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Scale matters: Indicators of ecological health along the urban–rural interface near Columbus, Georgia

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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 over a larger area. Therefore, our main objective 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 near the city of Columbus. 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 all streams with roads within 30 m, proportion of area that has agriculture on slopes >3%, proportion of all streams with adjacent agriculture, and proportion of all streams with adjacent forest cover. Cluster analysis was used to combine these variables into different groups, and resulting cluster means were used to rank regional areas according to degree of environmental impact. To assess the spatial accuracy of this tool results were compared to those obtained from a separate plot-level field-based forest condition study. Results derived using the landscape ecological assessment tool suggest that rural areas were the least environmentally impacted (or most healthy) of all areas in West Georgia, and support the findings from the field study. Results for developing areas were mixed between the two different studies and may be attributed to differences in scale. Overall, it appears that this tool is useful for broad generalizations about a given landscape, but is not detailed enough for site-specific management goals due to its inherent coarse spatial resolution (30 m × 30 m). However, these site-specific goals may be achieved using higher resolution (1 m × 1 m) satellite imagery and warrants further research. In any case, this tool is a useful asset for anyone needing a rapid diagnosis of ecosystem health in an inexpensive and timely manner.

1. Introduction

Urbanization effects on natural resources extend well beyond the boundaries of urbanized 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 monitoring research has used ground-based observations over small spatial areas and short time frames (Pettorelli et al., 2005). However, 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). These indicators can be either biotic (% forest cover, forest patch density, etc.) or abiotic (% urban cover, road density, etc.). Landscape ecological assessments that incorporate these types of satellite-derived data can provide information about 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, and much work has

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been accomplished through the integration of remotely sensed imagery and fine-scale biological datasets. Of particular interest is the research 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, using largely public-available datasets and ecologically relevant indicators of ecosystem health at broad spatial scales. They (Jones et al., 1997) 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.

Our overall goal was to develop a predictive ecological assessment tool utilizing census, land-cover, and forest fragmentation data in a geographic information systems (GIS) overlay analysis to determine landscape indicators of ecosystem health in a rapidly developing area of West Georgia (the Columbus metropolitan and surrounding area). Such information from this case study will provide a baseline inventory for landscape ecological indicators in the West Georgia region that can be tracked into the future to observe changes in ecosystem health as urban development continues. Our specific objectives were as follows: (1) determining which landscape indicators can be measured at this regional scale, (2) ascertaining if the methods developed by Jones et al. (1997) work with this smaller multi-county area, and (3) determining which areas of West Georgia display environmental impacts typically associated with urban development. These broad-scale environmental assessments can be used to enhance our understanding of information obtained from field-based ecological research, and to determine what features (biotic and abiotic) of the environment can be measured remotely as reliable indicators of ecological processes.

2. Materials and methods

2.1. Study area

The study area (hereafter referred to as West Georgia; Fig. 1) comprises Muscogee (location of Columbus urbanized area), Harris, Meriwether, and Troup counties in the west-central Georgia Piedmont, extending approximately from latitude 32°20′00″ and 33°15′00″ North, to longitude 84°30′00″ and 85°15′00″ West (Fig. 1). The study 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 to 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 more specific detail the reader is referred to Styers and Chappelka (2009).

2.2. 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. This information is 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 utilized because there were a similar number of census county subdivisions in most of the counties used (except Muscogee), that would help 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 (Styers, 2008). 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, a GIS 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.

2.3. Environmental indicator metrics

Determining the current state of health of an ecosystem is necessary to establish a detailed ecosystem management program for a defined area over the short and long term. Therefore, some definition of ecosystem health is needed, even if loosely defined, in order to set specific goals and assess the effectiveness of the management program. Within the context of ecosystem management, 'ecosystem health' can be defined as, "a condition wherein a forest has the capacity across the landscape for renewal, for recovery from a wide range of disturbances, and for retention of its ecological resiliency, while meeting current and future needs of people for desired levels of values, uses, products, and services" (Twery and Gottschalk, 1996).

