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Land fragmentation due to rapid urbanization in the Phoenix Metropolitan Area: Analyzing the spatiotemporal patterns and drivers

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A B S T R A C T

Rapid urbanization of the Phoenix Metropolitan Area exemplifies the dominant US Southwest urban growth pattern of the past six decades. Using a combination of multitemporal land cover data, gradient analysis, and landscape metrics, we quantify and characterize spatiotemporal patterns of land fragmentation observed in Phoenix. We analyze historical, qualitative data to identify five major socio-ecological drivers critical to understanding the urbanization processes and fragmentation patterns: population dynamics, water provisioning, technology and transportation, institutional factors, and topography. A second objective is to assess the applicability and accuracy of National Land cover Database (NLCD)-—a widely used land cover dataset—-to detect and measure urban growth and land fragmentation patterns in the relatively treeless desert biome of the US Southwest. In contrast to studies in the temperate eastern USA where NLCD has proved inaccurate for detection of exurban development, our study demonstrates that NLCD is a reliable data source for measuring land use in the southwest, even in low-density environments. By combining qualitative analyses of social-ecological drivers with fragmentation analyses, we move toward an improved understanding of urbanization and insights on the human modification framework used widely in land change science.

Introduction

Rapid expansion of the Phoenix Metropolitan Area exemplifies the dominant US Southwest urban growth pattern of the past six decades (Luckingham, 1984; Wu, Jenerette, Buyantuyev, & Redman, 2010). Even with the current housing market downturn that began in 2007, Phoenix continues to grow in population and remains the sixth largest city in the nation. Aggressive real estate development, especially since the World War II, has resulted in large scale, low-density residential development in the Greater Phoenix area (Buyantuyev & Wu, 2009; Gober & Burns, 2002; Heim, 2001; Keys, Wentz, & Redman, 2007; Redman & Kinzig, 2008; Roach et al., 2008). One consequence of this development is increasing land fragmentation, which may include subdivision of land into discrete land uses, conversion from native to designed land cover, or development in a non-contiguous or "leap frog" pattern (Clark, McChesney, Munroe, & Irwin, 2009; Heimlich & Anderson, 2001; Irwin & Bockstael, 2007; Theobald, 2001). Such landscape patterns significantly alter ecological functions and processes (Alberti, 2005; Turner, Gardner, & O' Neill, 2001) with important consequences for ecosystem services, including the loss of habitat and wildlife corridors, decreases in agricultural and forest productivity, as well as reduction and elimination of culturally-significant open spaces and natural amenities (Burchell et al., 1998; Carsjens & van der Knapp, 2002; Dale, Archer, Chang, & Ojima, 2005; Schipper, 2008).

In this paper, we analyze and characterize the rapid urbanization trends in Phoenix with a specific focus on land fragmentation patterns. The paper has two primary objectives: (i) to assess the applicability and accuracy of National Land cover Database (NLCD)—a widely used land cover dataset—-to detect and measure urban growth and land fragmentation patterns in the relatively treeless desert biome of the US Southwest; and (ii) to quantify and categorize the spatiotemporal patterns of land fragmentation. We conclude with a short discussion on drivers of changes in land use, land cover, and fragmentation in Phoenix.

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Study area and methods

Study area

The urbanized area of Greater Phoenix extends 120 km from east to west and 60 km north to south, encompassing a population of 4.2 million. There are 26 cities within the Phoenix Metropolitan Area, but the City of Phoenix is the dominant municipality (Fig. 1: Map of Study Site). The Phoenix Metropolitan Area (hereafter Phoenix) is situated in the Sonoran Desert and has a mean annual precipitation of 180 mm. Large supplies of surface water diverted from the Salt, Verde, Gila and Colorado Rivers, as well as regulated groundwater pumped from local aquifers, have made possible irrigated agriculture, industrial production, and lush vegetation relative to background flora. However, all sources are considered under risk in the face of climate change (Bolin, Seetharam & Pompeii, 2010; Gober, Kirkwood, Balling, Ellis, & Deitrick, 2010). While 60% of the land in Maricopa County is still covered by deserts, the urban built-up area has dramatically expanded from 3% of the total land in 1955 to almost 20% in 2001, mostly at the expense of agricultural and desert land (Redman & Kinzig, 2008). The expansion is continuously radiating outward, except where constrained by natural and institutional barriers, such as South Mountain or federally protected American Indian reservations.

Land conversion and fragmentation is most acute at the metropolitan fringe. Communities such as Cave Creek, Queen Creek, Buckeye, and Fountain Hills have undergone significant land use and land cover change over the last decade. To capture these and other fragmentation hot spots, we selected a set of transect windows using east-west, north-south, northeast-southwest, and northwest-southeast orientations that run through the central city of Phoenix. The extent of the study area matches that of the Central Arizona – Phoenix Long Term Ecological Research (CAP LTER) project (Grimm & Redman, 2004).

