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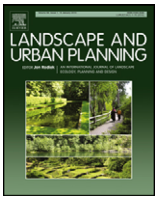

Multiscale analysis of the urbanization pattern of the Phoenix metropolitan landscape of USA: Time, space and thematic resolution

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ABSTRACT

Investigating the ecological consequences of urbanization require knowledge of land-cover dynamics. Quantification of land-use/land-cover change in Phoenix, Arizona during the period of 1985–2005 using landscape metrics computed from Landsat-derived maps revealed temporal patterns of landscape composition and configuration. With accelerated urbanization the landscape as a whole became more fragmented ecologically and more complex compositionally and geometrically. However, the majority of individual patches became more compact in shape. Urban land covers, especially xeric residential, increased substantially and the desert decreased by 20%. Spatial and thematic resolution of data was shown to have large effects on the analysis of land-cover pattern. Our results, while agreeing in general with previously reported scaling relations with respect to changing spatial grain and extent, showed that scaling relations are also robust and consistent across thematic resolutions and time periods. Some metrics behaved unpredictably and some exhibited scale-free behavior. Compositional metrics, such as patch density, diversity, evenness, and largest patch index, were well correlated with vegetative cover, its spatial variation, and population density. Many of these correlations exhibited hump-shaped patterns with respect to increasing grain size, indicating a characteristic scale at approximately 500–1000 m. By simultaneously manipulating spatial and thematic resolutions, the importance of the Modifiable Area Unit Problem in relating landscape patterns to vegetation and socio-economic variables was also demonstrated. Additionally, highly variable desert vegetation due to precipitation variability poses a challenge for accurately quantifying urbanization pattern in arid environments. Choosing appropriate spatial, temporal and thematic resolutions is essential in meeting this challenge.

1. Introduction

Urbanization, the most extreme anthropogenic land-cover transformation, has recently become an important theme in integrated ecological and socio-economic research (Alberti and Marzluff, 2004; Grimm et al., 2008, 2000; Pickett et al., 2001; Wu, 2008). Urban landscapes are characterized by highly dynamic and heterogeneous mosaics of patches that mediate societal–environmental interactions (Zipperer et al., 2000; Alberti, 2005; Wu, 2008). By measuring and comparing these mosaics across space and time and relating them to ecosystem properties or processes, one can start unraveling mechanisms of urban ecosystem development. Quantification of land transformations in urbanizing areas can be accomplished using tools of landscape pattern analysis (LPA) applied to categorical (thematic) maps (Dunn et al., 1991; Gustafson, 1998; Li and Wu, 2007; Turner et al., 2001). Landscape metrics and land-use/land-cover (LULC) maps, derived from remotely sensed images with various spatial, temporal and thematic resolutions, have been frequently used to characterize the patterns of urbanization (Buyantuyev and Wu, 2007; Dietzel et al., 2005; Herold et al., 2005, 2003; Huang et al., 2007; Irwin and Bockstael, 2007; Luck and Wu, 2002; Narumalani et al., 2004; Seto and Fragkias, 2005; Weng, 2007; Yu and Ng, 2007).

Quantification of time series of LULC maps of the same area is a crucial step toward understanding reciprocal relationships between landscape patterns and ecological and socio-economic processes. Potential caveats, such as the conceptual flaws in LPA, inherent limitations of landscape indices, and the improper use of these indices (Li and Wu, 2004), should be carefully considered and systematically tackled. One major problem that has been often overlooked is the effects of scale on LPA. Assuming that spectral properties of urban–suburban surfaces for a given season do not change from year to year, one can analyze land-cover dynamics by producing LULC maps using data from the same or a compatible sensor and processed using the same or a compatible classification

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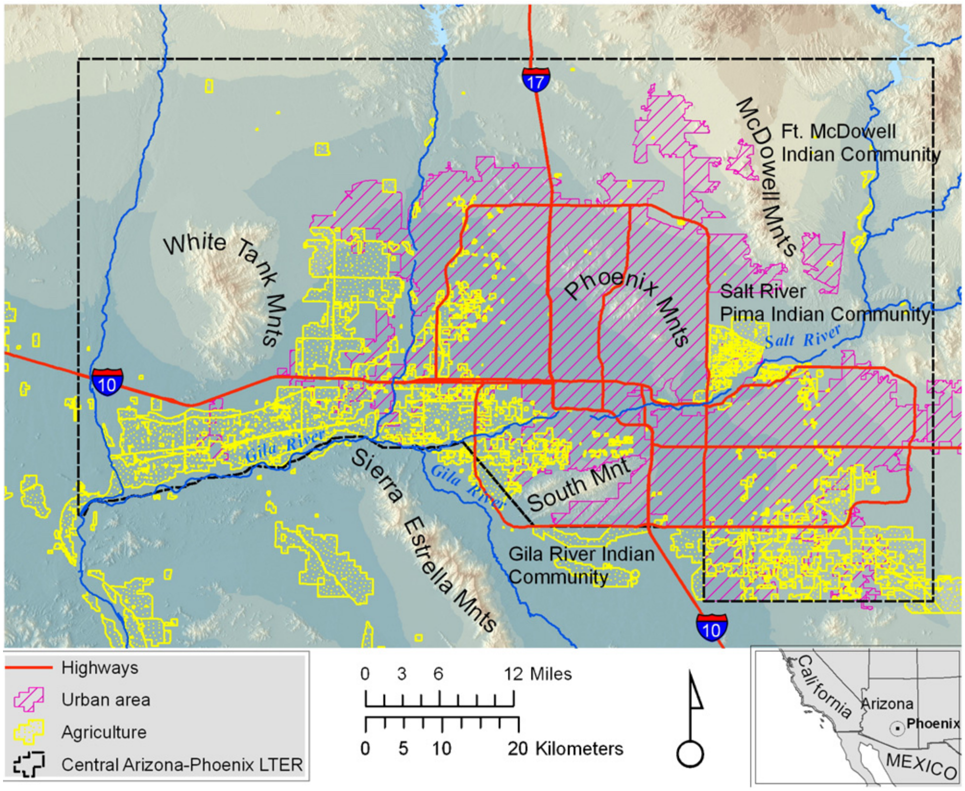

Fig. 1. Map of study area.

approach. Ideally, the scale of analysis, which in urban dynamics studies is often determined by data availability, should be commensurate with the so-called intrinsic or process scale (Wu and Li, 2006). However, urbanization processes take place at a whole spectrum of scales and require a hierarchical and pluralistic scaling approach (Wu, 1999, 2007).

The primary goal of this study is to quantify the spatiotemporal pattern of urbanization in the Phoenix metropolitan region between 1985 and 2005 at multiple spatial resolutions. While previous studies have systematically evaluated the effects of grain size and extent (Shen et al., 2004; Wu, 2004; Wu et al., 2002), and thematic detail (Baldwin et al., 2004; Buyantuyev and Wu, 2007; Castilla et al., 2009), here we investigate the combined effects of spatial (grain size) and thematic (number of land-cover categories) resolutions on the performance of landscape metrics in the context of LULC change. We also explore scale effects on correlations between landscape metrics and selected biophysical (NDVI) and socio-economic properties (income, population density) of the urban ecosystem. In addition, we discuss implications of scale effects on the ability of metrics to quantify land-cover dynamics. In particular, we ask whether landscape metrics are reliable indicators of change if data of different spatial or thematic resolutions are used in a relatively long (from several decades to more than 100 years) time-series analysis. Finally, we analyze sensitivity of landscape metrics to fluctuations in pattern due to inter-annual variations in precipitation and vegetation cover.