Based on the results from a separate field-study conducted within the same area of West Georgia (Styers, 2008), five general components of ecosystem health were targeted for analysis in this landscape-scale assessment: forests, air, water, soil, and demographic/landscape changes. Thus, for the development of this tool, an attempt was made to select indicator variables that measure different aspects of the environmental condition of these five general components at the landscape scale, each of which are typically affected by urban development. Using the methods developed by Jones et al. (1997) as a guide, we selected 10 landscape ecological indicators to analyze the West Georgia region, including: 'population density', 'population change', 'road density', 'percent forest land-cover', 'forest patch density', 'landscape Shannon's Diversity Index (SHDI)', 'proportion of all streams that have roads within 30 m', 'proportion of area that has agriculture/bare ground on slopes >3%', 'proportion of all streams with adjacent agriculture/bare ground', and 'proportion of all streams with adjacent forest cover'. Data for these 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

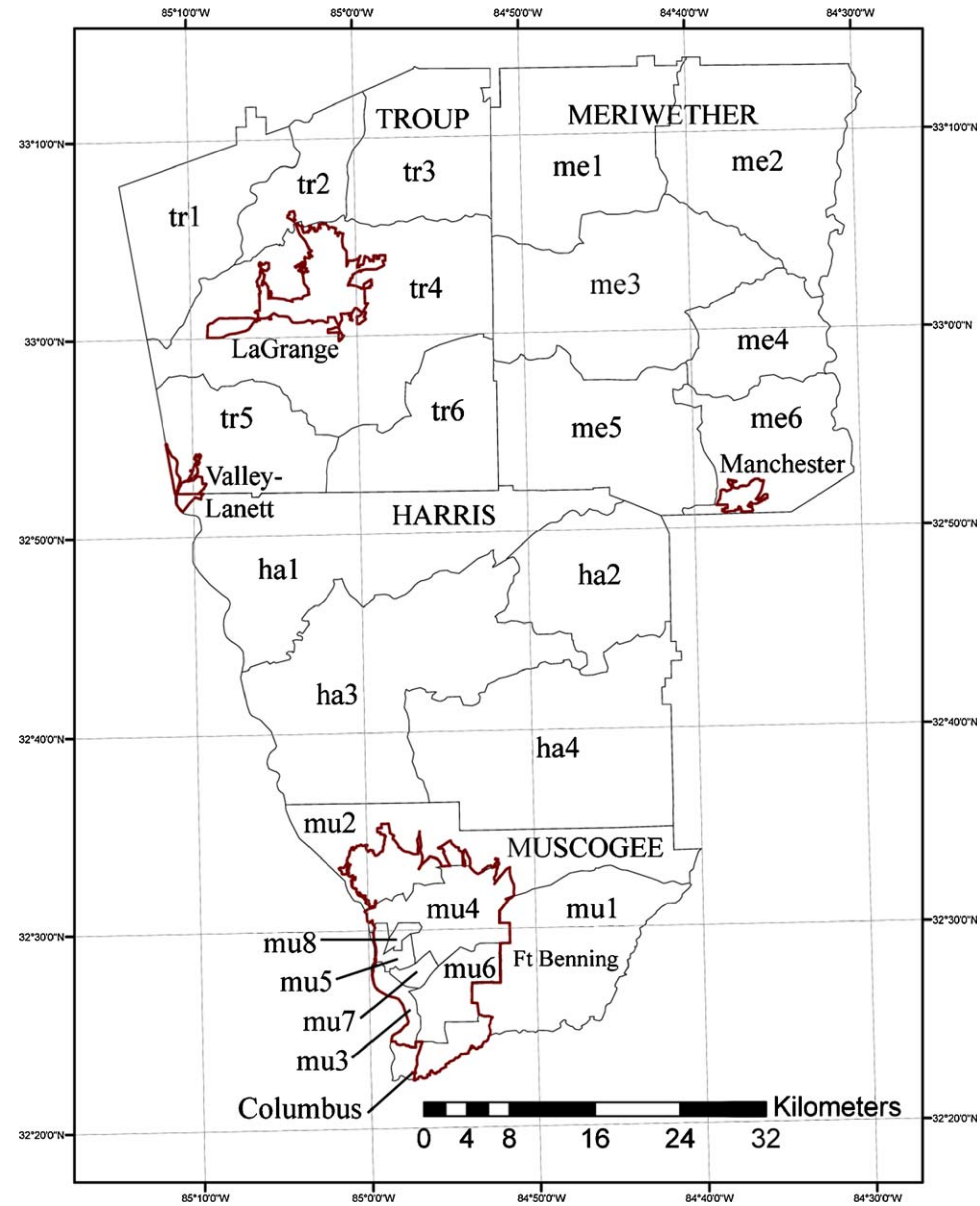

Fig. 1. Map of study area showing cities, counties, and census county subdivisions in West Georgia. *Note*: 1 Mu1-8 = Muscogee County census county subdivisions (CCSs); Ha1-4 = Harris County CCSs; Me1-6 = Meriwether County CCSs; Tr1-6 = Troup County CCSs.

