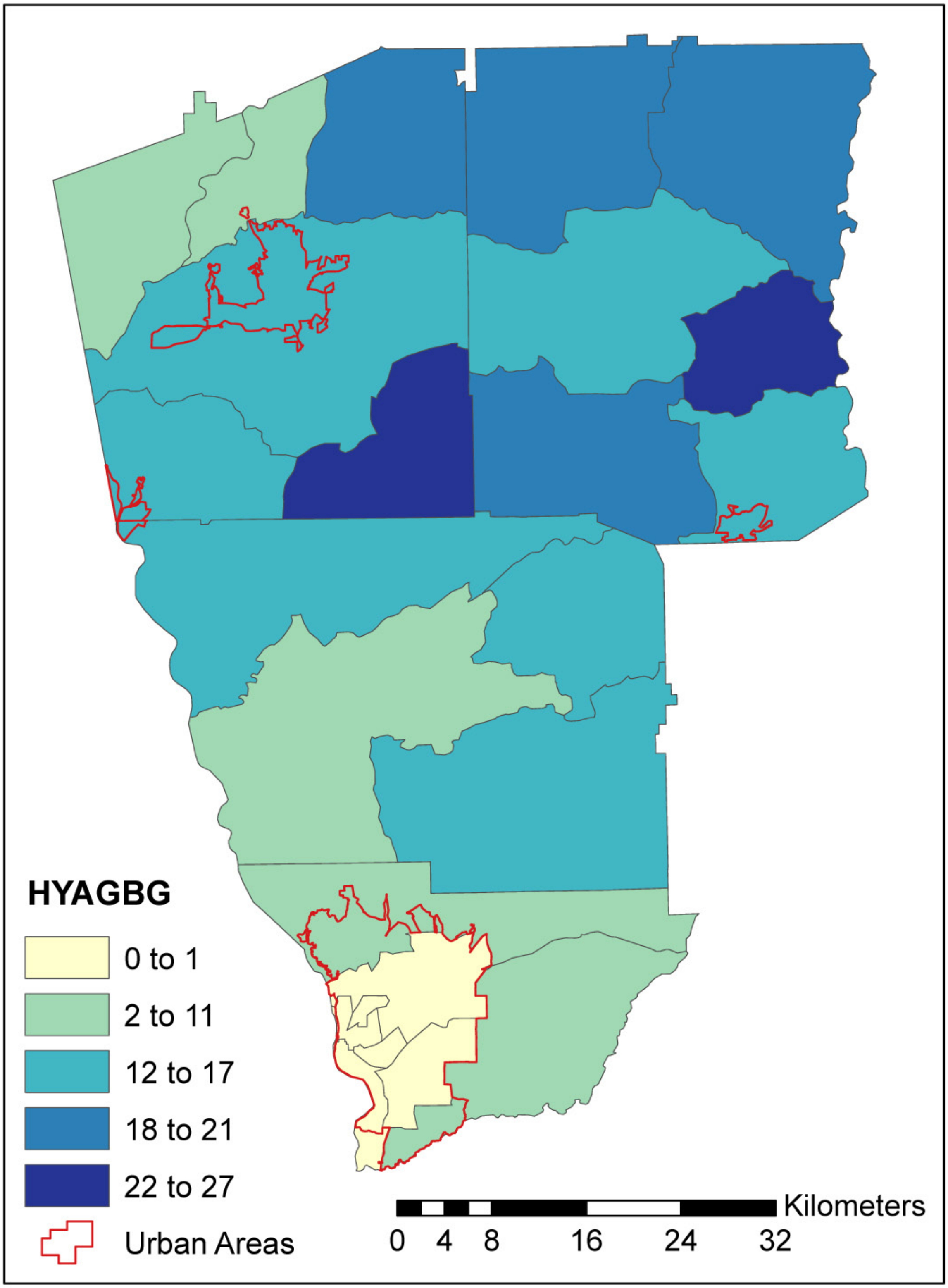

Figure 5.13 Percentage of streamlength with adjacent agriculture/bare ground in West Georgia by census county subdivision. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