Table 1
Accuracy re-assessment of the 1998 land-use/land-cover map (original statistics from the accuracy report by Stefanov et al., 2001 are in parentheses).

Class	Reference totals	Classified totals	No. correct	Producer's accuracy (%)	User's accuracy (%)	Kappa
Active agriculture	95 (99)	99 (99)	92 (93)	96.84 (93.94)	92.93 (93.94)	0.92 (0.93)
Cultivated grass	77 (77)	78 (78)	76 (76)	98.70 (98.70)	97.44 (97.44)	0.97 (0.97)
Fluvial and Lacustrine	80 (77)	88 (88)	78 (72)	97.50 (93.51)	88.64 (81.82)	0.88 (0.80)
Compacted soil (prior ag)	96 (81)	84 (84)	79 (71)	82.29 (87.65)	94.05 (84.52)	0.93 (0.83)
Vegetation	97 (80)	84 (84)	78 (61)	80.41 (76.25)	92.86 (72.62)	0.92 (0.70)
Commercial/industrial	43 (54)	71 (71)	35 (35)	81.40 (64.81)	49.30 (49.30)	0.47 (0.46)
Asphalt/concrete	75 (67)	71 (71)	67 (61)	89.33 (91.04)	94.37 (85.92)	0.94 (0.85)
Undisturbed (Desert)	95 (101)	95 (95)	86 (86)	90.53 (85.15)	90.53 (90.53)	0.90 (0.89)
Compacted soil	107 (110)	87 (87)	83 (83)	77.57 (75.45)	95.40 (95.40)	0.95 (0.96)
Mesic residential	70 (70)	72 (72)	62 (59)	88.57 (84.29)	86.11 (81.94)	0.85 (0.81)
Xeric residential	77 (86)	74 (74)	65 (62)	84.42 (72.09)	87.84 (83.78)	0.87 (0.82)
Water	69 (79)	78 (78)	68 (77)	98.55 (97.47)	87.18 (98.72)	0.86 (0.99)
Totals	981 (981)	981 (981)	869 (836)			
Overall accuracy	88.58% (85.22%)					
Overall kappa statistics	0.8753 (0.8385)					

Note: Class names are slightly modified but the order is preserved from the original classification. For class definitions see Stefanov et al. (2001).

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Table 2
Accuracy assessment of the 2005 land-use/land-cover map.

Class	Reference totals	Classified totals	No. correct	Producer's accuracy (%)	User's accuracy (%)	Kappa
Active agriculture	86	99	82	95.35	82.83	0.81
Cultivated grass	85	80	77	90.59	96.25	0.96
Fluvial and Lacustrine	77	80	71	92.21	88.75	0.88
Compacted soil (prior ag)	67	80	64	95.52	80.00	0.79
Vegetation	122	90	90	73.77	100.00	1.00
Commercial/industrial	43	70	36	83.72	51.43	0.49
Asphalt/concrete	66	70	56	84.85	80.00	0.79
Undisturbed (Desert)	108	110	95	87.96	86.36	0.85
Compacted soil	128	100	82	64.06	82.00	0.80
Mesic residential	101	100	71	70.30	71.00	0.68
Xeric residential	103	100	83	80.58	83.00	0.81
Water	71	78	69	98.18	88.46	0.88
Totals	1057	1057	876			
Overall accuracy	82.88%					
Overall kappa statistics	0.8127					

2. Materials and methods

2.1. Study area

Our study area is located at the Central Arizona–Phoenix Long-Term Ecological Research (CAPLTER) site in the northern Sonoran Desert. The area belongs to the Basin and Range Geological Province, characterized by the dominance of relatively flat terrain composed of alluvial plain and surrounded by isolated mountain ranges (Fig. 1). Phoenix is situated at the confluence of Gila and Salt Rivers: the latter is now entirely diverted to irrigation canals. The arid (mean annual precipitation = 180 mm and mean summer high temperature = 30.8 °C) climate supports desert biological communities. Arizona Upland subdivision with Paloverde-Mixed Cacti series and Lower Colorado River subdivision with Creosotebush-Bursage series are the two subdivisions of the Sonoran Desert scrub that are predominant in this area (Brown, 1994). Metropolitan Phoenix consists of 24 cities and towns and has a population of more than four million people. It is among the fastest growing urban areas in the United States with an estimated growth rate of 40% that took place between 1990 and 2000. Interestingly, the urban fringe has advanced into the desert and croplands by nearly 805 meters per year during the last decade of the last century (MIPP, 2000).

2.2. Creation of LULC, vegetation cover, and socio-economic maps

We used 20-year time-series data of LULC (1985–2005) of the Phoenix metro area (Arizona, USA), produced from atmospherically corrected and georectified Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) imagery using an expert system model (Stefanov, 2000). The model was originally developed based on data acquired in May 24 and June 18, 1998 (Stefanov et al., 2001) and then applied to spatially co-registered May 4, 1985; May 18, 1990; April 18, 1993; May 21, 2000; and the later March 8, 2005 Landsat images. The classification system performs *a posteriori* sorting of classes initially derived using Maximum Likelihood Classification. It makes use of geographically co-registered auxiliary data layers such as land-use map, image texture, water rights database, city boundaries, and Native American reservation boundaries. These layers are updated for each time period to reflect changes in land use. The final classification consists of 12 classes and has a reported overall accuracy of about 85% or higher (Table 1). User's accuracy for individual classes varied from 73% to 99% with the exception of the commercial/industrial class (49%). Using the 1985 map as a reference we further conducted additional map reclassification of the time series by overlaying pairs of consecutive maps and checking for unlikely transitions, such as the conversion of asphalt or residential classes back to desert. These transitions were eliminated where necessary to make the time series temporally consistent. By re-evaluating the accuracy of the 1998 map we confirmed the accuracy level was preserved and in some cases improved (Table 1). The accuracy was also assessed for the 2005 map which resulted in very similar levels (Table 2). Because we use data of the same spatial, spectral, and radiometric resolutions and apply the same classification method, the risk of detecting unreal changes is minimized at the extent possible at any given spatial or thematic resolution.

To estimate abundance of actively photosynthesizing vegetation we computed the Normalized Difference Vegetation Index (NDVI) from all raw Landsat images:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

where NIR corresponds to Landsat band 4 (0.76–0.9 μm), RED corresponds to band 3 (0.63–0.69 μm). The index is based on the property of green leaves to strongly absorb wavelengths in the RED and strongly reflect in the NIR zone of electromagnetic spectrum (Tucker, 1979).

Three socio-economic variables (human population density, median household income, and median age of housing structures) were selected based on previously established relationships of socio-economic status with a number of biophysical and ecological patterns or processes in Phoenix (Hope et al., 2003; Jenerette et al., 2007; Martin et al., 2004). We extracted these variables from the 2000 decennial U.S. Census for all block groups in the metropolitan statistical area. Block group is the smallest unit for which the desired socio-economic information was available. Since the data are provided in vector format they were rasterized directly to match the grain size of each level of analysis.