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).

2.4. Census demographic and TIGER® data

Population data 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. Population data for 1990 were also gathered to calculate the 'population change from 1990 to 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).

2.5. 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 2004–2005 (Fig. 2; Styers, 2008). The images were selected to provide leaf-on (August and September) and leaf-off (December) images to improve class assignments. These Landsat images (30 m $\times$ 30 m resolution) 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 that all were projected to the same coordinate system (UTM Zone 16N; datum NAD 83; spheroid WGS 84) and aligned properly for classification and GIS overlay analysis. The final classification scheme for the entire four-county scene contained

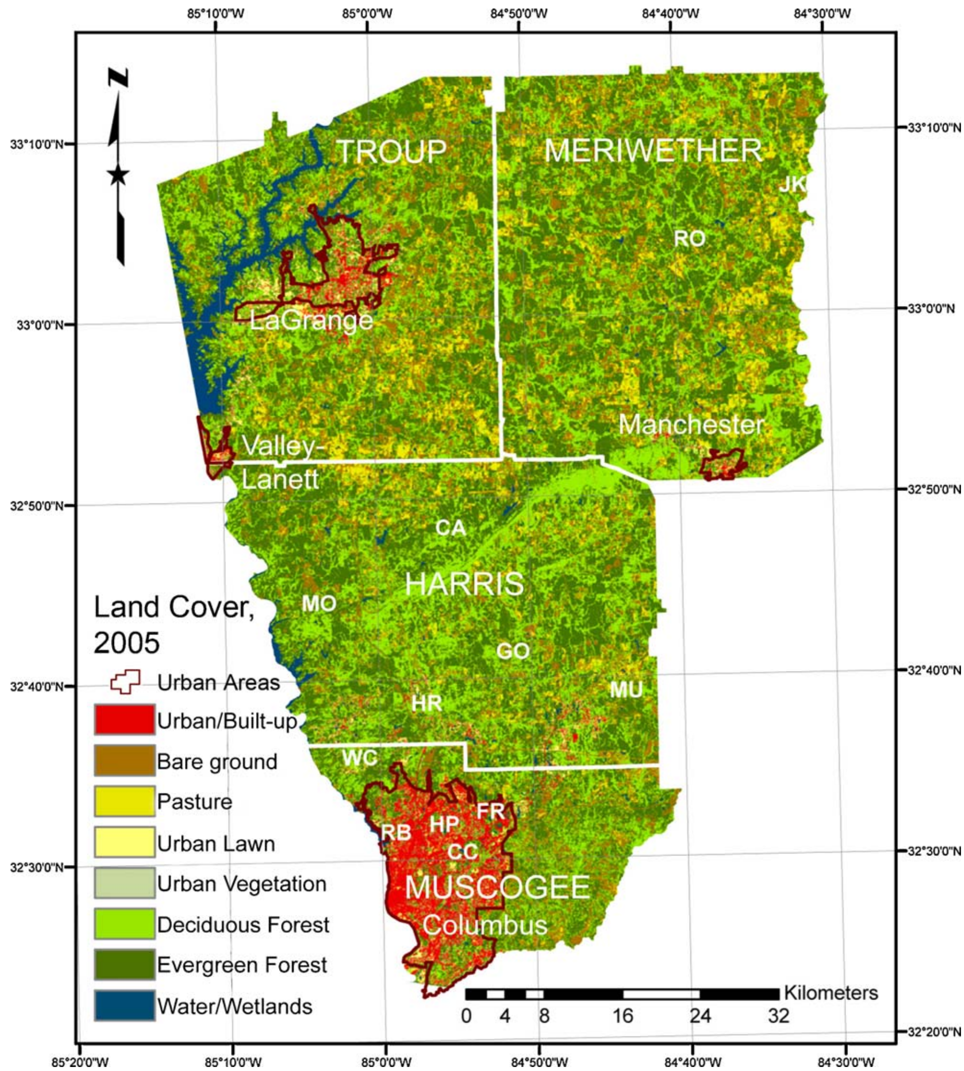

Fig. 2. Land-cover classification of West Georgia for 2005.