Methods and data

This study combines land cover data, landscape metrics, gradient analysis, and socioeconomic data. The major source of land cover data is the National Land Cover Database (NLCD), which provides seamless coverage for the United States. NLCD was the first nationwide initiative that provided consistent land cover inventory for the US and it has been widely used in studying urbanization (Burchfield, Overman, Puga, & Turner, 2006; Vogelmann, Sohl, Campbell, & Shaw, 1998) and landscape fragmentation (Heilman, Strittholt, Slosser, & Dellasala, 2009; Riitters et al., 2002). Due to problems arising from differences in source data and classification systems of NLCD in 1992 and 2001 (for details, see Homer et al., 2007), we "retrofitted" 1992 land cover classes to match 2001 classes (Fry, Coan, Homer, Meyer, & Wickham, 2009). After we generated land use maps for 1992 and

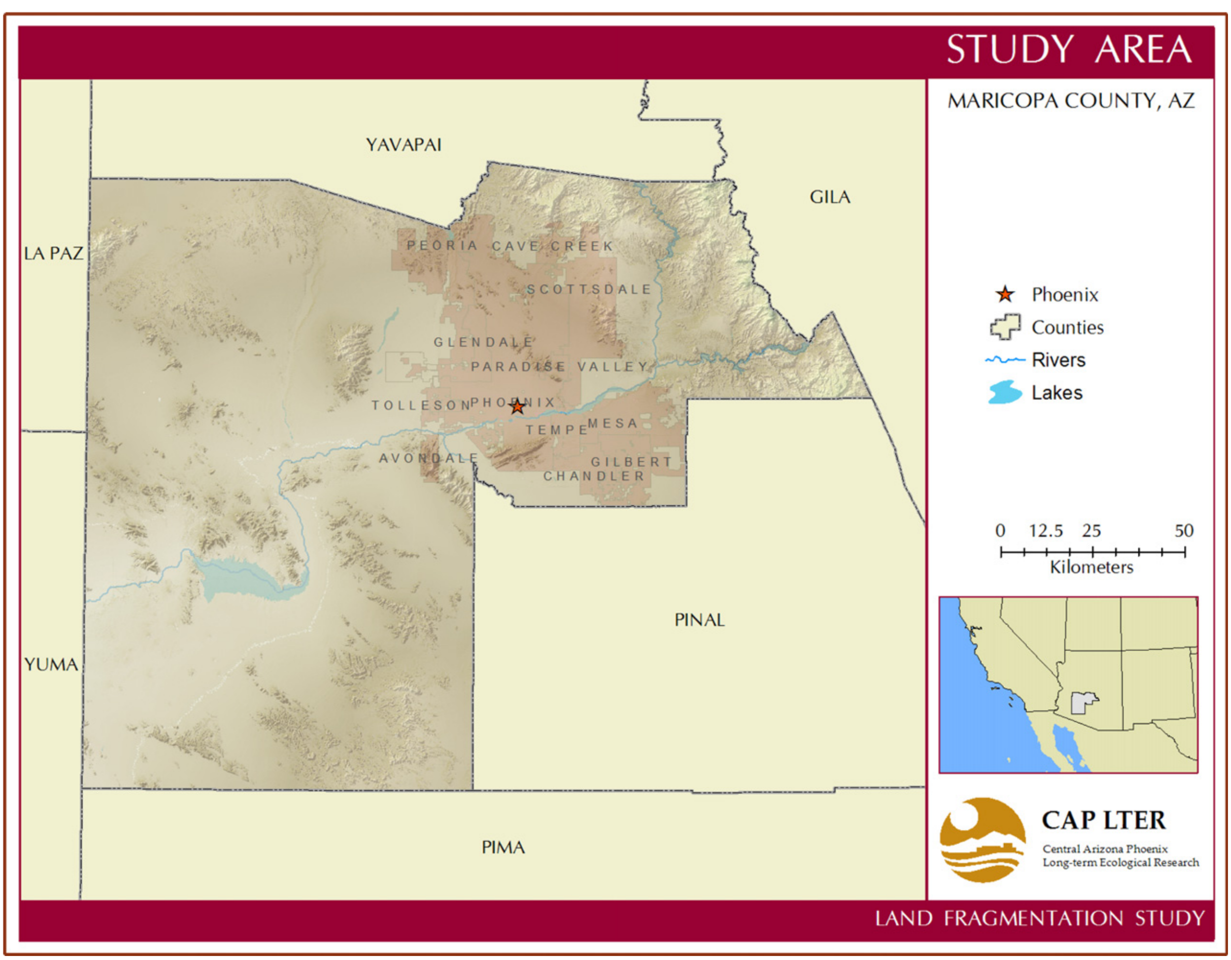

Fig. 1. Study area.

2001, we validated these maps based on expert knowledge of scientists in the CAP LTER.

The most common method to analyze land fragmentation is to apply landscape metrics on land cover maps extracted from remotely sensed data, which can identify and describe landscape patterns that are generally not directly observable to human eyes. As demonstrated in several previous studies (Cushman & McGarigal, 2002; Seto & Fragkias, 2005; Wu et al., 2010), landscape metrics can quantify and characterize the spatial patterns observed at a landscape based on the shape, size, number, and other spectral signatures of land parcels or patches captured in remote sensing data. Unlike in the past when detection and analysis of land use and land cover change were often considered a cumbersome task, increasing availability of land cover data derived from remotely sensed images have made it easier in recent years to study and corroborate the dynamic nature of urbanization (Batisani & Yarnal, 2009; Dietzel, Herold, Hempfill, & Clarke, 2005; Thapa & Murayama, 2000; Vogelman et al., 1998; Yang & Lo, 2002) and to detect urban land fragmentation patterns (Bhatta, Saraswathi, & Bandyopathyay, 2010; Luck & Wu, 2002; Munroe, Croissant, & York, 2005; Schneider & Woodcock, 2008; Ward, Phinn, & Murray, 2000).

The reliability of NLCD data for measuring characteristics of exurban development has been questioned with evidence from temperate forests in the eastern USA, where satellite images with moderate resolutions are found to be too coarse to detect low-density settlement (Irwin & Bockstael, 2007). In the case of arid regions of the southwestern USA, however, we hypothesize that NLCD, specifically the 2001 NLCD, provides sufficient accuracy of low- and medium-density development for the relatively treeless landscape of the region and the explicit considerations of impervious surface in the 2001 NLCD, which improved the accuracy of the dataset for urban areas (Homer, Huang, Yang, Wiley, & Coan, 2004; Stehman, Wickham, Smith, & Yang, 2003).