2.3. Multiscale landscape pattern analysis of LULC maps

LULC maps were first created for six different years and then progressively aggregated both spatially and thematically. Spatial patterns were quantified by a suite of landscape metrics using FRAGSTATS software (McGarigal and Marks, 1995). We computed 16 landscape-level metrics that can be categorized into two groups — compositional and configurational (Table 3). Compositional metrics include nine indices: Percent Total Area of Patch Type or Percent Class Area (%CA), Patch Density (PD), Edge Density (ED), Diversity (SHDI), Evenness (SHEI), Largest Patch (LPI), Mean Patch Size (MPS), Patch Size Standard Deviation (PSSD), and Patch Size Coefficient of Variation (PSCV). Seven configurational metrics are Landscape Shape Index (LSI), Mean Patch Shape Index (MPSI), Area-Weighted

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Table 3
List of landscape metrics used in the study (based on McGarigal and Marks, 1995; Wu et al., 2002).

Landscape metric	Description
Patch density (PD)	The number of patches per unit area (unit: patches/100 ha)
Edge density (ED)	The total length of all edge segments per ha for the land-cover class or landscape of consideration (unit: m/ha)
Percent Class Area (%CA)	Relative area of a specific patch type in a landscape
Shannon's Diversity (SHDI)	Compositional diversity as determined by a combination of richness (number of different patch types) and evenness (proportional distribution of area among patch types) $\mathrm{SHDI} = -\sum_{i=1}^{m} p_i \ln(p_i)$, where m = number of patch types, p_i = proportion of the landscape occupied by patch type i
Shannon's Evenness (SHEI)	The observed SHDI divided by the maximum SHDI for that number of patch types. It measures the degree of evenness of area distribution among patch types
Largest Patch Index (LPI)	Percent of the landscape occupied by the largest patch (unit: %)
Mean Patch Size (MPS)	The average area of all patches in the landscape (unit: ha)
Patch Size Standard Deviation (PSSD)	The standard deviation of patch size in the entire landscape (unit: ha)
Patch Size Coefficient of Variation (PSCV)	The standard deviation of patch size divided by mean patch size for the entire landscape (unit: %)
Landscape Shape Index (LSI)	A modified perimeter–area ratio of the form that measures the shape complexity of the whole landscape
Mean Patch Shape Index (MPSI)	Patch-level shape index averaged over all patches in the landscape. Shape index equals patch perimeter divided by the minimum perimeter possible for a maximally compact patch of the corresponding patch area
Area-Weighted Mean Shape Index (AWMPSI)	Mean patch shape index weighted by relative patch size
Perimeter–Area Fractal Dimension (PAFRAC)	The fractal dimension of the entire landscape which is equal to 2 divided by the slope of the regression line between the logarithm of patch area and the logarithm of patch perimeter
Mean Patch Fractal Dimension (MPFD)	The average fractal dimension of individual patches in the landscape which is the summation of fractal dimension for all patches divided by the total number of patches
Area-Weighted Mean Fractal Dimension (AWMPFD)	The patch fractal dimension weighted by relative patch area
Contagion (CONTAG)	Measures spatial aggregation of patches by computing the probability that two randomly chosen adjacent grid cells will be of the same patch type

Mean Shape Index (AWMPSI), Perimeter–Area Fractal Dimension (PAFRAC), Mean Patch Fractal Dimension (MPFD), Area-Weighted Mean Fractal Dimension (AWMFD), and Contagion (CONTAG).

To examine effects of thematic resolution we created a series of hierarchically nested land-cover classifications by progressively aggregating the original 12-class maps into 9-, 6-, 4-, and 2-class maps (30 maps in total) and applying pre-defined rules based on either physiognomic or functional similarities. Effects of spatial resolution were analyzed by degrading spatial resolution using the majority rule. All 30 maps were progressively resampled to a series of nested grain sizes from the original 1 × 1 (28.5 m) to 80 × 80 (2280 m) pixel on a side. Map extent was kept constant to ensure metrics of different time periods are congruent.

We analyzed scale effects on correlations between a subset of metrics (PD, SHDI, LPI, CONTAG, PSCV, PSSD, PAFRAC) and vegetation cover (NDVI) and socio-economic variables using the moving-window option in LPA analyses. An empirically chosen 11 × 11-pixel moving window was applied to grids of all combinations of thematic and spatial resolutions of LULC maps. The output from this procedure is a raster grid of each metric produced by passing the window over every pixel and writing the metric value for each individual window to the focal (center) pixel in the output grid (McGarigal and Marks, 1995). We produced two versions of NDVI derivatives – NDVI mean and NDVI standard deviation – using the same moving-window approach. Multiresolution socio-economic raster maps were used without further modifications. Cross correlations between grids of the same spatial scale were performed in ArcINFO by creating multiple grid stacks and computing Pearson's correlation matrices. Correlations with NDVI were computed for five years to examine their temporal patterns, but socio-economic variables were correlated only with maps of landscape metrics from 2000.

Table 4
Changes in percent of total area occupied by each land cover from the 9-category classification.

	1985	1990	1993	1998	2000	2005
Mesic residential	2.1	2.6	3.0	3.7	5.2	5.8
Xeric residential	2.9	4.9	5.3	8.7	9.8	10.5
Impervious	4.7	7.5	8.2	9.5	12.3	9.1
Agriculture	9.6	11.9	10.7	12.9	11.0	11.8
Golf and park veg	0.3	0.5	0.6	0.6	0.4	0.3
Dense vegetation	8.5	2.8	10.9	5.7	2.7	11.1
Riverine unveg	1.7	1.9	1.9	2.1	2.1	2.1
Desert	69.9	67.8	59.0	56.7	56.3	49.0
Water	0.3	0.1	0.3	0.2	0.2	0.4

3. Results

3.1. Characterization of general urbanization trends and major land-cover transitions

The last two decades mark dramatic urbanization in the region. Percent of class area reflected general trends of the process (Table 4). The intermediate thematic classification (nine classes) is shown here for brevity. The area of undisturbed (desert) class decreased by 21% (from 70% in 1985 to 57% in 1998 and 49% in 2005). Urban classes – impervious (includes asphalt/concrete and industrial/commercial) and both residential – increased between 4% and 8%. The highest growth rate was associated with the xeric residential class, which reflects a shift toward the prevalence of xeriscaped neighborhoods in the 1980s and 1990s. Other classes, with the exception of dense vegetation, stayed at approximately the same level. The area covered by dense vegetation fluctuated extensively in response to seasonal rainfall, but it did not exhibit any temporal trend. There is a high probability of sparsely vegetated desert being converted into this class. Overall, transition probabilities reveal that urbanization during this period occurred mostly at the expense of desert and, secondarily, by replacing agriculture (Table 5 and Fig. 2). Fig. 2 displays realistic conversions to three most common urban and agricultural classes. Reciprocal switches between two residential classes (Fig. 2A and B) may reflect frequent changes in landscaping, however, high transition probabilities from impervious surfaces to residential classes (Fig. 2A and B), and vice versa (Fig. 2C), are likely the result of misclassifications. In addition, overgrown desert trees in heavily irrigated xeric residential yards, such as mesquite, develop dense closed canopy and at certain times may look like dense mesic vegetation. Evidently, agricultural expansion encroaching into desert ceased after 2000 (Fig. 2D).

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Table 5
Land-cover transition probabilities for all time periods (mean of five transition periods). Probabilities of >0.1 are shown in bold.