the following eight land-cover characterization classes: urban/built-up, bare ground, pasture, urban lawn, urban vegetation, deciduous forest, evergreen forest, and water/wetlands (Styers, 2008). 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. These categories were recoded from the original classification to reflect a more general cover type (Styers, 2008). 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. 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 using a combination of fieldwork and a high-resolution 1-m color Digital Ortho Quarter Quads (DOQQs) for reference (date of imagery February 1999; accessed USGS Seamless Data Server 13 June 2006), along with the Landsat TM images, to verify the classification of thirty randomly generated points (Jensen, 2005). The overall classification accuracy for the West Georgia land-cover classification was 93% (Kappa = 0.9080). For more information on the classification process, the reader is referred to Styers (2008).

2.6. Fragmentation analysis

Once the 2004–2005 land-cover classification for the West Georgia region was produced, it was used as input into Fragstats to summarize landscape indicator values following procedures described by McGarigal et al. (2002). Many landscape metrics can be calculated using Fragstats; however, our 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' and 'landscape SHDI' metrics were calculated for each of the 24 census county subdivisions. Forest patch density 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 patch number since it allows comparison of areas of different sizes, such as with variably sized census county subdivisions. Landscape 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. The "patch types" in the landscape SHDI 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.

2.7. GIS overlay analysis

A 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 in a GIS resulting in the 'proportion of roads crossing streams' metric. The percentage (road length/streamlength) 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, each of 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 two classes: 1 = 0–3% and 2 = >3%. 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 used in the analysis. 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 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.

2.8. Landscape indicator data analysis

Since cluster analysis is sensitive to broad ranges in data values, each of the landscape indicator variable values were standardized using the mean and standard deviation of the original value (Jones et al., 1997). 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.

Cluster analysis was performed to identify groups of census county subdivisions with similar ecological indicator characteristics to identify areas of the study region having adverse environmental impact. Several cluster combinations were examined and the one that produced the most distinct separation of census county subdivisions was selected as the final output. The 10 metrics described above were used as landscape indicators in the cluster analysis. Spearman's rank correlations suggested multicollinearity between some of the potential predictor variables which 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 10 variables were included, however, because they measured different aspects of the same environment, namely different characteristics of water, air, and soil quality (Jones et al., 1997). Because 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. 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 impact score assignments.

A cluster analysis was performed using each of the landscape indicator variables to examine which areas of West Georgia were distinctly different from one another with regards to environmental impact. The 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 ranked from low to high, based on whether the indicator was an ecologically positive or negative attribute. For example, 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 to 2000', 'road density', 'forest patch density', '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 three highest scores for the negative indicators and the three lowest scores for the positive indicators were noted. Groups of census county subdivisions were ranked in order of low to high RCEI scores using variable means for census county subdivisions within each of the clusters, with the greatest RCEI (most environmentally impacted areas) receiving the lowest (poorest) rank. The resulting ranks were used 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 a GIS (Environmental Systems Research Institute, 2005).

3. Results

3.1. Population density, population change, and road density

Population density values from 2000 varied greatly in West Georgia from urban to rural areas. Population density in urban census county subdivisions (Fig. 1) ranged from 659 to 2029 people/km^2 (Table 1). The majority of individuals 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 to 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. By contrast, rural subdivisions had very low population densities, from 10 to 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 and 2000 was calculated for each of the census county subdivisions in West Georgia (Table 1). Changes in urban census county subdivisions ranged from −18 to +30% during this time period. Interestingly, the values for each of the subdivisions, except for one were negative, indicating that there was an exodus from many urban areas. The one subdivision that exhibited population growth (30%), considerably above the national average of 13% (from 1990 to 2000), was in the older, north-central suburbs of Columbus. In the developing areas of West Georgia, population change between 1990 and 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

Table 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: COSUB Mu1-8 = Muscogee County census county subdivisions (CCSs); Ha1-4 = Harris County CCSs; Me1-6 = Meriwether County CCSs; Tr1-6 = Troup County CCSs; POPDENS = population density; POPCHG = population change from 1990 to 2000; RDDENS = road density; RDXHY = roads crossing streams; AGBG3 = agriculture/bare ground on slopes > 3%; HYAGBG = streams with adjacent agriculture/bare ground land-cover; HYFOR = streams with adjacent forest land-cover; FORCVR = total forest land-cover; FORPD = forest patch density; SHDI = Shannon's Landscape Diversity Index.

the north of LaGrange. Further, all subdivisions in this group had increases in population during this period except for one. 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. Rural subdivisions in West Georgia had mixed growth trends, ranging from −6 to +17% from 1990 to 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.