Testing the accuracy of NLCD

To validate the accuracy of NLCD, we used two highly detailed, geocoded land use maps collected from the Maricopa County Assessor's Office parcel data (MCAPD) of 2001 and the Maricopa Association of Governments land use coverage (MAGLC) data of 2000. MCAPD is based primarily on the County Tax Assessor's Data, which systematically organizes land use categories with detailed property descriptions. Boundaries of all private and public parcels, which number more than 1 million, are digitized and classified under one of the 2092 "property use codes." Using sensitivity analysis (Batty & Howes, 2001), we checked the distribution of parcels to ensure that MCAPD is a reliable reference, mainly to eliminate the possibility of errors resulting from the conversion of this vector data to a raster format in the accuracy assessment. MAGLC is derived from aerial photographs and it has 46 major land use categories (see Appendix A for supplementary information covering general description of all the dataset used in the study, land use classification system, and sensitivity analysis).

After reprojection (UTM Zone 12, WGS 1983), the MCAPD and MAGLC dataset were resampled to 30 m × 30 m cell size to match the resolution of NLCD. The MCAPD with its 2092 property use codes and MAGLC with its 46 land use categories were subsequently reclassified into six land use classes matching NLCD classification: developed, high intensity (DHI), developed, medium intensity (DMI), developed, low intensity (DLI), open space or very low intensity (VLI), transportation (TRP), and undeveloped (UND) (see Appendix A). Only those land cover categories with more than 5% impervious surface were

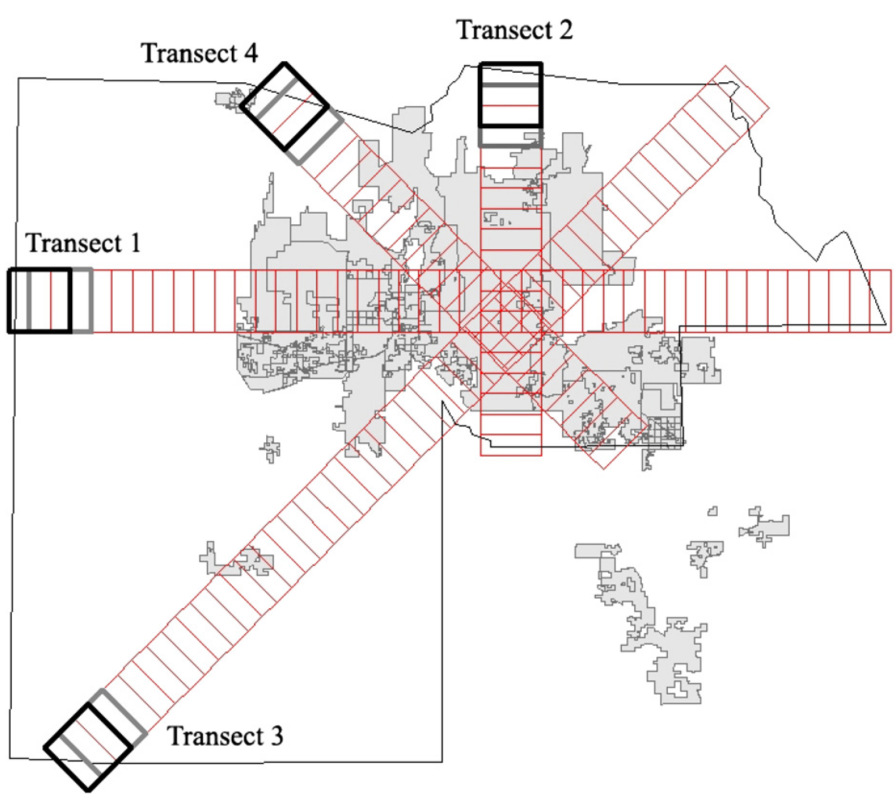

Fig. 2. Using four transects through the urban center area. The measures were calculated along the transects with a 15 km × 15 km overlap moving window. The window moves 5 km each time.

Table 1
Land fragmentation metrics.

Pattern measure	Definition	Explanation
Class area (km^2)	$\sum_i a_{ik}$	a_{ik} = area of patch i with land use k; Units = km^2
Percentage of landscape	$\frac{\sum_i a_{ik}}{A}$	A = total landscape area (km^2); Units = %
Number of patches	n_k	n_k = total number of patches in land use k
Patch density	$\frac{n_k}{A}$	Same definitions as above; Units = 1/km^2
Mean patch size	$\frac{\sum_i a_{ik}}{n_k}$	Same definitions as above; units = km^2
Mean perimeter-to-area ratio	$\frac{\sum_i \frac{I_{ik}}{a_{ik}}}{10^6 \cdot n_k}$	l_{ik} = total perimeter length of patch i with land use k; units = m/m^2
Contrasting edge ratio	$\frac{e_{kj}}{e_{kk}}$	E_{kj} = total length of edge shared between cells with the focal land use k and contrasting land use j; e_{kk} = total length of edge shared between cells with the focal land use k
Contrasting edge proportion	$\frac{e_{kj}}{e_{kj}+e_{kk}}$	Same definitions as above; varies between 0 and 1
Mean dispersion	$\frac{\sum_i p_{iik}}{n_k}$	p_{jik} = proportion of cells of contrasting land use j that are within a specified distance of cell i with focal land use k; n_k = total number of cells with land use k; varies between 0 and 1
Contrast weighted edge density (CWED)	$\frac{e_{kj} \cdot d_{kj}}{100A}$	Same definitions as above; d_{kj} = edge contrast weight, here d_{kj} = 1 units = m/hectare
Contagion (CONTAGION)	$\left[1+\frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left[(p_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]\cdot\left[In(p_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]}{2\ln(m)}\right]100$	P_i = proportion of the landscape occupied by patch type (class) i; g_{ik} = number of adjacencies (joins) between pixels of patch classes i and k based on the double-count method; m = number of patch classes present in the landscape, including the landscape border if present.

