

Urban Planning

Spatiotemporal analysis of Shiraz metropolitan area expansion during 1986-2014: Using remote sensing imagery and landscape metrics

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Abstract

This Paper attempts to investigate the patterns of land cover changes and also the process of urban growth in Shiraz Metropolitan Area. Since detailed information of current urban processes is required for future developments and managements of urban areas, this study utilizes remote sensing data and landscape metrics, as useful tools to gather information on urban growth and dynamics, in order to examine the spatial pattern of Shiraz metropolitan area (SMA) from 1986 to 2014. Since, the northwestern areas of SMA are superior in terms of ecological advantages, analysis of types and patterns of SMA growth were separately examined for each sector (NW, NE, SE, and SW). Five landscape metrics were used to analyze compactness and dispersion of urban patches derived from remotely sensed images. The results showed that over the past 28 years, SMA experienced sweeping changes with unexplainable growth during 1996-2006: a great horizontal expansion with 5.89 percent annual growth rate. After facing great urban sprawl, especially on the edge of the main city in the 96-06 period, periphery rural areas beyond the city borders started growing drastically during last decade. While measuring landscape metrics indicates a process of compactness in the growth patterns of NE, SE and SW areas, NW is going to be more dispersed in the coming years.

Keywords: Shiraz metropolitan area, Urban growth, Spatiotemporal analysis, Remote sensing, Landscape.

1. INTRODUCTION

In the advent of approaching the second half of the twentieth century, the perception of the city and metropolitan areas became different compared to the past. While in 1950 only two cities had a population greater than 10 million people, in 2007, nineteen cities with more than 10 million people existed in the world, out of which four were in the developed countries and fifteen in developing countries. It has been predicted this number will increase to 27 by 2025, with 22 of these cities in the developing countries [1]. This significant increase in urbanization in the last decades has had great impacts on the analysis of urban growth patterns [2- 4].

Prior to this, numerous studies on urban form like bid-rent theory [5], central place theory [6], multiple-nucleus model [7] and monocentric model [8-10] have postulated that the growth of cities can either be uniform or linear, but most of them did not deal with intra-urban relations or

the spatiotemporal dynamics of urban form. Actually, these researches are based on socioeconomic theories, without paying attention to spatial-temporal patterns of urban changes [3, 11].

It is factual that cities are a reflection of the economic, environmental, technological and social processes nevertheless; these processes are profoundly affected by changes in the spatial structure of the cities [12]. Since 1980s, when the role of planning and urban form became evident in achieving sustainable development, discussions on urban forms also gained more and more attention. And urban compaction has become a popular topic in urban studies and a powerful rival of urban sprawl [2]. Consequently, urban researchers consider compact cities against dispersed urban areas in the study of urban development patterns nowadays. As a matter of fact, today the process of urban development is investigated in the form of time and space rather than applying a linear approach to urban development.

Evolution of urban spatial structure, characterizing urban compactness or dispersion, and expressing patterns and processes of urban development have been of great interest to many researchers. For example, Galster et al.

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(2001) expressed eight dimensions of urban sprawl [13]; Ewing et al. (2002) developed a sprawl index with four factors, such as residential density, neighborhood mixed, strength of activity centers and accessibility [14]; Tsai (2005) presented four quantitative factors such as metropolitan size, density, degree of equal distribution and degree of clustering to characterize compactness or dispersion of metropolitan areas [4], and Forman (2008) presented four main structures to examine spatial patterns of urbanization [15].

However, new tools and methods like satellite imagery and landscape metrics are gradually gaining usefulness in the spatial analysis of urban areas. One of the newest approaches in urban planning is the use of remote sensing data which examines spatiotemporal patterns of urban areas and is used repeatedly in recent years, in urban studies [3, 12, 16-19]. At the moment, there exist a number of studies and models regarding urban forms and urban growth, using the remote sensing data and GIS techniques, especially for mapping, monitoring, measuring and analyzing of compactness and dispersion of urban areas [20- 25].