Road densities in 2000 for the West Georgia area did not vary as much as the population density statistics suggest (Table 1). In urban census county subdivisions, road densities ranged from 7.83 to 15.5 km of road length per area of km^2. Developing census county subdivisions had road density values between 0.46 and 5.09 km/km^2, while rural subdivisions ranged between 1.27 and 3.19 km/km^2. There were few differences in road densities in rural and developing areas in West Georgia.

3.2. Percentage of urban/built-up, bare ground, grass, and forest lands

The generalized 2004–2005 land-cover of the four-county area in West Georgia (Fig. 2 and Table 1) 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, and evergreen forest), and water/wetlands. 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). Bare ground and grass cover in urban areas of West Georgia were virtually nonexistent, with 0% bare ground and grass ranging from 0.48 to 2.22%. In contrast, bare ground in developing areas was 8–13% while in rural areas it increased in range from 12 to 21%. Similarly, grass cover in rural subdivisions ranged from 6 to 15% excluding the Fort Benning subdivision (1.24%). Pasture cover in developing areas ranged from 2 to 8%, and was mostly a mixture of animal and feed pastures, cultivated lawns, and golf courses.

3.3. Forest patch density and Shannon's Landscape Diversity Index

In the urban census county subdivisions, forest patch density ranged between 11.37 and 24.89/100 ha (Table 1). However, values in rural and developing areas were similar, ranging from 1.15 to 2.84/100 ha and 0.66–3.91/100 ha, respectively, and were much lower than urban forest patch density values.

Landscape SHDI values were between 0.69 and 1.12 (Table 1) in urban census county subdivisions. Surprisingly, landscape SHDI values were similar in rural areas (0.67–0.96). Developing subdivisions had the least and greatest overall landscape SHDI values (0.56–1.15), and this wide range demonstrates the similarity of these areas to both rural and urban land-use types.

3.4. Agriculture/bare ground on slopes >3% and streamlength with adjacent roads, agriculture/bare ground, and forest cover

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. In the urban census county subdivisions, this value ranged from 32 to 66% (Table 1). However, the total amount of bare ground, urban lawn, and pasture land-cover in urban subdivisions was also fairly low (4–14%). In developing subdivisions in West Georgia, the amount of agriculture/bare ground on slopes >3% was between 43 and 77%, which has the greatest value of any of the 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 proportion of road length within 30 m of a stream relative to the total amount of streamlength in a given area was also calculated. In urban census county subdivisions, these values ranged between 1 and 57% (Table 1). Rural and developing census

Table 2
Cluster mean values of 10 indicator variables and corresponding relative cumulative environmental impact scores.

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

Notes: POPDENS = population density; POPCHG = population change from 1990 to 2000; RDDENS = road density; RDXHY = roads crossing streams; AGBG3 = agriculture/bare ground on slopes > 3%; HYAGBG = streams with adjacent agriculture/bare ground land-cover; HYFOR = streams with adjacent forest land-cover; FORCVR = total forest land-cover; FORPD = forest patch density; SHDI = Shannon's Landscape Diversity Index. Values in bold are the three greatest values for each variable and were used to calculate RCEI score totals.
[a] Not included in RCEI scoring (see Section 4 for details).
[b] Tie broken using actual variable values.

county subdivisions had much lower values, ranging from 1 to 3% and 1–4%, respectively.

The proportion of total streamlength with adjacent forest vs. agriculture/bare ground was assessed to examine stream ecosystem health in West Georgia. In urban census county subdivisions, 0–1% of the total streamlength had adjacent agriculture/bare ground cover while 4–48% was forested (Table 1). 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%. In developing census county subdivisions, streams having adjacent agricultural lands occurred about 7–16% of the time, while 56–83% was forested. The values for rural subdivisions are even higher, with 9–27% of adjacent agriculture/bare ground cover and 72–83% forest land-cover. Further, over half of the census county subdivisions in this group had streams with less than 20% adjacent agriculture/bare ground cover.