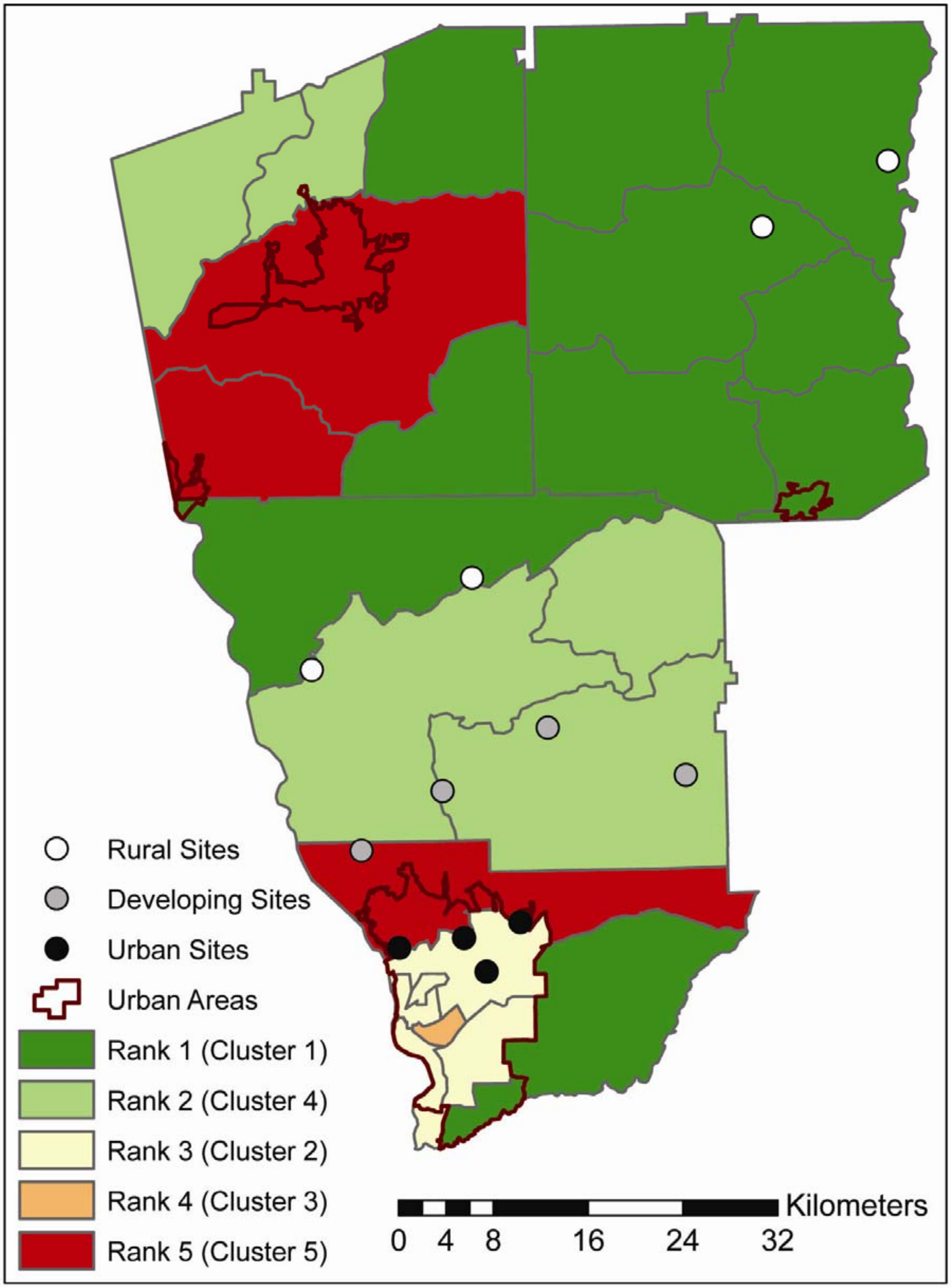

Figure 5.14 Clusters ranked by relative cumulative environmental impact score (RCEI) for West Georgia. Color scheme courtesy of Color Brewer©. Source: Diane M. Styers, 2008.