Besides taking advantage of remote sensing data and investigating changes of urban areas in different periods, other studies have utilized the proven techniques of landscape ecology such as landscape metrics to explain patterns of land cover changes [16-17,26-28]. The combination of remote sensing and landscape metrics can evaluate the process of urban growth with some degree of accuracy, especially in urban studies in which there is no access to appropriate information [29].

Since detailed information of the current urban process and patterns is required for the future development and management of urban areas, a tool which is able to provide such useful information on urban growth and dynamics is needed. By increasing the accessibility to satellite images, and improving their resolutions, remote sensing images will be a useful tool for monitoring and analyzing the urban sprawl and land cover changes on a temporal scale, having advantages in terms of cost and time [20, 29].

Islamic republic of Iran, like other developing countries, recently experienced massive demographic changes, with the consequence of widespread change in the face of cities. In addition to its population growth, rural-urban migration in Iran has also increased dramatically, with a resultant urbanization rate of 31.4 % of the total population in the first National census held in 1956. While in the last National census held in 2011, this rate increased to 71.4%. Hence these massive demographic changes, as well as the issuing of land to people in marginal areas of cities by government, have caused urban sprawl and displacement of population from the center to the periphery of the Iranian cities. Therefore, the study of patterns of spatiotemporal changes seems necessary in Iranian metropolitan areas.

Therefore, the current research utilized remote sensing data and landscape metrics in order to investigate the spatial

pattern of Shiraz metropolitan area (SMA) from 1986 to 2014, with the aim of providing answers to the following questions: What is the differences between growth types of SMA expansion in four geographical directions (NW, NE, SE, SW) Fig. 1? How will the SMA expansion in four geographical directions be like in the coming years, will it be more dispersed or more compact?

2. MATERIALS AND METHODS

2.1. Study area

Shiraz, the sixth largest city of Iran in terms of population, is located in the south of the country Fig. 1. The latest administrative area of the city occupies 43725 hectares, and the SMA population, which includes the city and surrounding rural areas, as well as Sadra new town, was 1.557 million according to the last National census by Statistical Center of Iran. The annual population growth rate over the past three decades has been 2.04, of which 93% live in urban areas [30].

Shiraz, with its characteristic large size and also being a notable political, administrative and demographic center in the Iran's southern region, is located on the way of transit corridors, with remarkably high population and migration growth. Environmental features, such as north, south and west highlands, together with Maharloo Lake at the east side of Shiraz, provides special conditions from a morphological point of view [31-32]. The height of SMA ranges from 1,488 meters above sea level in the far eastern part, to 1,700 meters in the far northwestern part of the metropolitan area. Over the years, the northwest of the city has always been the main sustainer of the city. The difference between the annual rainfall of the far northwestern and far east southern parts of the metropolitan area is about 300 mm [31]. Prevailing winds blow from this side and the city slopes from the northwest to the southeast, with one of the major rivers, Khoshk, taking its course along that same direction. Hence, the northwestern areas are superior in terms of ecological advantage.

Therefore, the suitability of the weather conditions of the northwest area and bad weather conditions of the east and south, together with the low depth of underground water of southeast area, have created social and environmental differences between the south and northwest regions of the city. These differences results in clearly distinct tendency of financial flows and land market towards north-western areas and also people's desire to live in that part of SMA. These factors, together with the high value placed on lands in those areas than other areas, have necessitated the development of northwest of SMA, to a considerable extent. Therefore, the main objective of this study is to analyze the major trends and growth patterns of SMA expansion in different directions in a 28-year period which is divided in three periods as 1986-1996, 1996-2006 and 2006-2014.