3.5. Cluster ranks and RCEI scores

A cluster analysis using each of the 10 landscape indicator variables was performed to examine which areas of West Georgia were distinctly different from one another with regards to environmental impact. Several analyses were conducted and the best fit resulted in five clusters (Table 2 and Fig. 3). Cluster 1 was ranked 1st and the 10 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 and 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. Landscape 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 and 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. Landscape 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 and 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 these portions of the City of 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. Landscape 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 and 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 the least of any subdivision 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. Landscape 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 and 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. Landscape SHDI was the highest of all subdivisions in Cluster 5.

4. Discussion

Population statistics in West Georgia (2000 Census) varied greatly from urban to rural areas. As in most growing metropolitan areas, population density was greatest in urban areas (e.g., Columbus, LaGrange) and decreases with distance from the city centers (Medley et al., 1995) with very low densities observed in rural areas of West Georgia. Population change (1990–2000) statistics, however, indicate that there was an exodus from the city center of Columbus. These results 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. Recently there has been considerable build-up at the Fort Benning military base and a KIA automobile production plant and several associated automobile parts manufacturing plants are currently under construction around the City of LaGrange, GA. However, without more recent data, this hypothesis cannot be confirmed. In contrast, population around the city of LaGrange had the greatest increase during this time. It is

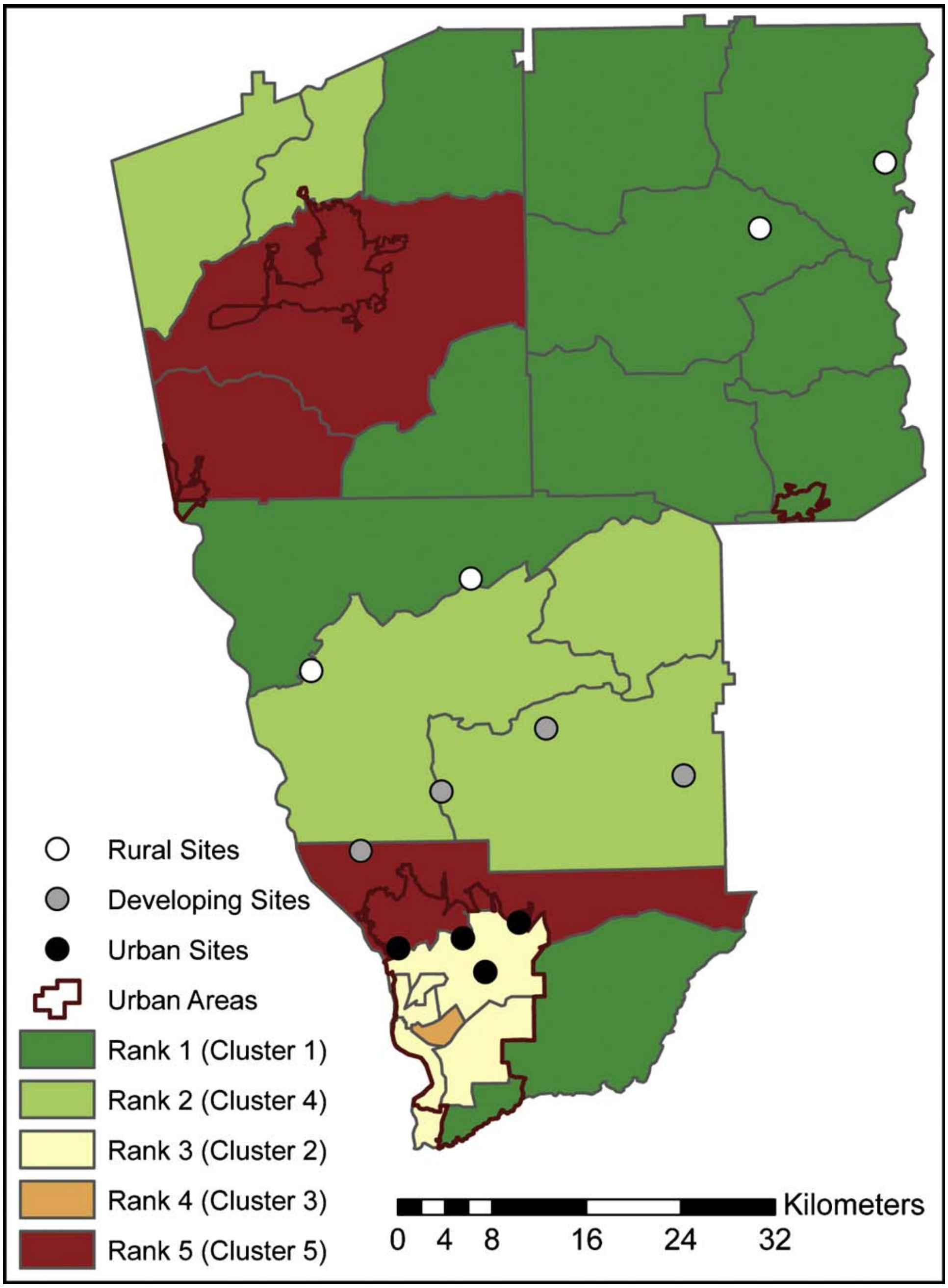

Fig. 3. Clusters ranked by low (1) to high (5) relative cumulative environmental impact score for West Georgia. Color scheme courtesy of Color Brewer©.

possible that some of this growth could be due to the sprawling 28-county Atlanta metropolitan area. According to the 2006 Census population estimates (U.S. Census Bureau, 2006), metro Atlanta is currently the fastest growing metropolitan area in the United States, and some commuters to Atlanta are moving into the northern West Georgia region.

Land-cover conversion appears to have kept pace with population change statistics, and landscape patterns seem to reflect development patterns in West Georgia. Rural areas had the greatest amount of forested land of any of the land use types, but the overall amount of forested land in developing and several urban areas remained quite high. However, greater patch density values were observed in urban areas and suggest more patchiness among urban forests in West Georgia, possibly resulting from forest fragmentation due to residential and commercial development. These results are consistent with research by Zipperer (1993), who reported increased deforestation in forested patches in urban areas of Maryland. Landscape SHDI values for West Georgia were mixed, with developing areas having the least and greatest values, and in between, urban areas having greater values than rural 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.