Table 5.1 Census county subdivision (CCS) values for each of the 10 landscape ecological indicators for the West Georgia region.

COSUB	LANDUSE	POPDENS	POPCHG	RDDENS	RDXHY	AGBG3	HYAGBG	HYFOR	FORCVR	FORPD	SHDI
mu3	urban	659	-4%	8.73	1%	32%	1%	28%	30%	11.37	1.12
mu4	urban	812	30%	7.83	9%	44%	0%	46%	37%	13.24	1.01
mu5	urban	1191	-14%	13.48	12%	54%	0%	32%	23%	17.33	0.93
mu6	urban	1279	0%	8.86	12%	66%	1%	48%	38%	15.57	0.95
mu7	urban	1583	-18%	12.27	57%	60%	0%	14%	21%	24.89	0.71
mu8	urban	2029	-1%	15.50	4%	37%	0%	4%	20%	20.69	0.69
ha2	developing	18	30%	1.69	2%	57%	15%	83%	84%	0.94	0.56
ha3	developing	18	37%	1.73	3%	70%	9%	83%	85%	0.66	0.59
ha4	developing	27	43%	1.62	2%	43%	15%	80%	78%	1.73	0.76
mu2	developing	179	-7%	3.19	4%	55%	11%	67%	69%	3.91	1.02
tr1	developing	12	12%	0.93	1%	76%	7%	64%	74%	0.85	0.79
tr2	developing	6	50%	0.46	1%	77%	7%	56%	68%	1.44	0.98
tr4	developing	293	4%	5.09	3%	62%	14%	60%	63%	2.83	1.15
tr5	developing	42	2%	1.92	2%	66%	16%	64%	63%	2.43	1.12
ha1	rural	14	15%	1.34	2%	56%	13%	77%	79%	1.46	0.71
me1	rural	18	13%	1.46	2%	49%	19%	81%	75%	1.67	0.74
me2	rural	10	4%	1.47	2%	32%	18%	77%	71%	2.26	0.82
me3	rural	11	-3%	1.27	1%	50%	15%	83%	79%	1.24	0.67
me4	rural	23	-6%	1.56	1%	41%	23%	73%	63%	2.49	0.96
me5	rural	14	-6%	1.44	2%	62%	17%	80%	76%	1.71	0.76
me6	rural	41	0%	1.85	3%	71%	21%	73%	73%	2.26	0.86
mu1	rural	179	-5%	3.19	2%	58%	9%	83%	78%	1.15	0.68
tr3	rural	30	-2%	1.38	1%	66%	21%	78%	74%	1.94	0.75
tr6	rural	15	17%	1.28	2%	69%	27%	72%	65%	2.84	0.90

Note:

[1] Mu1-8 = Muscogee County CCSs; Ha1-4 = Harris County CCSs; Me1-6 = Meriwether County CCSs; Tr1-6 = Troup County CCSs.

Table 5.2 Area and percentages of land-cover types in West Georgia for 2005.

Class	**Area (ha)**	**Cover**
Urban	16618	4%
Bareground	59240	12%
Pasture	26192	6%
Urban Grass	5729	1%
Urban Vegetation	3266	1%
Deciduous	140318	31%
Evergreen	186182	41%
Water	17117	4%
Total	454662	100%

Table 5.3 Cluster mean values for 10 landscape ecological indicator variables and corresponding relative cumulative environmental impact scores.