	TO								
	Mesic residential	Xeric residential	Impervious	Agriculture	Golf and park veg	Dense vegetation	Riverine unveg	Desert	Water
FROM									
Mesic residential	0.23	**0.11**	0.05	0.03	0.08	0.04	0.01	0.01	0.02
Xeric residential	**0.23**	0.43	**0.13**	0.02	0.07	0.03	0.01	0.02	0.04
Impervious	**0.12**	**0.17**	0.37	0.03	**0.11**	0.06	0.03	0.03	**0.10**
Agriculture	**0.11**	0.06	0.07	0.71	0.04	0.11	0.04	0.03	0.05
Golf and park veg	0.01	0.01	0.01	0.00	0.45	0.00	0.00	0.00	0.01
Dense vegetation	0.09	0.05	0.07	0.06	0.06	0.18	0.08	0.06	0.07
Riverine unveg	0.01	0.00	0.01	0.01	0.01	0.03	0.69	0.00	**0.27**
Desert	**0.20**	**0.17**	**0.28**	**0.15**	**0.18**	**0.53**	**0.10**	0.84	**0.15**
Water	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.28

3.2. *Compositional and configurational changes in landscape pattern*

PD and ED increased substantially in response to urban growth. Both metrics grew steadily which indicates the increasing fragmentation of the landscape. There is a notable spike in edge density in 1993 which we attribute to the proliferation of vegetation patches (discussed later). The highest rate of change of both metrics is observed in the period between 1998 and 2000 (Fig. 3). Diversity metrics are influenced by the number of land-cover categories (richness) and evenness. Since the former in our analysis was held constant at each level of thematic resolution, the diversity metric's (SHDI) pattern resembles that of the evenness (SHEI). SHEI exhibited an increase in the distribution of area among patch types (classes) by 20% from the intermediate level of about 0.5. The evolution of both SHDI and SHEI suggests the increase in landscape fragmentation and a trend to the equalization of class areas with increasing proportions of urban and agricultural land covers and the decreasing dominance of untransformed desert. Desert represented the largest patch in the region which continued to shrink as urbanization proceeded (LPI trend in Fig. 3). The lowest drop in LPI in the earlier period occurred in 1993 which is further evidence of the desert area being split by numerous vegetation patches. MPS declined from 1.2 to 0.8 ha (28.5 m grain size) and the absolute variation of patch size (PSSD) dropped even more dramatically from 1985 to 1993 (Fig. 3). The relative variation of patch size (PSCV) decreased in the similar manner until 1998 and mostly increased afterwards.

Dynamics of selected measures of landscape configuration also exhibited gradual changes but some indices remained relatively unchanged (Fig. 3). LSI evolved in a pattern analogous to ED suggesting the increasing irregularity of the landscape as a whole with continued urbanization. It also had a noteworthy spike in 1993 which we believe reflects a sharp increase in highly irregular vegetation patches.

Contagion, which measures the degree of clumping of patches, decreased by about 15% signifying increased landscape disaggregation. PAFRAC, MPSI, and MPFD did not change during the 20-year period. MPFD and MPSI stayed close to 1 indicating the commonness of simple and compact shapes. However, normal-

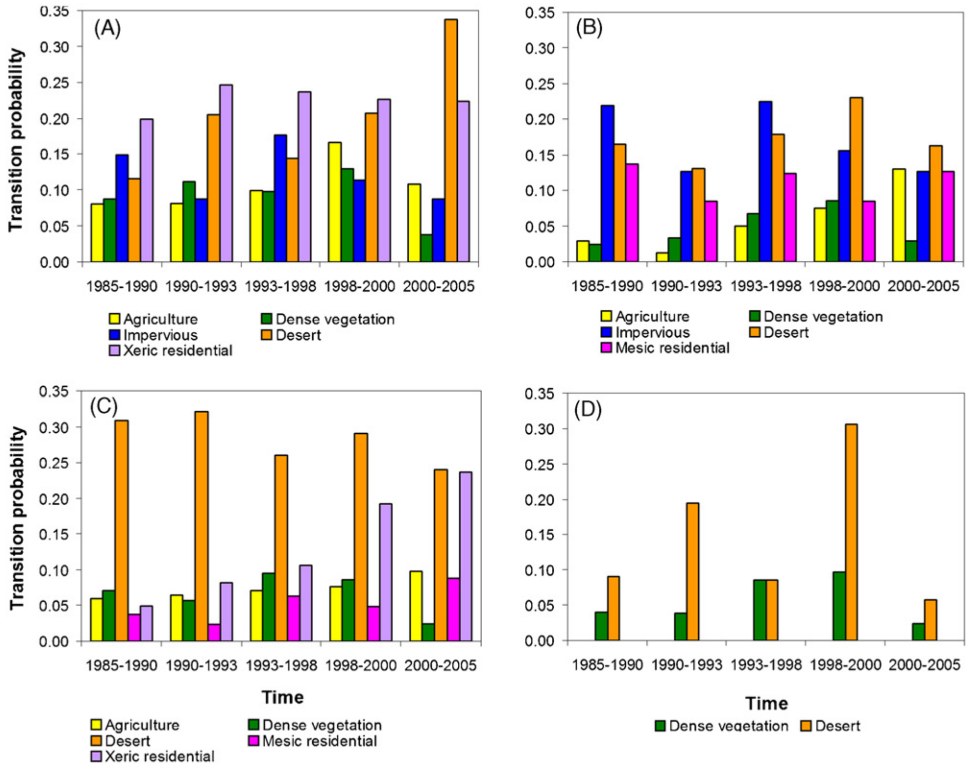

Fig. 2. Transition probabilities to mesic residential (A), xeric residential (B), impervious (C), and agriculture (D) from selected land-cover classes at five time periods.

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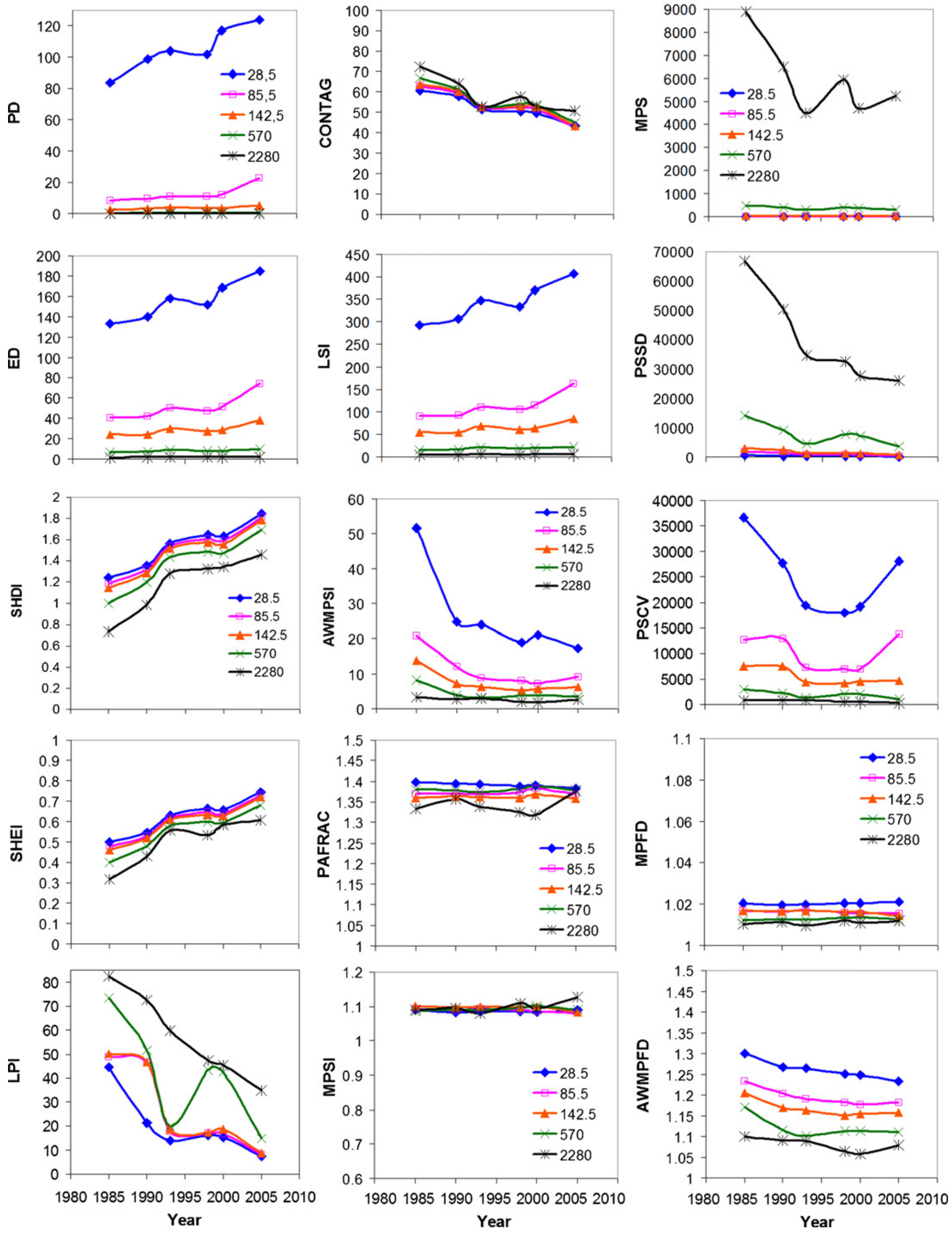