All the measures are computed based on raster data with 30 m × 30 m cells.
Metrics 1 and 2 are the area of land type and its percentage of landscape. They provide basic information for urban sprawl. Metrics 3 and 4 are number of patches and patch density. They measure the fragmentation degree from the patch number aspect. Increased patch number and density generally represent an increased fragmentation. Metrics 5 and 6 are mean patch size and mean perimeter-to-area ratio, and they focus on size and shape of the patches. If the total area of a land use type keeps the same or increases, a decrease of mean patch size of this class type indicates an increase in the fragmentation. Perimeter-area ratio is a simple measure of shape complexity. An increase of the value indicates a more complex patch shape or the decrease in patch size with a constant shape.

considered "developed", which is consistent with Irwin & Bockstael (2007). We overlaid the land cover map created from the 2001 NLCD and the reference map (i.e., MCAPD) and generated an error matrix by calculating the total cell numbers intersected in both (Congalton & Green, 1993). We also compared the accuracy of NLCD with the MAGLC dataset.

Measuring land fragmentation and spatial heterogeneity

We selected two methods to analyze urban growth patterns and their spatial heterogeneity: (i.) average fragmentation for the whole landscape at the class level to reflect landscape composition, especially its relationship to density; and (ii.) fragmentation distribution along the transects at the landscape level to capture landscape configuration (Cushman & McGarigal, 2002). The transect methodology was applied to detect fragmentation along the urban-rural gradient, as well as the directionality of urbanization patterns. Considering the benefits of using a full coverage moving windows analysis (Riitters et al., 2002) in the transect analysis (Luck & Wu, 2002; Yu & Ng, 2007), we applied the same size transect block of 15 km × 15 km across the study area, in which the block moves along the transect overlapping at 5 km intervals and generates a mean value for the center pixel to be used for the fragmentation analysis (Fig. 2).

Since we are interested primarily in the spatiotemporal patterns of urbanization, we reclassified the six NLCD classes into two: developed and undeveloped.[1] We rasterized the land cover map with a cell size of 30m for analysis in FRAGSTAT, a landscape pattern analysis program (McGarigal, Cushman, Neel, & Ene, 2002). We also considered the sensitivity of both the resampled cell size and the sensitivity of landscape metrics (Saura & Martinez-Millan, 2001; Wickham & Ritters, 1995). To be consistent with the Irwin & Bockstael study (2007), we chose the same suite of landscape pattern metrics reflecting area, density, shape, edge, and spatial relationship of the land types and selected two to three metrics for each of these categories. Selected landscape metrics for this study were patch density, mean patch size, mean perimeter-to-area ratio, contrasting edge ratio and contrasting edge proportion between developed and undeveloped land, mean dispersion, contrast weighted edge density, and contagion (see Table 1 for descriptions). The increase of patch number, density, edge, complexity of the shapes, and dispersions can indicate an increase in land fragmentation. Lower patch sizes and contagion values exhibit a disconnected land use area, and higher fragmentation. The contrasting edge ratio and proportion are normalized by the length of like edges and by the sum of like edges and contrasting edges, as shown in Table 1. When measuring the landscape fragmentation metrics of each developed land type (e.g.,

[1] Developed - characterized by a high percentage (30 percent or greater) of constructed materials such as asphalt, concrete and buildings; "undeveloped" - characterized by water, barren, forest, shrub land, herbaceous upland, woody wetlands and emergent herbaceous wetlands.

Table 2
Comparison of 2001 NLCD land cover and 2001 Maricopa County parcel data.

Land use Codes	Actual land use[a]	No. of developed cells from County Parcel 2001	No. of developed cells in 2001 NLCD[b]	% labeled developed by 2001 NLCD	Irwin and Bocksteal (2007)	MAGLC accuracy
1	Developed, High Intensity (DHI)	6411511	4446419	69.35	83	85.11
2	Developed, Medium Intensity (DMI)	3766422	2769014	73.52	62	95.46
3	Developed, Low Intensity (DLI)	7355092	5900874	80.23	26	66.43
4	Open space, Very Low Intensity (VLI)	10640799	7064870	66.39	8	63.14
5	Transportation	27315	25721	94.16	80	82.42
6	Undeveloped	27800940	2432922	8.75	6	3.38

[a] Developed categories have at least 5% impervious surface and these categories are based on the percentage of constructed materials, such as buildings, asphalt, concrete, etc.
[b] Grid cells are 30 × 30 m.

high density development), we define the "focal land use" to be the developed land type at that density, and "contrasting land use" to be "undeveloped" land. When measuring the fragmentation metrics of undeveloped land, we define the "focal land use" as the "undeveloped" land, and "contrasting land use" to be "all developed," in which different density land development are aggregate to one land type.

Results and discussions

Accuracy of NLCD for the US Southwest

At the outset of this study, we hypothesized that the NLCD would accurately capture urbanization and sprawl in the US southwest, mainly because of sparse vegetation coverage in the region, which minimizes chances of misclassification of low-density settlements as vegetation classes, such as cultivated land, forest, or grassland. Similar to the Irwin & Bockstael's study (2007), we tested this hypothesis by comparing NLCD with the highly detailed MCAPD based on "Tax Assessor Data" and contrasted both datasets to check how NLCD performed in each of the land use classes. The summary results are presented here in an error matrix (Table 2).