CLUSTER	POPDENS*	POPCHG	RDDENS	RDXHY	AGBG3	HYAGBG	HYFOR	FORCVR	FORPD	SHDI*	RCEI	RANK
1	36	3%	1.62	2%	55%	18%	78%	73%	1.90	0.78	2	1
2	1194	2%	10.88	8%	46%	1%	31%	29%	15.64	0.94	6 **	3
3	1583	-18%	12.27	57%	60%	0%	14%	21%	24.89	0.71	6 **	4
4	16	34%	1.28	2%	65%	11%	73%	78%	1.12	0.74	3	2
5	171	0%	3.40	3%	61%	14%	64%	65%	3.05	1.10	7	5

Notes:

[1] * = Not included in RCEI scoring (see discussion for details).

[2] ** = Tie broken using actual variable values.

3 Values in red are the three greatest values for each variable used to calculate RCEI score totals.

Table 5.4 Standard ANOVA values and means (±SE) for forest condition variables collected in West Georgia (from Chapter 2).

	Standard ANOVA		**Tukey-Kramer HSD Comparisons**					
Variable	**Mean Square**	**Prob > F**	**Urban (n=4)**		**Developing (n=4)**		**Rural (n=4)**	
Total number of tree species	11.19	0.04	4.67 ± 0.54	(a)	8.00 ± 1.03	(b)	6.58 ± 0.58	(a,b)
% Insect incidence for all trees	4.70	0.48	2.50 ± 1.81		0.33 ± 0.33		1.33 ± 1.03	
% Disease incidence for all trees	14.51	0.59	4.25 ± 1.75		4.00 ± 4.00		0.83 ± 0.63	
% Mechanical damage incidence for all trees	279.90	0.09	30.25 ± 2.96	(a)	19.25 ± 3.18	(a,b)	13.83 ± 6.96	(b)
% Insect + Disease + Mech damage for all trees	452.34	0.04	37.00 ± 3.82	(a)	23.58 ± 3.91	(a,b)	16.00 ± 6.53	(b)
% Trees with lichens	1320.08	0.22	51.83 ± 21.46	(a)	74.08 ± 11.67	(a,b)	87.83 ± 5.78	(b)
Mean number of lichen species per tree	6.23	0.14	0.75 ± 0.43	(a)	2.50 ± 1.04	(b)	3.17 ± 0.90	(b)
Mean lichen abundance rank for all hardwoods	1.44	0.13	0.42 ± 0.16	(a)	1.25 ± 0.48	(b)	1.58 ± 0.42	(b)
Mean number of crustose species on water oaks	0.90	0.68	4.61 ± 0.85		4.15 ± 0.66		5.09 ± 0.70	
Mean number of foliose species on water oaks	1.19	0.24	1.29 ± 0.53	(a,b)	0.68 ± 0.30	(a)	1.77 ± 0.39	(b)
Crustose:Foliose ratio (on water oaks)	131.15	0.10	9.72 ± 3.65		15.95 ± 4.03		4.52 ± 1.83	
Mean lichen abundance rank for water oaks	91.97	0.57	26.15 ± 8.15		17.50 ± 4.00		25.42 ± 5.66	
Mean dominance of crustose over foliose	0.16	0.21	1.23 ± 0.18		1.04 ± 0.04		1.44 ± 0.17	

Notes:

[1] SE = standard error of the mean.

[2] n = number of study sites sampled.

[3] Mean values in a row with different letters (variables in bold) are significantly different ($p < 0.05$) based on Tukey-adjusted least squares means.

6. SUMMARY AND CONCLUSIONS

Urbanization and related air pollution exposure are linked to forest ecosystem condition in urban and rapidly developing areas of West Georgia, as suggested from analyses of indicators of ecosystem health at both local and regional scales.