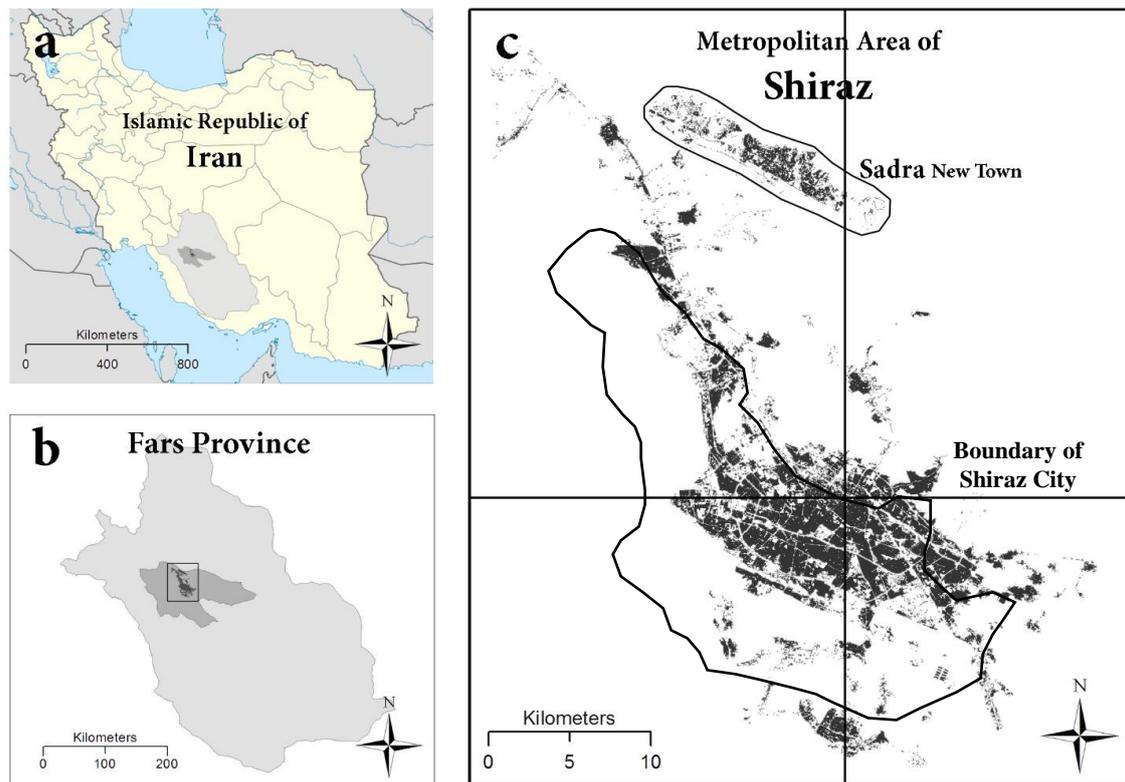


Fig. 1 SMA location in Iran and Fars province, and study sectors based on four geographical directions; A: Fars province location in Iran, B: Shiraz county location in Fars province, C: SMA and four sectors, including Shiraz City, Sadra New Town and periphery rural areas (Source: Authors)

2.2. Data processing

This research analyzed the growth pattern of SMA in the last three decades, using satellite images from Landsat sensors available on <https://landsat.usgs.gov/>, the official website of U.S. Geological Survey (USGS) [33]. Data were Satellite images of 2nd November, 1986 and 13th November, 1996 from the Landsat TM, and images of 29th June, 2nd July and 21st July 2006, and images of 4th September, 20th September and 19th August 2014 from the Landsat ETM + with paths 163/row 39 and 162/row 40. Three different images were used for the growth analysis of SMA in 2006 and 2014, because of the gap needed to be filled in the satellite images of ETM + sensor which have been impaired since 2003. All images represented have a spatial resolution of 30m × 30m, and ArcGIS 10.2 as GIS software, Envi 5.1 as remote sensing software and FRAGSTATS v4 as a tool for calculating landscape metrics were used in the data processing.

The SMA boundary selected for the study was just a little beyond the city border services, taking into considerations the surrounding villages, as well as Sadra new town which have a significant impact on the development of SMA. ISODATA unsupervised classification method, which is done by the software program, was used for classification of four satellite images to determine the urban class instead of using supervised classification which is conducted by the user himself.