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). The amount of agriculture/bare ground on slopes >3% was greatest in developing areas. 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. Overall values for rural areas were not much lower than urban and developing areas. However, the larger total amount of bare ground and pasture land-cover in rural areas could possibly be the reason for the broad range in values observed in these locations.

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 water quality than those located outside of this distance (Jones et al., 1997). The amount of roads within 30 m of a stream for urban areas had 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, possibly indicating 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. 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 lower 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. Many of the urban census county subdivisions were forested for at least 1/3 of the total amount of land-cover, 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). Likewise, the majority of total land-cover for developing areas was forested, suggesting that 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. 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. 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.

The landscape indicator analysis results discussed 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 to 2006 (Styers, 2008) 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 (Fig. 3). 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 forest condition field data collected in a separate study (Styers and Chappelka, 2009), 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, 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. For more details on this study the reader is referred to Styers (2008) and Styers and Chappelka (2009).

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 (Styers, 2008). 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; Styers, 2008) 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 in 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 (Fig. 3), 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. 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 resolution (30 m × 30 m). 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 regional 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.

Implications of scale in ecological research are readily apparent from this analysis. In West Georgia, it appears that "developing" areas along the urban–rural interface are key to understanding changes in ecosystem structure and function. Based on the plot-level data, developing areas were similar to rural areas; however, regional data suggest that developing areas were more similar to urban areas. Is it possible that the indicators selected for the broad-scale assessment were appropriate for detecting early stress on an ecosystem, such that conditions favorable to environmental impacts are noticeable prior to individual species or forest stand responses? Future studies conducted in West Georgia and elsewhere could select sites that would respond in a "typical" 'urban' and 'rural' fashion based on preliminary/prior data. Remaining sites could be placed "developing" that have known or predicted values ranging between those of urban and rural, and sampling efforts could be focused there. Further, utilizing finer-scale (e.g., 1 m resolution or finer) satellite data for the regional study area could improve the ecosystem assessment tool and enhance its predictive capabilities in order to gain a clearer picture of the urban–rural interface zone in West Georgia and other areas.

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References

Brown, D.G., Johnson, K.M., Loveland, T.R., Theobald, D.M., 2005. Rural land-use trends in the coterminous United States, 1950–2000. Ecol. Appl. 15 (6), 1851–1863.