As reported in Table 2, we compared the accuracy of NLCD with both the 2001 MCAPD as well as the 2000 MAGLC. The primary focus of this table is to show a comparison of number of cells identified as "developed" cells in the MCAPD and the percentage of those cells accurately identified in the NLCD. In sum, the results support our claim that the 2001 NLCD recognizes "low-density land use" category in Phoenix at a much higher rate than what the Irwin & Bocksteal study (2007) reported for the same category in Maryland. In this case, 80% of the "developed, low intensity (DLI)" areas and 66% of the "open space, very low intensity (VLI)" areas were correctly identified, compared to 26% and 8% respectively found in Maryland. Thematic accuracy is consistently high across all other land use classes as well, suggesting that the overall accuracy of NLCD is satisfactory for arid regions with sparse vegetation. Our comparison of NLCD to the MAGLC dataset also reaffirmed the accuracy of NLCD data for Phoenix, showing 66% and 63% for DLI and VLI respectively, reconfirming the satisfactory accuracy level of NLCD.

Spatial and temporal patterns of land fragmentation and spatial heterogeneity

Table 3 reports the results of fragmentation metrics applied to land use maps generated from the NLCD 1992 and 2001 dataset. In this table, all residential and non-residential developed land use types are grouped in the "developed" category and all other land use types with no footprints of residential properties, such as deserts, agricultural lands, and forests are categorized as "undeveloped." To capture and differentiate the exact nature of fragmentation patterns that occurred among different urban land use types and their spatial variations across the study area, the "developed" land use category is further disaggregated into three distinct types: high density, low-mid density, and very low-density. As indicated in the changes reported in the "class area pattern measure" and the "percentage of landscape measure" in the table, quite a significant conversion and modification in land use/cover types occurred between 1992 and 2001, corresponding with urban expansion at the urban-rural fringe.

The analysis shows a rapid increase in the area of "medium" to "very low-density" development from 1992 to 2001, indicative of suburban sprawl and exurbanization. The decrease of patch density and the increase of mean patch size of overall development, except very low-density development, potentially capture "in-fill development" in Phoenix (Heim, 2001). The decrease of mean perimeter-to-area ratio for the "all development" indicates that the patch shape tends to be less complex. A comparison of the results among various land use types that fall under "developed" category – ranging from the high to very low-density developed areas – indicates that high density areas are experiencing a decrease of land fragmentation, while most metrics for low-density development indicate an increasing level of fragmentation from 1992 to 2001. The differences are especially clear in contrasting edges and dispersion metrics. Contrasting edge ratio dramatically increased by 355.87%, and mean dispersion (1 km) increased by 119.93% during the ten years.

If we focus on one year and compare the three developed land types, the most obvious phenomenon, as we expected, is the changes from undeveloped to areas to very low-density, to mid-low, and to high density; the fragmentation is shown increasing, especially in 2001, and it is corroborated by most of other fragmentation metrics, such as patch size, contrasting edge and dispersion. Low-density development, which typically happens on the urban-rural fringe, contributes to an increasing level of land fragmentation in undeveloped areas. For both developed and undeveloped area, the growth rate of the mean dispersion measured within 5 km distance is not as high as the mean dispersion within 1 km, suggesting that urban growth is penetrating into undeveloped areas mostly within 1 km of the existing developed area. This finding suggests that development is occurring in a more contiguous rather than "leap frog" fashion.

Because the scale and thematic resolution of land cover data can strongly influence the evaluation of landscape pattern and fragmentation (Buyantuyev, Wu, & Gries, 2009; Wu, 2004), we considered a set of transects with different orientations and consistently applied them with two fragmentation metrics: contrast weighed edge density (CWED) and contagion (CONTAG) metrics. We applied a 450 × 450m (210 m radius) square moving window analysis for the whole area. The results are raster data of land fragmentation distribution. To test the fragmentation gradients to the city center, based on the spatial fragmentation map, four transects at eight directions through the urban center area were

Table 3
Aggregate land use pattern measures.

Pattern measures	Developed												Undeveloped		
	All developed			High density			Low-mid density			Very low-density					
	1992	2001	% change	1992	2001	% change	1992	2001	% change	1992	2001	% change	1992	2001	% change
Class area (km^2)	1380	2200	59.46	476	110	−76.92	758	1469	93.96	146	621	325.23	22444	21624	−3.66
Percentage of landscape (%)	5.79	9.23	59.46	2.00	0.46	−76.92	3.18	6.17	93.96	0.61	2.61	325.23	94.21	90.77	−3.66
Number of patches	20459	9227	−54.90	43041	6551	−84.78	15464	9580	−38.05	9611	20336	111.59	12283	6001	−51.14
Patch density ($1/km^2$)	1.00	0.39	−61.44	1.81	0.27	−84.78	0.65	0.40	−38.05	0.40	0.85	111.59	0.52	0.25	−51.14
Mean patch size (km^2)	0.07	0.24	253.57	0.01	0.02	51.64	0.05	0.15	213.09	0.02	0.03	100.97	1.83	3.60	97.20
Mean perimeter-to-area ratio (m/m^2)	1086.24	890.46	−18.02	1095.12	794.19	−27.48	1067.14	856.83	−19.71	1035.15	840.35	−18.82	1050.24	762.73	−27.38
Contrasting edge ratio [a]	0.22	0.35	63.25	0.35	0.03	−91.08	0.12	0.17	40.01	0.23	1.04	355.87	0.01	0.03	156.85
contrasting edge proportion [a]	0.18	0.26	46.71	0.26	0.03	−88.31	0.11	0.15	34.13	0.19	0.51	174.17	0.01	0.03	152.12
Contrast weighted edge density (m/hectare)	7.56	18.53	145.14	3.99	0.10	−97.62	2.46	6.53	165.41	0.84	11.91	1319.77	7.56	18.53	145.14
Mean dispersion (1 km^2) [a]	0.24	0.31	29.39	0.33	0.10	−68.47	0.18	0.20	14.21	0.28	0.61	119.93	0.01	0.03	114.14
Mean dispersion (5 km^2) [a]	0.36	0.39	8.69	0.42	0.17	−58.89	0.31	0.29	−3.98	0.46	0.67	44.72	0.02	0.04	79.94

For "High density (Low-Mid density, Very low-density) developed" land use measures, focal land use = High-density (Low-Mid density, Very low-density) developed, contrasting land use = undeveloped.
For Undeveloped, focal land use = undeveloped, contrasting land use = developed, and the calculation is based on two land types only.
[a] For "All developed" land use measures, focal land use = developed, contrasting land use = undeveloped.

selected, and measures were calculated each time for a 15 × 15 km block, which moves 5 km each time along the transects (Fig. 3).