6.1 Forest Stand Structure and Condition

- Of the forest stand structure variables measured for mature trees, only the number of hardwoods and tree species richness were different between land-use types, and the lowest values observed of both were in urban areas.
- None of the canopy, understory, or ground cover vegetation variables measured differed between land-use types.
- Mechanical injury to mature trees was greatest in urban areas.
- The percentage of trees with lichens, lichen abundance, and lichen species richness were all greatest in rural and least in urban areas.
- Housing density, forest edge, upper canopy height, tree dbh, and combined injury from insects, disease, and mechanical injury were the variables that were linked to lichen incidence, as evidenced from regression models.

- Percent pasture land-cover, distance to nearest road, and percent canopy cover were the variables linked to lichen species richness, based on regression models.

6.2 Forest Elemental Concentrations

- Of the variables measured, lichens collected *in situ* appeared to be the best indicator of urbanization regarding differences in elemental concentrations among land-use types, and Cu, N, Pb, S, and Zn concentrations were all greatest at urban sites.
- Lichen transplant data suggest *P. perforatum* had the greatest elemental concentrations measured except Pb, but no differences were observed between land-use types.
- Temporal (seasonal) differences in elemental concentrations were observed in all lichen tissues analyzed.
- Only N concentrations in soil differed between land-use types, with urban areas having the greatest values measured.
- No discernable trends were observed regarding elemental concentrations in tree core data.

6.3 Urbanization *vs.* Biological Correlations

- Urbanized land area in West Georgia increased from 2% in 2001 to 4% in 2005, while deciduous forest land-cover showed no change (31%) and pasture land-cover decreased from 9% to 6% over the four-year period.
- Land-cover characterization classes and forest fragmentation metrics were all significantly correlated to population, housing, and road densities.
- There were significant inverse correlations between forest land-cover and population, housing, and road densities; tree species richness and forest patch density; urban land-cover and lichen species richness; and lichen incidence and forest perimeter-area fractal dimension.
- Overall, there were 168 significant correlations ($p \leq 0.10$) between the 17 urbanization and the 30 biological variables measured.

6.4 Regional Indicators of Ecosystem Health

- Rapidly developing areas in northern Muscogee County, just outside the Columbus city limits, and in central and western Troup County, which includes the City of LaGrange, were the most environmentally impacted areas in West Georgia study area. These areas were characterized by moderate population and road densities, low population growth between 1990 and 2000, moderate overall forest cover, riparian forest cover, forest patch density, and amount of roads near streams, and had high values for agriculture/bare ground located on slopes >3% and streams with adjacent agriculture/bare ground land-cover.

- Highly urbanized areas in the city center of Columbus were impacted nearly as greatly as those in “developing areas of West Georgia. These areas are characterized by high population and road densities, negative population growth between 1990 to 2000, low overall forest cover and riparian forest cover, and high forest patch density, agriculture/bare ground located on slopes >3%, and amount of roads near streams.
- Regional landscape indicator variables measured supported field-based forest condition results.
- Rural areas that had the best forest condition values also had the lowest environmental impact scores. Urban areas, in contrast, had the poorest forest condition values and moderate to high environmental impact scores.

6.5 Synthesis

Overall, there are distinct aspects of urbanization (land-use change, etc.) and potential air pollution exposure that appear to be related to forest ecosystem conditions in urban and rapidly developing areas of West Georgia. Although structural differences were not observed between forest stands in urban *vs.* rural areas, (with the exception of tree species richness), differences in forest condition were noted. This finding was exhibited by indicators of ecosystem health at both local and regional scales. Of all the plot-level variables measured, lichens appeared to be the bioindicator most sensitive to land-use change and/or air pollution effects. Lichen incidence, abundance, and species richness were all greatest within rural forests and least in urban forests in West Georgia. Further, urban environments consistently had higher concentrations of Cu, N, Pb, S, and Zn in lichen tissue than either rural or developing land-use types. Concentrations of N, S, and all metals (except Pb) were greatest in tissues of *P. perforatum vs. U. strigosa* lichens. Although spatial and temporal differences in lichen incidence, abundance, species richness, and elemental concentrations in tissues were noted, the exact mechanism(s) behind these changes has yet to be determined.