Burton, M.L., Samuelson, L.J., Pan, S., 2005. Riparian woody plant diversity and forest structure along an urban–rural gradient. Urban Ecosyst. 8 (1), 93–106.

Environmental Systems Research Institute, 2005. Arcgis® Desktop, Version 9.1. Environmental Systems Research Institute, Redlands, CA.

Jensen, J.R., 2005. Introductory Digital Image Processsing: A Remote-sensing Perspective, 3rd ed. Prentice-Hall, Upper Sadddle River, NJ.

Jones, K.B., Riitters, K.H., Wickham, J.D., Tankersley, Jr., R.D., O'Neill, R.V., Chaloud, D.J., Smith, E.R., Neale, A.C., 1997. An Ecological Assessment of the United States Mid-Atlantic Region: A Landscape Atlas (Report No. 600/R-97/130). U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

Kerr, J.T., Ostrovsky, M., 2003. From space to species: ecological applications for remote sensing. Trends Ecol. Evol. 18, 299–305.

Macie, E.A., Hermansen, L.A., 2002. Human Influences on Forest Ecosystems: The Southern Wildland-Urban Interface Assessment (Gen. Tech. Rep. SRS-55). U.S. Department of Agriculture, Forest Service, Southern Research Station.

McGarigal, K., Cushman, S.A., Neel, M.C., Ene, E., 2002. Fragstats: Spatial Pattern Analysis Program for Categorical Maps. University of Massachusetts, Amherst, MA.

McKinney, M.L., 2006. Urbanization as a major cause of biotic homogenization. Biol. Conserv. 127 (3), 247–260.

Medley, K.E., McDonnell, M.J., Pickett, S.T.A., 1995. Forest-landscape structure along an urban-to-rural gradient. Prof. Geogr. 47 (2), 159–168.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends Ecol. Evol. 20, 503–510.

Sabin, L.D., Hee Lim, J., Teresa Venezia, M., Winer, A.M., Schiff, K.C., Stolzenbach, K.D., 2006. Dry deposition and resuspension of particle-associated metals near a freeway in Los Angeles. Atmos. Environ. 40 (39), 7528–7538.

Schoonover, J.E., Lockaby, B.G., 2006. Land cover impacts on stream nutrients and fecal coliform in the lower piedmont of West Georgia. J. Hydrol. 331 (3–4), 371–382.

Sepp, K., Bastian, O., 2007. Studying landscape change: indicators, assessment and application. Landsc. Urban Plan. 79 (2), 125–126.

Styers, D.M., 2008. Urban Sprawl and Atmospheric Pollution Effects on Forests in the Georgia Piedmont. Doctoral Dissertation. School of Forestry & Wildlife Sciences, Auburn University, Auburn, AL, 232 pp.

Styers, D.M., Chappelka, A.H., 2009. Urbanization and atmospheric deposition: use of bioindicators in determining patterns of land-use change in West Georgia. Water Air Soil Pollut. 200, 371–386.

Twery, M., Gottschalk, K.W., 1996. Forest health: another fuzzy concept. J. For. 94 (8), 20.

U.S. Census Bureau, 2005. Topologically Integrated Geographic Encoding and Referencing System (Tiger). Retrieved September 24, 2006, from http://www.census.gov/geo/www/tiger/.

U.S. Census Bureau, 2006. State & County Quickfacts. Retrieved October 17, 2006, from http://quickfacts.census.gov/qfd/states/13000lk.html.

U.S. Geological Survey, 2004. National Elevation Dataset (Ned) 1 Arc Second. Retrieved June 13, 2005, from http://seamless.usgs.gov/website/seamless/products/1arc.asp.

U.S. Geological Survey, 2005. Landsat 5 Thematic Mapper (Tm) Product Description. Retrieved June 1, 2007, from http://eros.usgs.gov/products/satellite/tm.html.

University of Georgia, 2007. Georgia Geology. Retrieved March 11, 2007, from http://www.gly.uga.edu/default.php?PK=0&&iPage=5.

Zipperer, W.C., 1993. Deforestation patterns and their effects on forest patches. Landsc. Ecol. 8, 177–184.

Zipperer, W.C., Wu, J., Pouyat, R.V., Pickett, S.T.A., 2000. The application of ecological principles to urban and urbanizing landscapes. Ecol. Appl. 10 (3), 685–688.