Fig. 3 illustrates land fragmentation along the urban-rural gradient covered in the four transects using two metrics: CWED and CONTAG. Results from all the transects show that land fragmentation reaches the highest point at the urban-rural fringe and subsequently decreases to the lowest points at the city center area and remote undeveloped areas. Comparing the fragmentation change between 1992 and 2001, two peaks observed at both sides of the city center in these transects confirm what previous studies have claimed: higher fragmentation levels are generally associated with the low-density developed areas (Clark et al., 2009; Dale et al., 2005; Theobald, 2001). Along all transects, peaks of fragmentation are shifting outwards around 10 km from city center. Fragmentation grew the fastest at 30–40 km east to the city center (Table 4). Transect 1, with an east-west orientation, shows a similar gradient fluctuation as transect 3, which has a southwest-northwest orientation. They both show a rapid increase of fragmentation at 30 km east of the urban center. Transect 2 has a similar gradient as that of transect 4. They exhibit a rapid increase of fragmentation between 1992 and 2001 at 35–40 km north of the urban center. As transects 2 and 4 travel through both urban and rural areas, the overall fragmentation level is higher than that of transects 1 and 3.

These transects can be used to explore relationships between land fragmentation and sprawl, and the potential drivers of suburbanization. Low-density residential areas, consisting mainly of single family dwellings are strongly associated with higher levels of fragmentation. Similarly, the asymmetric "peaks" and "valleys" in the fragmentation curve characterizes urban-rural fragmentation gradients, confirming that areas of greatest fragmentation are located at the urban-rural fringe. It fragmentation curve forms a distinct "monocentric" pattern centered on Phoenix, with expansion of development creating a continuously dense urban center and a highly fragmented rural area. During 1992–2001, the urban core of the regions shows decreased fragmentation, while rural areas witnessed increased fragmentation. The peaks of fragmentation shifted outwards from the city center during the study period. Fragmentation grew the fastest north and east of Phoenix city center, and particularly in Scottsdale, Fountain Hills, Apache Junction, and Mesa. Exploration into the potential drivers of these changes, to which we now turn, can help explain past land fragmentation patterns and predict the future trends and directions of land fragmentation.

The drivers of Phoenix's rapid urban growth

The pattern of land fragmentation in Phoenix is the result of a combination of biophysical and social processes, particularly urban population dynamics, water provisioning, transportation, institutional factors, and topography. During the study period (1992 and 2000), Phoenix grew in population from 2,272,582 to 3,199,440 (41% increase), mainly from an influx of new migrants attracted by booming economic opportunities in the valley. Recent estimates put the population of Metropolitan Phoenix at 4.4 million (US Census Bureau, 2010). Much of the valley is "master-planned" for low intensity, single family residences, but there has also been infilling of high density residential development (e.g., multistoried apartments, condominiums) in the urban core areas of Phoenix. Until the recent slump in the housing market, single family housing in the fringe expanded aggressively, driven by rampant speculation (Gober & Burns, 2002).

The rapid development of several peripheral cities in Phoenix particularly between the 1980s through 2006 occurred mainly through aggressive acquisition and annexation of formerly agricultural and desert lands. Population growth aside, the drivers of this