Fig. 3. Land-use and land-cover dynamics in the Central Arizona–Phoenix LTER quantified by landscape-level metrics at different grain sizes. Colored lines are selected grain sizes in meters (for definitions of displayed metrics see Table 3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

ized versions of both the shape and fractal dimension of patches – AWMPSI and AWMPFD – decreased in semi-linear and linear fashion respectively indicating a drift toward compactness of patches in the landscape (Fig. 3). This contradicts the LSI trend and suggests that characteristics of shape of the whole landscape and that at the level of individual patches do not necessarily agree.

3.3. Scaling relations and effects of scale

Spatial and thematic resolutions have significant effects on most landscape metrics (Figs. 3 and 4). Effects of spatial resolution (grain size and extent) have already been thoroughly investigated using contrived (Shen et al., 2004) and real data (Wu, 2004; Wu et al., 2002). These studies found three general types of response to changes in grain size: a group of metrics showing consistent scaling relations, described by either power-law or linear functions; metrics showing a staircase-like response; and metrics that had unpredictable behavior (Shen et al., 2004; Wu, 2004; Wu et al., 2002). In this study we essentially replicated the approach, but added a new dimension — thematic resolution. We evaluate robustness in metrics' behavior, which in our study indicates the similarity of scaling relations between different level of thematic resolution and across different years. The most robust metrics are believed to

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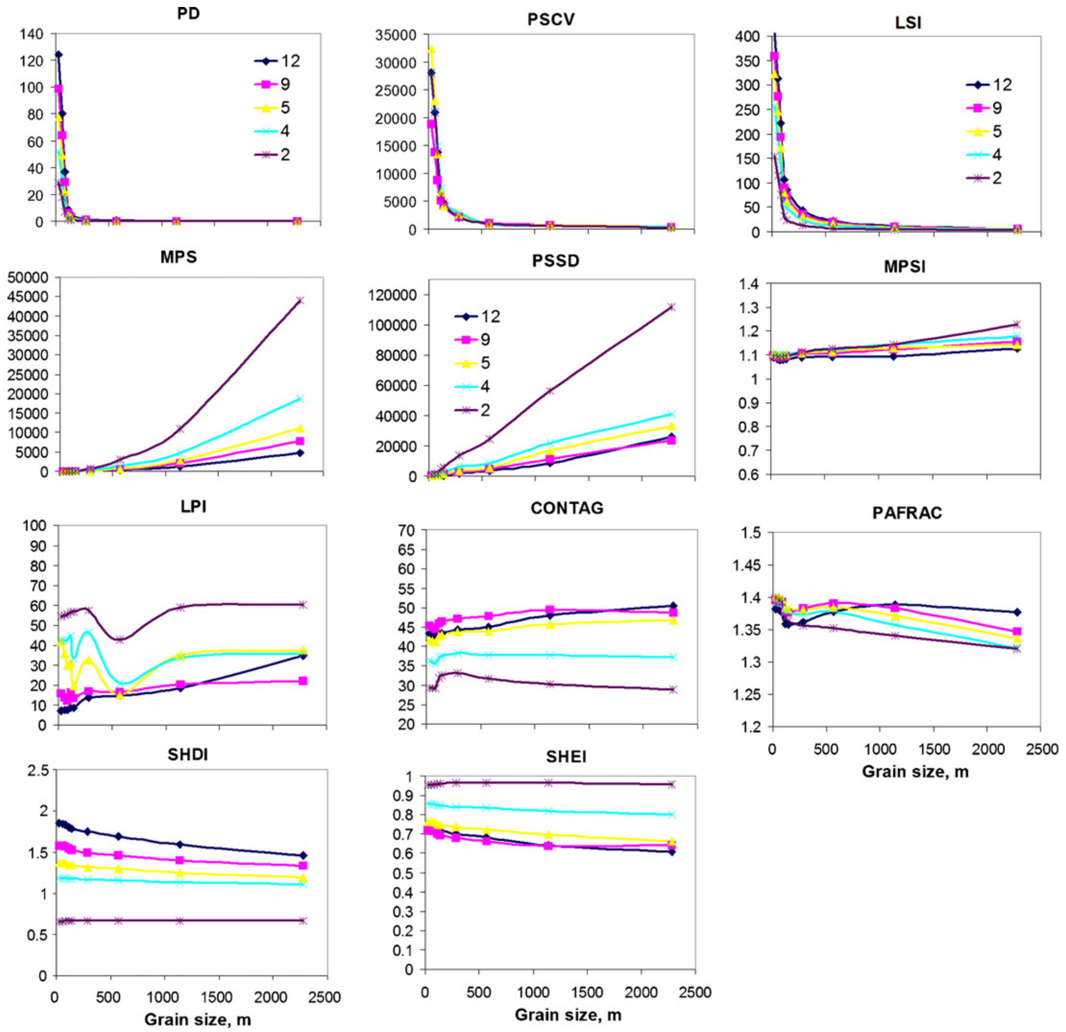

Fig. 4. Examples of landscape metric scalograms showing the combined effects of spatial and thematic resolutions. Although the displayed are metrics computed for 2005 maps, these relations are similar for all time periods studied. Lines of different colors are levels of thematic resolution (number of classes). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

be the best candidates for conducting temporal analyses of land-cover changes.

Our results generally agree with previous findings, with some metrics showing different behaviors. In particular, we did not find the staircase-like behavior and instead had metrics that did not change at coarser thematic resolutions or exhibited very weak linear relationships with grain size at finer thematic resolution (Fig. 4, SHDI, SHEI, MPFD (not shown)). Most metrics decreased (PD, ED, LSI, PSCV, AWMPFD, and AWMPSI) or increased (MPS) following a power-law function, and PSSD changed linearly (Fig. 4, some metrics are not shown). Unlike previous studies, we found that LPI behaved unpredictably and was in the same group as CONTAG, PAFRAC, and MPSI (Fig. 4). All metrics, except LPI, CONTAG, PAFRAC, and MPSI, were robust across all combinations of thematic and spatial resolutions (Fig. 4) and highly consistent from year to year (Fig. 3).