Classification accuracy assessment, as the next step in image processing, is commonly carried out by using two out of the various available methods: One that requires a reference image to compare with the classified images, and

the other which generates a random set of points by GPS receiver. Their usage are quite tasking, especially when several satellite images with different times have been used. Since acquiring the reference maps of SMA could not be possible, the method of rule-based rationality evaluation by Liu and Zhou (2004) was applied [20, 34]. It involves selection of a random set of Pixels of the first image and tracking the changes of the pixels in images of the following years. Based on this methodology, three modes are possible: 1. Class of pixel is unchanged, 2. Class of pixel is converted from non-urban to urban, and 3. Class of pixel is converted from urban to non-urban.

The first and second modes involve accepting the classification of the pixels but owing to the assumption that the conversion from an urban to non-urban class may not happen, and when the third mode occurs, the classification will not be accepted. Finally, the number of correctly classified pixels relative to the total pixels will serve as the overall accuracy of the classification.

In this study, 2000 pixels were selected randomly from classified images, and it was discovered that class of 268 pixels had been converted from urban to non-urban. Consequently, by accepting the classification of the remaining 1732 pixels, the overall classification accuracy was 86.6%. In various urban studies, an accuracy greater than 85% is usually considered adequate [3, 20, 35]. Therefore, the current assessment of accuracy was accepted.

2.2.1. Determination of growth types

As it was said before, applying remote sensing imagery

and GIS techniques in urban planning provides scholars a great opportunity to investigate the physical aspects of urban areas more than ever. In this study, the patterns of land cover changes and also the process of urban growth in SMA is going to be evaluated by using the combination of remote sensing and landscape metrics. The reason this period of 1986-2014 was selected is that SMA has been experiencing massive changes during last three decades right after the war due to several factors such as immigration of war-affected population and also issuing of land to people in marginal areas of the city.

So in order to investigate the current patterns, two urban area maps of the adjacent study years were overlapped to get the growth maps for the three different study periods: 1986-1996, 1996-2006 and 2006-2014. So far, various methods and orientations have been implemented for analyzing the urban sprawl and growth, for example, measuring mixed land use or activity in urban centers [4,13-14,36-37]. But since this study utilized satellite images which can only be used to check the land cover changes, classification of urban growth types to infill development, edge-expansion and leapfrog development, seems appropriate. The Infill development usually occurs in unbuilt areas surrounded by built-up areas inside the urban regions. Edge-expansion growth is a newly developed urban area that mainly arises from the edge of the existing urban areas. Leapfrog development or outlying growth is a newly developed area that is not associated spatially with the existing urban areas [19, 28].

In order to determine the growth type of the newly development areas, two urban area maps of the adjacent study years were overlapped, while the urban patches in the 2-year overlay map were divided into two groups;

newly developed areas and existing areas. The three types of urban growths were distinguished used the index by Xu et al. (2007):

$$S = \frac{L_c}{P}$$

Where L_c is the length of the common boundary of a newly developed patch and a pre-developed patch and P is the perimeter of this newly developed patch. Also, S indicates the relative relationship between newly developed areas and existing ones. If $S \geq 0.5$ the type of urban growth is identified as infill development, for $0 < S < 0.5$ it is edge expansion while $S=0$ implies leapfrog development [38].

Also urban area maps have been divided into four sectors from the core area of SMA: Northeast (NE), Northwest (NW), Southwest (SW) and Southeast (SE).

2.2.2. Urban growth patterns

In order to investigate urban growth patterns of SMA, landscape metrics was utilized in the present study. Owing to the fact that some of landscape metrics measure the same characteristics of patches [39], and there are no special rules for applying these metrics in urban studies [12], the selection of efficient metrics was made discreetly by the authors, in order to obtain the best possible performance used in analyzing the compactness and dispersion processes of urban growth patterns of SMA. To measure the pattern and process of urban growth, five landscape metrics were used in accordance with the general paradigm of compactness and dispersion Table 1. The metrics for each of four separate sectors were calculated in FRAGSTATS v4.