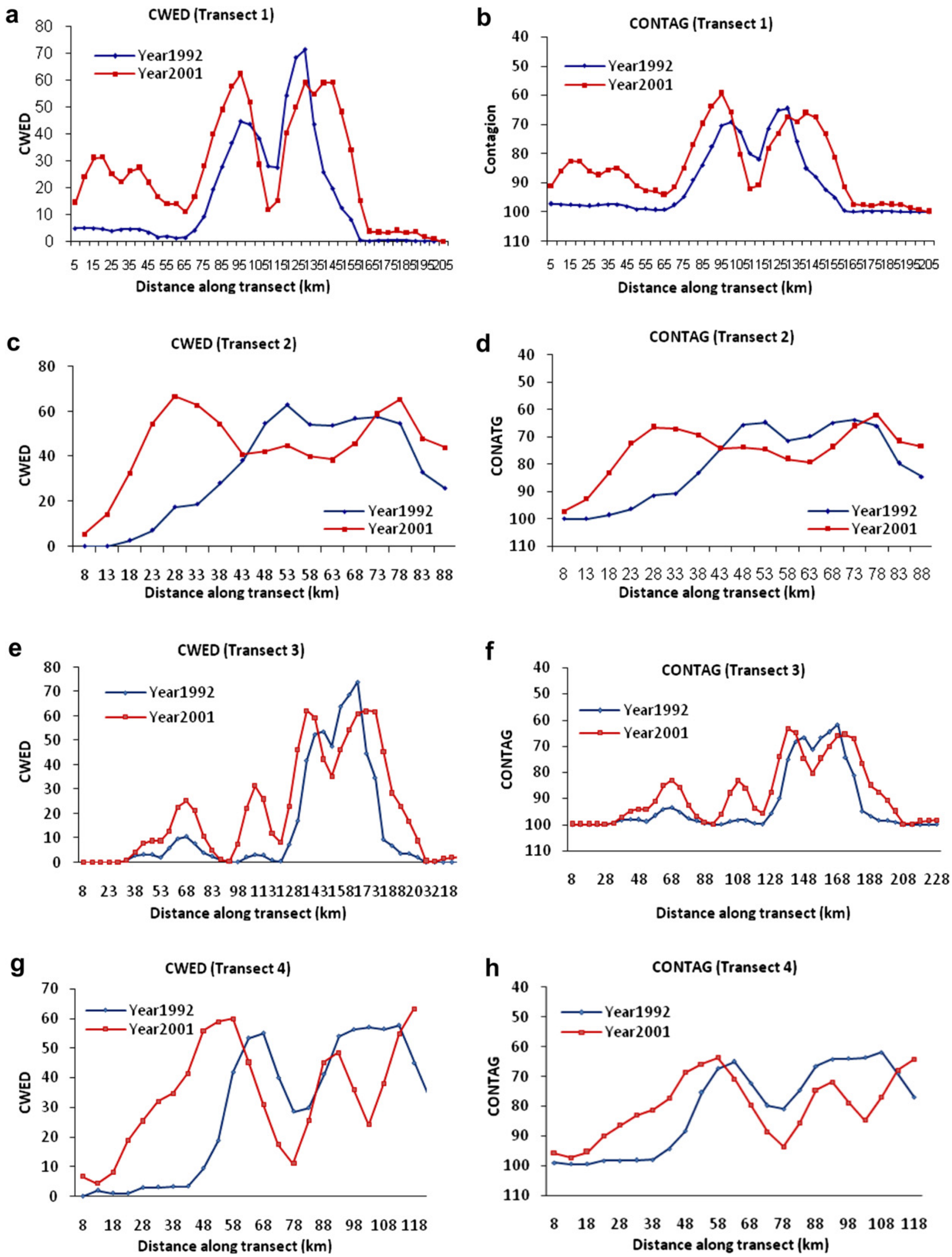

Fig. 3. Spatial patterns of land fragmentation.

land use change pattern can only be explained by examining the historical land use legacy of this area. First of all, it is important to note that rapid urbanization of this desert city is not possible without ensuring adequate and reliable water supply. Water provision has played a key role in settlement patterns in this area, starting from the prehistoric Hohokam civilization, which built extensive canals for irrigated agriculture in the valley, sustaining a permanent settlement for nearly a thousand years (Redman & Kinzig, 2008). Modern development is dependent on water diverted from near and distant rivers, including the Salt, Gila, Verde, and Colorado. The first

Table 4
Results of landscape metrics.

Transect	Metrics	Distance from city center to the fragmentation peak on one side (km)			Distance from city center to the fragmentation peak on the other side (km)			Distance from city center to the location where fragmentation increased the fastest from 1992–2001
		1992	2001	Shifting from 1992–2001	1992	2001	Shifting from 1992–2001	
1	CWED	20	20	0	15	15	0	30
	CONTAG	15	20	5	15	25	10	30
2	CWED	10	35	25	10	15	5	35
	CONTAG	10	35	25	10	15	5	35
3	CWED	15	25	10	15	20	5	30
	CONTAG	5	15	10	15	20	5	30
4	CWED	20	25	5	15	35	20	40
	CONTAG	20	25	5	25	35	10	40

modern settlement was established in 1870, using many of the ancient Hohokam canals for irrigation, and the city gradually expanded outward with the growing demand for agricultural lands, particularly cotton farms (Gober, 2006; Redman & Kinzig 2008).

In 1911, the Bureau of Reclamation built the Roosevelt dam to provide water for the growing agricultural activities in the valley (Luckingham, 1984). Growth in population and agricultural production led to a continuing search for "new" water sources, including Colorado River water transported in the Central Arizona Project canals, begun in 1973, and concerted efforts in groundwater pumping (Glennon, 2009). Since the passage of the Arizona Groundwater Management Act in 1980, reliance on groundwater has been curtailed, but it is unlikely that safe yield, meaning that groundwater pumping is equal to recharge, will be achieved by the stated goal of 2025 (Gober, Kirkwood, Balling, Ellis, & Deitrick, 2010). Water sources for residential development have come largely from retirement of agriculture, which reduced its water use from 1.3 million acre-feet in 1985 to 0.7 million acre-feet in 2005 (Gober et al., 2010). Assured Water Supply Rules (1994) associated with the Groundwater Management Act require developers to supply 100 years of "assured water" for all new residential developments outside of municipal water provision boundaries, which many achieve by purchasing farmland with senior water rights (Heim, 2001). The 100 years of assured water, however, is not iron-clad since state legislation allows exemptions for smaller developments and relaxed rules for municipal water providers that spend funds on water conservation and education (Hirt, Gustafson, & Larson, 2008). Transfer of water and water rights can have significant in suburban sprawl and exurbanizations (Díaz-Caravantes & Sánchez-Flores, 2011). Purchasing agricultural lands that have senior water rights is a common means of securing water supplies for development in Phoenix. In the past six decades, a significant increase in the total urban area at the expense of desert and agricultural lands has been the major land use/cover change trend. In the 1950s, the urban area was only about 3% of the total land, while the desert was 82% and agriculture area was 14%. By the late 1990s, the urban area increased to 18% and the desert and agricultural lands decreased to 66% and 11% respectively (Redman & Kinzig, 2008).