3.4. Multiscale correlations between landscape metrics and pattern explanatory variables

We have learned from temporal patterns of various landscape metrics and NDVI images that the value of these metrics at each time period may be sensitive to vegetation cover. The socio-economic structure of the landscape can also have a direct effect on heterogeneity and may be used to explain variability in landscape metrics. Our moving-window LPA analysis revealed that six out of seven selected metrics correlated with NDVI mean and standard deviation. Four metrics (PD, SHDI, PSCV, PSSD) were positively and two (LPI and CONTAG) were negatively correlated (Fig. 5). The graphs demonstrate changes in correlation as a function of grain size. All correlations with NDVI are generally low at the finest scale and have a hump-shaped behavior (inverted for negatively correlated metrics) often peaking in the area between 500 and 1000 m pixel sizes for most thematic resolutions. This peak may indicate a characteristic scale at which these pairs of variables most strongly interact. This scale range seems to confirm the appropriateness of spatial resolution decisions built in the design of the Moderate Resolution Imaging Spectroradiometer (MODIS), a key remote-sensing instrument which plays a vital role in global environmental monitoring (Justice et al., 1998). An interesting pattern is observed when we make comparisons across levels of thematic detail. Although correlation strength declines significantly and consistently with decreasing thematic resolution when the 12-class and 2-class data are considered, the pattern is reversed if we compare 9-, 6-, and 4-class correlations. Metrics computed from 4-class maps can be correlated with NDVI as strongly as the 12-class level (Fig. 5).

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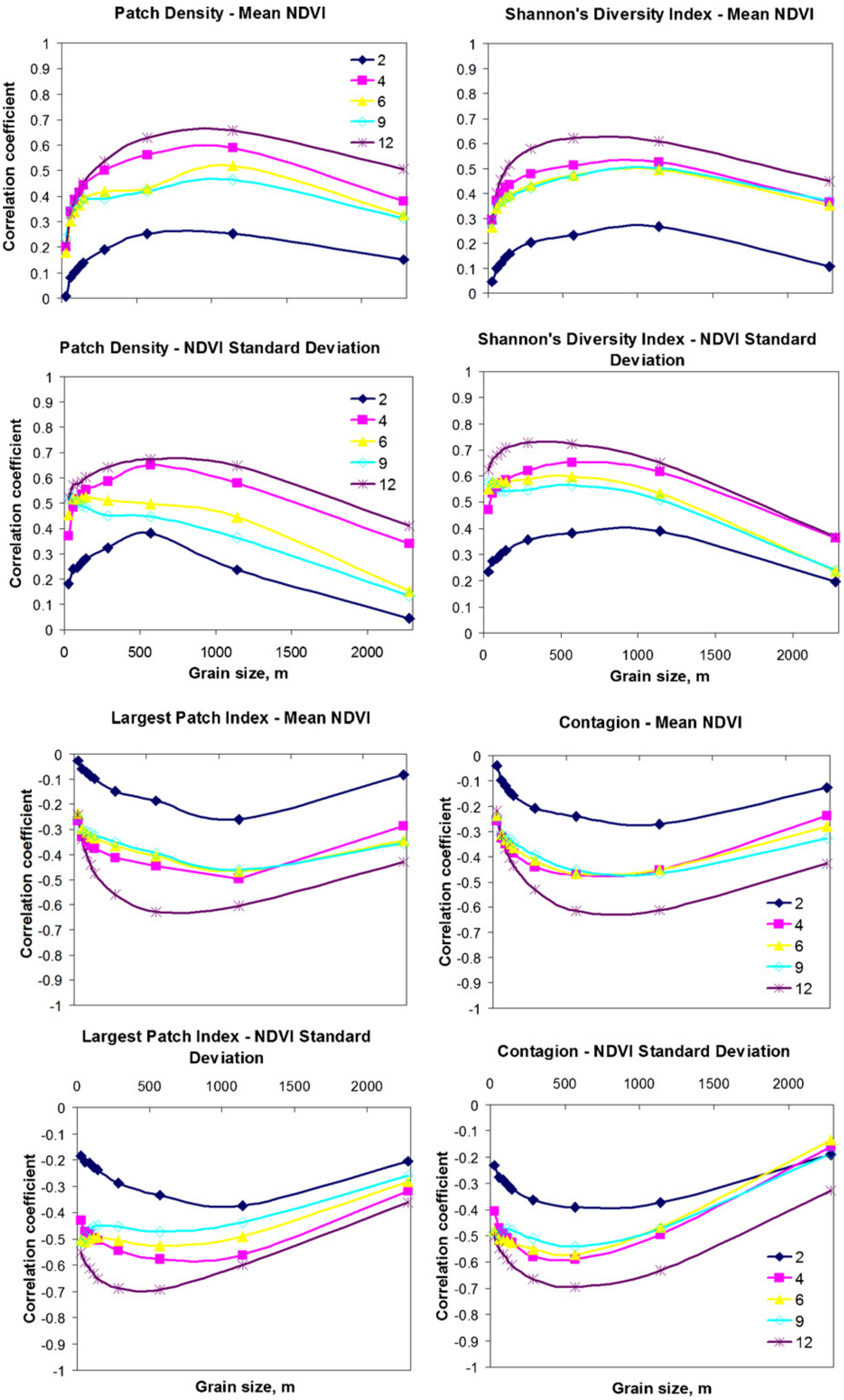

Fig. 5. Examples of the effects of spatial and thematic resolutions on correlations between landscape metrics and NDVI mean and standard deviation. Number of data points (n) used to calculate correlation varies between 9400,000 for the original spatial resolution and 1440 for the coarsest resolution of 2850 × 2850 m. Lines of different colors are levels of thematic resolution (number of classes). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The higher NDVI generally implies higher spatial variation in spectrally distinct vegetative cover that tends to be quite patchy in both the desert and urban environments of the area. This leads to an increase in patch density, diversity, and landscape fragmentation. Those indices that correlated positively with NDVI were also positively correlated with human population density, although the increase in grain size produced a less predictable pattern (Fig. 6). Higher population density implies more patches per unit area, but this only holds true at finer thematic resolutions. Effects of thematic resolution are less consistent as different colored lines cross multiple times. Metrics derived from the 9-class level are most highly correlated and those computed from 2- and 4-class levels are uncorrelated. The response of correlation to grain size here takes the form of an asymptotically climbing pattern. Correlations with income and housing age (not shown) are very low or zero.