Table 1 Landscape metrics and their descriptions [39].

Metrics/abbreviation	Description	Unit	Range
Total Area (CA) ¹	AREA equals the area (m ²) of the patch, divided by 10,000 (to convert to hectares).	Hectares	AREA > 0, without limit.
Number of Patches (NP) ²	NP equals the number of patches of the corresponding patch type (class).	None	NP ≥ 1, without limit.
Number of Disjunct Core Areas (NDCA) ³	NDCA equals the sum of the number of disjunct core areas contained within each patch of the corresponding patch type; that is, the number of disjunct core areas contained within the landscape.	None	NDCA ≥ 0, without limit.
Mean Euclidean Nearest Neighbor Distance (ENN_MN) ⁴	ENN equals the distance (m) to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance. Note that the edge-to-edge distances are from cell center to cell center.	Meters	ENN > 0, without limit.
Area Weighted Mean Proximity Index (PROX_AM) ⁵	PROX equals the sum of patch area (m ²) divided by the nearest edge-to-edge distance squared (m ²) between the patch and the focal patch of all patches of the corresponding patch type whose edges are within a specified distance (m) of the focal patch.	None	PROX ≥ 0

3. RESULTS AND DISCUSSION

3.1. Growth types of SMA

Shortly after the Iran-Iraq war (1980-1988), SMA

experienced sweeping changes. Over the past 28 years, the growth rate of SMA has been more than 3.21% per year and its area has increased tremendously from 5992.56 hectares in 1986 to 14,550.75 hectares in 2014 Fig. 2. During this period, edge-expansion with 41.89 % of total growth was

the highest portion of growth of SMA Table 2 and Fig. 3. With the approval of the master plan of the city in 1989 and a prediction that someday the city would be in dire need of new development areas, the construction of new towns and settlements began, such as new neighborhoods within a

short distance from the city center, and Sadra new town further away. During this period, growth of the city was as a result of natural development processes, and the expansion of SMA corresponded with the traditional growth pattern of Shiraz (East-west linear growth).

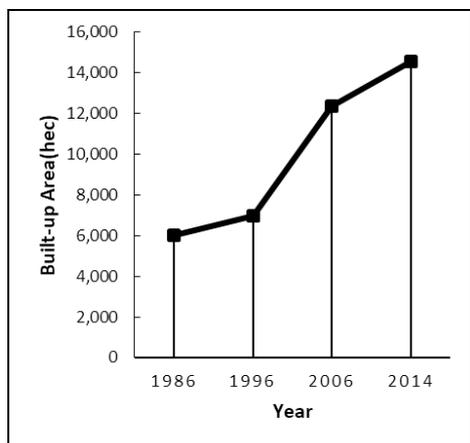


Fig. 2 Area of growth changes over various periods, based on three growth types (Source: Authors)

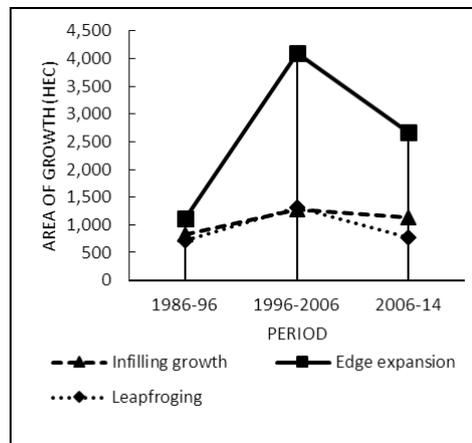


Fig. 3 The approval of the master plan of the city in 1989

Table 2 Area and proportion of growth changes over various periods, based on three growth types and different sectors (Source: Authors).