Historically, government employment opportunities, especially with the military, played an important role in the local economy with the establishment of four military bases around Phoenix (Konig, 1982). Rapid growth in defense contracts and electronic industries, such as Honeywell, Lockheed Martin and Intel, public expenditures on freeways, schools, and water infrastructure, and strong commitments to low taxes and pro-growth policies helped sustain a growing population and metropolitan region after the Second World War. New residents were also drawn to Phoenix by an amenable winter climate and ample availability of affordable, single family dwellings (Gober, 2006). Many cities in the Phoenix Metropolitan Area have successfully promoted such amenities along with excellent health services to retiree populations (Frey, Liaw & Lin, 2000; Duncombe, Robbins, & Wolf, 2003; Glaeser & Tobio, 2007; Gober, 2006; Rudzitis, 1999).

Dominance of the automobile is another key factor in explaining the shape, extent, and configuration of urbanization in Phoenix (Glaeser & Kahn, 2003). Although Phoenix has invested in a light rail and bus system, only 2.3 percent of workers regularly use public transportation to commute (US Census Bureau, 2010). Despite heavy reliance on cars, Phoenix was late in freeway construction. Interstate 10 did not traverse the metropolitan region until 1990. In part this reflected a reluctance of residents to become the next Los Angeles (Gober, 2006), but also because the orthogonal system of wide surface streets provided a good alternative to intra-urban freeways (Gammage, 1999). Eventually, however, traffic congestion fueled expansion of the state and federal highway system in the 1990s, looping around the city and pushing development outward, especially to the east, southeast, and north (Gober, 2006). This expansion of highway and freeway network during the 1990s was imminent given the rapid economic and population growth of the era. Major growth took place in relatively smaller cities at the periphery, such as Buckeye, Chandler, Gilbert, Peoria, Sun City, Fountain Hills, and Surprise. These cities were hit the hardest by the recent housing bust, leaving many empty houses and apartment complexes. Real estate developers, well supported by the local growth policies, have been very aggressive in pursuit of "opportunities for capital gains" (Heim, 2001), often resulting in exurban expansion on desert and farmland creating significant spatial heterogeneity in land use patterns within the valley.

Spatial heterogeneity in the valley is tied closely to local topography and institutional factors (Bolin, Grineski & Collins, 2005). The basin and range topography with isolated mountains in Phoenix has created opportunities for residential development to expand into the foothills and jump over the mountains (many of which are held by public entities). Phoenix is surrounded by the Tonto National Forest, four military bases, large city mountain parks, and state trust land, which act as barriers to continuous urban growth. Topographic variation also influences microclimates and creates aesthetically pleasing and valuable scenic views, which encourages residents and developers to move farther out into the foothills and mountains. Growth onto Forest Service or city parkland is unlikely, but conversion of state trust land has been relatively common (Gammage, 1999). Indian reservations also act as local growth controls. In Phoenix, urbanization skipped over Indian communities to the eastern reach of Mesa and Scottsdale and the city of Fountain Hills, leaving rural landscapes on Indian community land in between (Gober, 2006). There has also been tough competition among the valley cities for new lands to develop their territories. Annexation allowed cities, especially Phoenix, to expand rapidly, increase property tax bases, and incorporate middle-class and wealthy regions (Luckingham, 1984). In some cases this has led to "annexation wars" such as the battle for Ahwatukee by Tempe, Chandler, and Phoenix, won by the latter during an emergency midnight city council meeting (Heim, 2001). Similar annexation conflicts erupted between Gilbert, Mesa, and Chandler in the southeast valley for the Williams Air Force Base (Lang & LeFurgy, 2007). Much of the conflict surrounding growth and annexation of undeveloped land in the Phoenix valley is associated with the growth imperative of cities and emergence in the 1990s of numerous "boomburbs," cities with double digit growth, over 100,000 in population, and an increasingly voracious appetite for city expansion (Lang & LeFurgy, 2007).

Conclusions

This paper employs a combination of qualitative and quantitative analyses of social-ecological drivers and fragmentation analyses of urban gradients to improve understanding of urbanization processes in a rapidly growing Sunbelt city. In particular, our analysis demonstrates that land cover fragmentation rates are highest in areas dominated by low-density land cover and that rates of change between 1992 and 2001 were highest in a band stretching from 30 to 40 km from the city center. Second, we find that despite increased fragmentation rates in the low-density fringe, urban growth has been more contiguous than "leap frog" in pattern. Availability of water, presence of public and American Indian reservation lands, topography, and several institutional barriers all work to create sharper lines between developed and undeveloped land than typically found on the jagged edges of metropolitan areas. The relatively treeless desert environment also improves accuracy of the NLCD for urban land cover analysis. We found that NLCD is very accurate in detecting low-density land cover, much higher than for similar studies conducted in the humid temperate regions of the eastern United States. For metropolitan Phoenix, 80% of the developed, low intensity areas and 66% of the open space, very low intensity areas were correctly identified, compared to 26% and 8% respectively found in Maryland. Others conducting fragmentation analyses in metropolitan regions, especially in dryland and grassland environments, may consider using NLCD before higher resolution data to save time and resources and to improve comparability of results across the region.

Since 2007, Phoenix has suffered through a long downturn in housing prices, persistent foreclosures, and distressed sales. Communities on the fragmented fringe have been most vulnerable to the housing bust. This pause in the long trajectory of meteoric development in the region offers an opportunity to reassess priorities for future growth. Although Phoenix does not show a high degree of leap frog development, there is plenty of space for careful infill development that can reduce fragmentation and strengthen social and ecological benefits from more compact urban forms. Any efforts to do so, however, must take into account the multitude of social and biophysical realities; some of which are discussed in this paper will continue to shape the region's future. Population and physical growth of the region will undoubtedly continue, but it is our recommendation that planners and developers not ignore the present opportunities that exist in fragmented landscapes.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.apgeog.2011.04.004.

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