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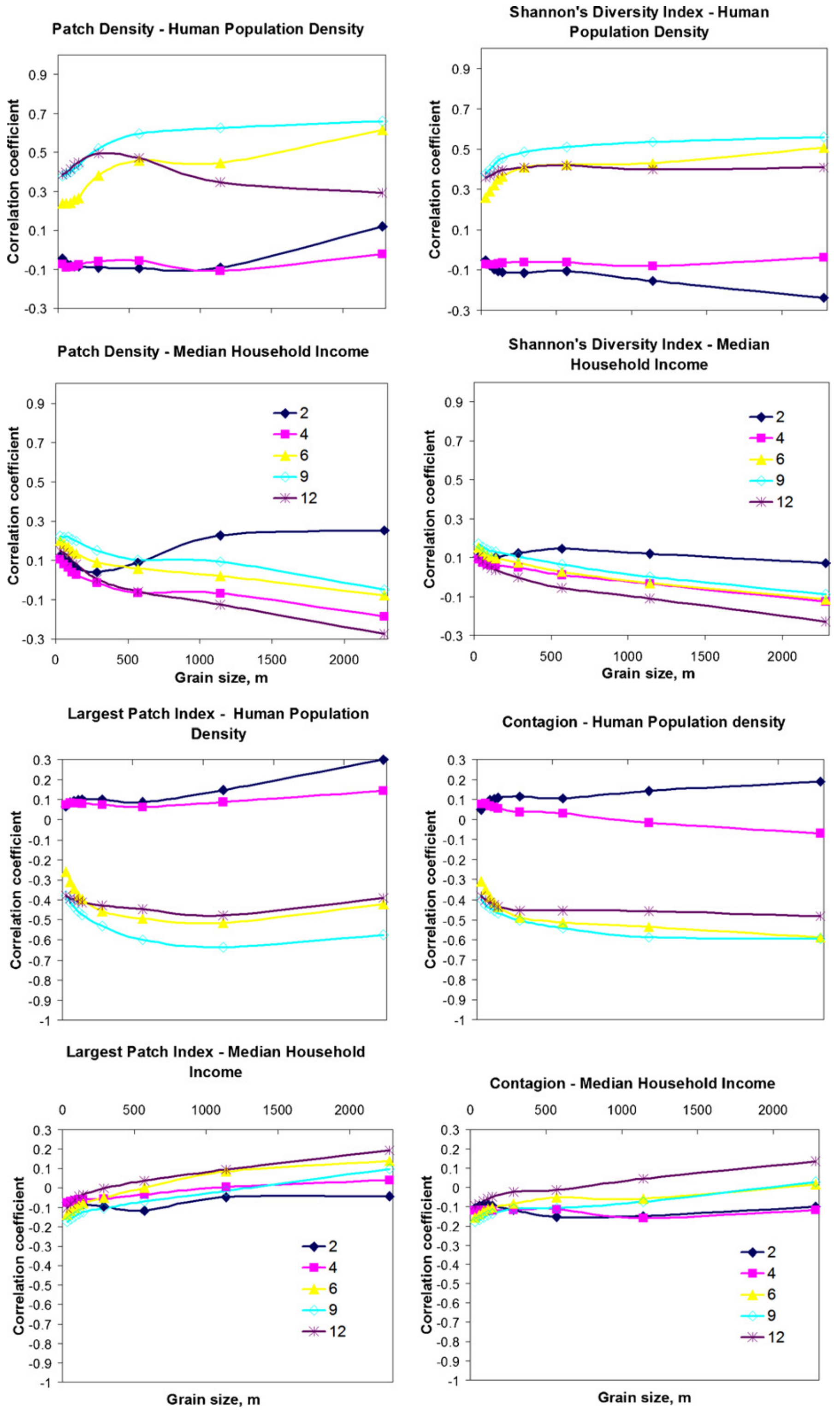

Fig. 6. Examples of the effects of spatial and thematic resolutions on correlations between landscape metrics and socio-economic variables. Number of data points (n) used to calculate correlation varies between 9400,000 for the original spatial resolution and 1440 for the coarsest resolution of 2850 × 2850 m. Lines of different colors are levels of thematic resolution (number of classes). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

3.5. Effects of inter-annual vegetation dynamics on NDVI-landscape metric correlations

Mean NDVI correlations with landscape metrics vary considerably among different years (Fig. 6). They can change from almost zero (PSCV) during a very wet year (1993) to 0.7 (PD) in the dry 2000 (Fig. 7). The difference in seasonal precipitation (rainfall accumulated from the beginning of each year to each Landsat image acquisition date) between these two years is 141 mm. These temporal patterns suggest that relationships change in response to vegetation abundance, which is driven by the amount of seasonal precipitation in the desert. Patch density, diversity, evenness,

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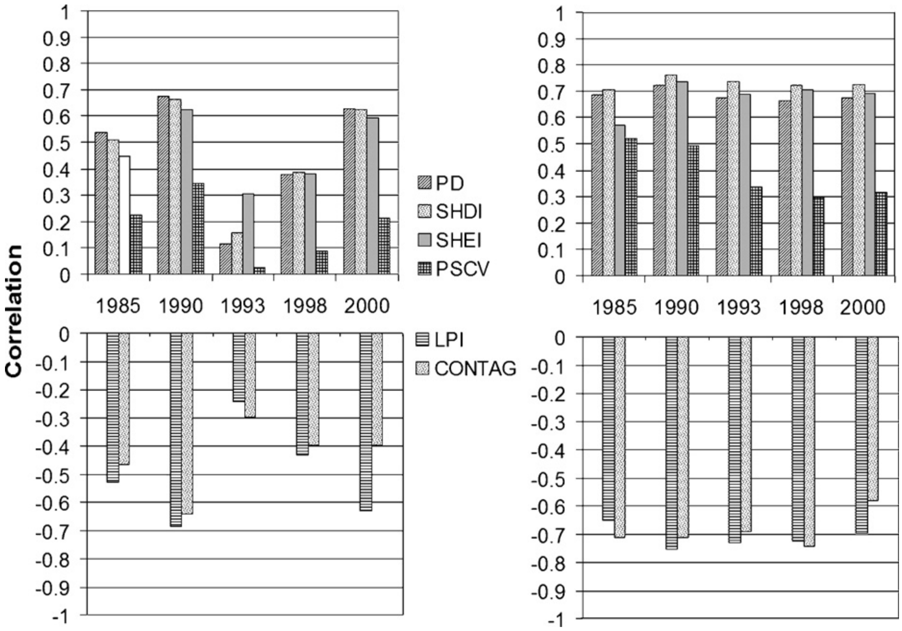

Fig. 7. Correlations between selected landscape metrics with mean NDVI and NDVI standard deviation computed at the 570 m grain size and 11 × 11 pixel moving window (n = 23,474).

and variation in patch size increase significantly with the overall regional increase in vegetative cover. Conversely, landscape fragmentation, as detected by declining LPI and CONTAG, increase dramatically with increased NDVI. However, the driest year (1985) was characterized by intermediate correlations, indicating a possible NDVI (or precipitation) threshold after which correlations actually decrease. In contrast to mean NDVI, correlations of metrics with NDVI standard deviation are insensitive to changes in vegetative cover and remain high.

4. Discussion

4.1. Main characteristics of LULC change in the urbanizing Central Arizona–Phoenix region in 1985–2005

Quantification of land-cover change and its ecological implications is a fundamental challenge faced by ecologists engaged in understanding co-evolution of human society and ecosystems (Vitousek, 1994). Urban and urbanizing landscapes are hot spots of such interactions that transform soils (Kaye et al., 2006; Pouyat et al., 2008) and affect species distribution and performance (Francois et al., 2008; Vallet et al., 2008). Investigation of ecological and societal processes in relation to highly heterogeneous spatial structure of these areas requires elaborate approaches (Grimm and Redman, 2004; Zipperer et al., 2000). We quantified major urbanization trends in the rapidly growing Phoenix metropolitan area from 1985 to 2005 and found urban land covers or uses, especially the xeric residential class, increased substantially at the expense of Sonoran Desert.

Over the 20-year period, the landscape became more fragmented ecologically, which is indicated by the steady increase in density of patches and edges, decreases in mean patch size, contagion, and the area occupied by the largest patch (desert). Landscape diversity grew primarily due to the increasing equality of proportional abundances of existing land-cover classes. Metrics that describe boundary complexities and fractal properties of individual patches did not change (MPSI, MPFD, PAFRAC) or they decreased (AWMPSI, AWMPD) during the study period (Fig. 3). While the landscape as a whole became more complex geometrically, the statistical majority of patches exhibited a slight trend toward compactness of shape.