Direction	Growth type	Growth 86-96		Growth 96-06		Growth 06-14	
		Area (hec)	Proportion (%)	Area (hec)	Proportion (%)	Area (hec)	Proportion (%)
NW	Infilling growth	279.45	30.65	441.23	17.72	346.86	17.15
	Edge expansion	397.62	43.62	1262.51	50.71	1217.39	60.18
	Leapfrogging	234.57	25.73	786.11	31.57	458.72	22.68
	Total Growth	911.64	100	2489.85	100	2022.97	100
NE	Infilling growth	64.68	28.86	99.90	25.52	109.48	54.09
	Edge expansion	88.75	39.60	250.22	63.93	69.72	34.45
	Leapfrogging	70.66	31.53	41.28	10.55	23.19	11.46
	Total Growth	224.08	100	391.41	100	202.39	100
SE	Infilling growth	296.73	31.34	391.36	20.18	352.25	27.65
	Edge expansion	367.64	38.83	1265.89	65.28	756.55	59.38
	Leapfrogging	282.48	29.83	281.91	14.54	165.31	12.97
	Total Growth	946.86	100	1939.16	100	1274.11	100
SW	Infilling growth	188.49	32.86	345.69	18.32	333.24	30.59
	Edge expansion	255.69	44.58	1327.18	70.35	630.06	57.84
	Leapfrogging	129.41	22.56	213.70	11.33	126.06	11.57
	Total Growth	573.59	100	1886.57	100	1089.35	100
Shiraz Growth	Infilling growth	829.35	31.22	1278.18	19.06	1141.83	24.88
	Edge expansion	1109.70	41.78	4105.80	61.22	2673.72	58.27
	Leapfrogging	717.12	27.00	1323.00	19.73	773.28	16.85
	Total Growth	2656.17	100.00	6706.98	100.00	4588.83	100.00

During the first decade SMA annual growth rate of 1.54 % shows to be less severe compared to the subsequent period Table 4. New growth occurred mainly

at the edge of the city while leapfrogging growth was mainly due to the commencement of construction of new settlements in this decade Fig. 4.

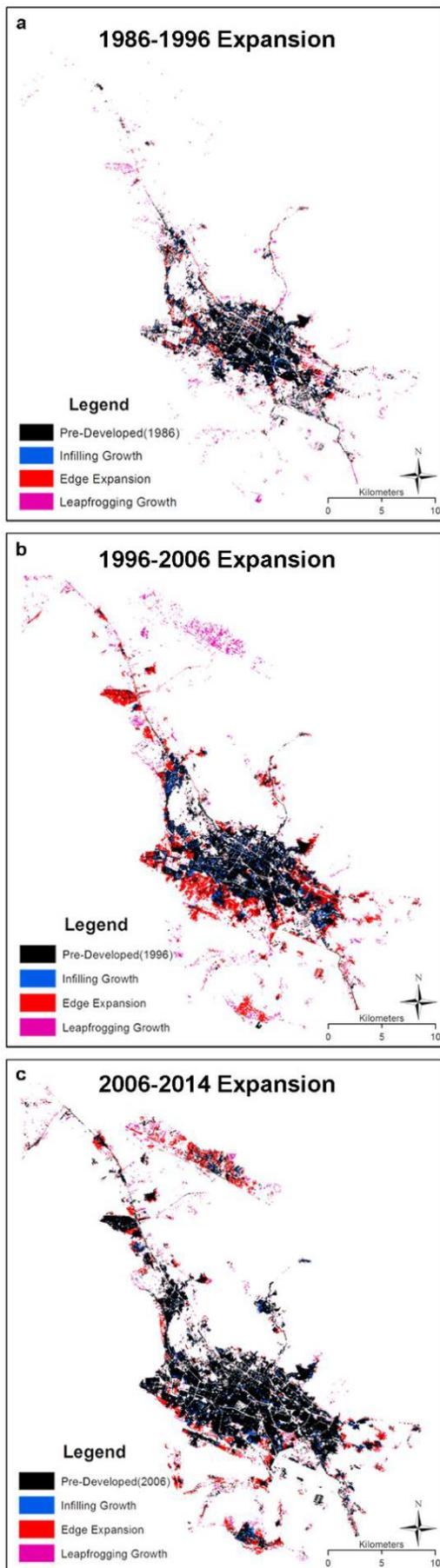


Fig. 4 Land cover changes over various periods (source: Authors)