Attempts to determine correlations between various aspects of urbanization and lichen communities were made and results suggest that several physical (e.g., temperature, moisture, light, wind) and chemical (e.g., increases in potential air pollutants) factors may be involved. Many significant correlations were observed between urbanization and biological variables. The most highly significant were those related to forest edge effects. Forest edges are generally a result of development associated with urbanization and "open" forest boundaries are also possibly exposed to higher concentrations of air pollutants, especially those near roadways. It has been previously reported in other studies that lichens can be more abundant and diverse along forest edges due to the unique microclimate in these areas (e.g., temperature, moisture, light, wind). However, greater pollution exposure to lichen edge communities or to those within small urban forest patches (with little to no "interior") may be related to the decreases in lichen incidence, abundance, and species richness observed in urban areas. It is possible that edge effects, air pollution exposure, and/or other unmeasured variables are linked to lichen community composition and species richness in West Georgia.

However, this study was correlative in nature and thus cause and effect relationships cannot be proven.

"Urbanization" is a complex assemblage of processes that operates at many different scales. To validate findings observed at the plot-level, some correlation to surrounding land-uses and landscape characteristics is needed. Based on a regional landscape ecological assessment of West Georgia it appears that, overall, the field observations are supported. Rural areas that had the best forest condition values also had the lowest environmental impact scores. Urban areas, in contrast, had the poorest forest condition values and moderate to high environmental impact scores. The major differences between the local *vs.* regional ecosystem assessments resided within the developing land-use types. Based on plot-level data, the developing areas measured in West Georgia were generally similar to rural areas for most variables measured. In a few cases, however, these areas more closely resembled urban land-use types. The regional ecological assessment appeared to reflect the similarities to urban areas more so than the field-based assessment, as these areas had higher environmental impact scores than much of the urban areas surrounding Columbus. It is possible that the indicators selected for the broad-scale assessment were appropriate for detecting early stress on an ecosystem, such that conditions favorable to high environmental impacts are noticeable prior to individual species or forest stand responses. However, additional research needs to be conducted before confirming this hypothesis.

6.6 Future Directions

This research demonstrated differences in forest health along an urban-to-rural gradient in West Georgia that are evident at the forest-stand and regional scales. The most significant plot-level information was obtained from the lichen studies conducted as part of this project. To gain a better understanding about the mechanisms driving lichen species composition and richness in urban *vs.* rural environments of West Georgia, five directions for future research are suggested.

First, lichen taxonomic surveys and controlled studies are needed to obtain more information about lichen community structure and to determine if species present in urban *vs.* rural areas are a result of different air quality environments (i.e., are the species present in urban areas pollution-tolerant nitrophytic species). Second, preliminary studies of lichen tissue elemental concentrations suggest differences between land-use types. Analysis of actual accumulation and uptake of N, S, and metals could provide a better indication of the role of lichens in forest biogeochemistry cycles. It would be possible to conduct lichen transplant studies in conjunction with tree physiology, soil dynamics in the lower horizons, and/or decomposition studies. Third, it is suggested that more fragmentation analyses, such as patch dynamics studies (e.g., size, shape, context), be conducted to better determine edge effects on lichen communities in urban *vs.* rural areas. Fourth, more work with pollution monitoring and facility emissions data (e.g., using radioisotopic labeled markers unique to specific anthropogenic pollutant emissions) would facilitate studies of exposure-response relationships in plants and regional transport modeling. Lastly, finer-scale (e.g., 1 m resolution or finer) satellite data for the entire West Georgia study area could improve regional ecosystem assessments and enhance their predictive capabilities. In all cases, more sampling sites need to be placed in “developing” areas to gain a clearer picture of the urban-rural interface zone in West Georgia.