4.2. Comparing scaling relations to previous findings and assessing the effects of scale on correlation analysis in the context of Modifiable Areal Unit Problem (MAUP)

Our study agrees well with previously reported scaling properties of real and modeled landscapes (Shen et al., 2004; Wu, 2004; Wu et al., 2002), but some of our metrics indicated different scaling relations. Our approach differed in that we focused on combined effects of spatial and thematic resolution on the ability of landscape pattern analysis to quantify changes in land-use/land-cover. By taking this approach we directly address the Modifiable Areal Unit Problem, a well-known problem in spatial analysis that has two aspects: the scale effect and the zoning effect (Fotheringham, 1989; Jelinski and Wu, 1996; Openshaw, 1984). Scale effect refers to the variation in the results of statistical analysis caused by the decreasing spatial resolution (i.e. grain size) of data. The zoning effect produces results of statistical analysis that are different if areal units of the same phenomenon or process are defined differently (i.e. different classification schemes). Unlike previous studies of scaling relations in landscape ecology, our maps are derived from satellite data and created using a more detailed classification system. A multitemporal perspective allowed us to evaluate the robustness of the behavior of different metrics using six replicates (time periods). LPA of the time series confirmed decreasing and increasing power laws and increasing linear scaling relations for half of the metrics analyzed. The relations were robust for all time periods and thematic resolutions. While some of the remaining metrics behaved erratically with increasing grain size and thematic detail, others showed no scaling relations at all (Fig. 4). This new empirical evidence of consistency in scaling relations (in some cases) is encouraging.

Researchers in geography and other social sciences have long observed the instability in correlations or regression parameters as a result of the MAUP (Fotheringham and Wong, 1991; Openshaw and Taylor, 1979). In our study we tested correlations between landscape metrics and selected biophysical (NDVI) and socioeconomic variables across the range of spatial and thematic scales.

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The analysis demonstrated that correlations change significantly as a result of both MAUP effects (Figs. 5 and 6). Moreover, for variables that are correlated with metrics the relationship follows a hump-shaped or asymptotically climbing pattern, indicating a characteristic scale (a range of scales) at which pairs of compared variables are most likely to strongly interact. In the case of correlations of compositional metrics, such as PD, SHDI, or LPI, with NDVI and its spatial variation, such a characteristic scale is identified between grain sizes of 500 and 1000 m and using 12-category thematic classification (Fig. 5).

4.3. Problem of thematic resolution in LULC change studies

While contemporary remote-sensing technology offers an opportunity for standardization and provides high temporal resolution, the problem of thematic resolution in historical LULC change studies requires proper consideration. Detailed information about landscape patterns in the past decreases dramatically as we expand the time frame of analysis. Historical data often do not conform to modern classifications or the level of classification detail being currently used. Classification schemes evolve over the time which may require additional cross-tabulation or semantic analysis. In general, we have limited power to conduct long historical studies of landscape dynamics with a sufficiently high level of thematic detail. On the other hand, considering the pace of innovation in the technology it is likely that new land-cover categories that never existed before will become common in urban areas. Such new surfaces will have intended or unintended major influences on ecological processes and may have very different spectral properties, which will require major changes in classification systems. A good example is the development of sustainable building materials or pervious and cool pavements designed to alleviate extensive urban heating, manage storm water, and reduce pollution (http://www.asusmart.com/pavements.php). Lastly, the failure of remote-sensing systems may also create gaps in data for LULC mapping that will require the use of alternative data sources, with implications for LULC classifications. Therefore, the problem of thematic resolution for long-term ecological studies of urban areas is critical. We recognize two related issues — the compatibility of classification schemes and the level of thematic detail. The compatibility issue can be solved by adjusting all classifications to a common thematic resolution. Our results suggest that consideration of thematic resolution should be done in concert with modifying the spatial resolution of data. It is also possible to use some of the landscape metrics computed from data with varying levels of spatial and thematic detail to analyze changes, if reliable scaling relations can be established between datasets. Generally, however, it is difficult to find such relationships for metrics used to describe configuration of patches.

4.4. Effects of variability in desert vegetation on temporal landscape pattern analysis in Phoenix

The extremely variable physiognomy of desert vegetation in the Sonoran Desert creates additional challenges for studies of landscape temporal dynamics. Some landscape metrics were sensitive to inter-annual fluctuations in vegetation cover, which in turn depend heavily on precipitation amount and timing. A good knowledge of seasonal phenological cycles and long-term vegetation dynamics of the geographic area under consideration is a critical factor in interpreting LULC change and determining the success of temporal LPA. In the desert environment, for example, acquisition of images at approximately the same time of year does not guarantee the accurateness of pattern depiction because phenological cycles vary broadly from year to year. Besides complex phenology, remote sensing of desert vegetation is constrained by sparse vegetative cover, spectrally unique plant adaptations to desert climate, and bright soil background conditions (Asner, 2004; Okin and Roberts, 2004). All these factors greatly reduce mapping capabilities of desert vegetation in the area.

The ability to map vegetation patterns accurately is highly desirable for ecological studies of the urban landscape (Buyantuyev et al., 2007). Vegetation was mapped both as a separate class and as an integrative component of several other classes. The maps we used in temporal analysis were made from images collected in March through late May which corresponds to the peak of growth in the Sonoran Desert. However, due to inter-annual variations the spring growth can be significantly delayed or almost unseen during droughts. In wet years, vegetation cover proliferates leading to considerable changes in landscape composition and configuration of patches. Our data demonstrated that spikes in PD, ED, SHDI, SHEI, LPI, MPS, LSI, and CONTAG in 1993 are directly related to higher primary productivity. All these metrics indicate increased fragmentation and shape complexity of patches, which may not necessarily reflect the effects of urbanization and inferences made based on LPA. One solution would be to use a long time-series of data and conduct additional analysis of untransformed ecosystems during leaf-on (presence of desert ephemerals) and leaf-off stages. Once mapped, such patches should be retained on later maps unless they undergo major land-use/land-cover transformations. The potentially highly productive patches can also be labeled as a separate land cover.

5. Conclusions

We systematically evaluated the effects of spatial and thematic resolution in the context of this temporal analysis. We found that urban land covers, especially xeric residential land cover, increased substantially while the undisturbed desert decreased by 21%. The landscape as a whole became more fragmented ecologically and more complex compositionally and geometrically as measured by groups of compositional and configurational landscape metrics, but the majority of individual patches became more compact.

Our results, while agreeing in general with previously reported scaling relations with respect to changing spatial grain and extent, showed that scaling relations are also robust and consistent across thematic resolutions and time periods. In particular, some metrics behaved unpredictably and some exhibited scale-free behavior. Compositional metrics were correlated significantly with vegetative cover, its spatial variation, and population density. Many of these relationships revealed hump-shaped patterns with respect to increasing grain size, indicating a characteristic scale at grain sizes of approximately 500–1000 m. By simultaneously manipulating spatial and thematic resolutions, we demonstrated the importance of the MAUP problem in relating landscape patterns to vegetation and socio-economic variables. Additionally, highly variable desert vegetation due to precipitation variability poses a challenge for accurately quantifying urbanization pattern in arid environments. Choosing appropriate spatial, temporal and thematic resolutions is essential in meeting this challenge.

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