During the second decade, 1996-2006, SMA experienced unexplainable growth. In the middle of this decade, unhealthy revenues such as selling building density and collecting building violation were introduced into the financial structure of Iranian municipalities. It started in 1995 and so far has continued [40]. Also, the city witnessed a shortage of appropriate programs to predict the direction of the future development. In 1989, studies of “Shiraz Master Plan” were initiated with a ten-year horizon. The plan was finally approved in 1995 and its implementation gave rise to the approval of other special plans like “The Preservation and Organizing Gardens of Shiraz” (approved in 2001) which had remained virtually unused since 2002 [31]. In consequence the horizon was passed and the negotiation for providing an update of Master Plan was in process.

Owing to these circumstances, in the period 96-06, a great horizontal expansion occurred, with a 5.89 % annual growth rate Table 4. This resulted in an increase in the land area of SMA from 6982.47 to 12,379.68 hectares at the end of the period Fig. 2. With a lack of proper planning and unstable revenue sources, and also by allowing “Employee housing cooperatives” to construct new settlements and neighborhood, marginal expansion was quickly intensified. Therefore, with indiscriminate construction on the edges of the urban areas, edge-expansion singly contributed substantially to the urban growth, comprising 60% of total growth of SMA compared to infill development (20%) and leapfrog development (20%) during this period Table 2. Northwest development of the metropolitan area made a significant contribution of 37.12% of the total growth Table 3. Apart from being good natural barriers against floods, forests and gardens of the northwest of SMA are good source of fresh air in the city. Therefore, while the development of the city to the northwest is inevitable, the quality of this development has created a great deal of sensitivity. By raising the built-up area of SMA to the thresholds of the city on its eastern and southern regions, the development of the metropolitan area, as well as maintaining its ecological heritage has become a critical issue.

The third period, 2006-2014, is a period of subsiding unbridled growth of SMA, with 2.04% annual growth rate over the past ten years Table 4. The built-up area of SMA increased from 12379.68 to 14550.75 hectares Fig. 2. In this period, owing to new construction of residential settlements, practically, unused spaces among former residential settlements of SMA attracted majority of the total growth during 06-14 Fig. 4. The main issue lies with the intensification of the growth of the northwest. During this period, 44% of the total urban growth belonged to this side Table 3. In 2007, with the addition of a city zone in the north-western of Shiraz, city border was extended by 10 km away on this side, also in 2013, by approval of Shiraz city council, another new zone in this region was added to the city and this time city border was extended by 7 km away.

It can be seen that the contribution of Sadra to the total horizontal growth of the northwest was about 855.81 of 2022.97 hectares (42.3%), during 06-14. Total urban

growth of SMA was 4588.83 hectares, during this period, of which Sadra contributed 18.64%. Also during 96-06, Sadra contributed about 15.55% of total growth of northwest and 5.77% of total growth of SMA. One of the Iran's major policies in the late 1980s was construction of new towns in the vicinity of big cities to attract overflow crowd of the cities. During the construction of Sadra which began in 1991, a population of 230000 in 2016 was

predicted but the final approved plan was made for a 500000 [41]. But according to the latest population and housing census in 2011, the population of Sadra was about 39 thousands, and it contributed only 25 % of the total growth of SMA. Therefore it can be concluded that Sadra new town has failed to achieve its goals. The rapid rate of Sadra's construction can also be attributed to its cheaper urban lands than other areas of northwest.

Table 1 Area and proportion of growth changes over various periods, based on different sectors (source: Authors).

Growth	Growth 86-96		Growth 96-06		Growth 06-14	
	Area (hec)	Proportion (%)	Area (hec)	Proportion (%)	Area (hec)	Proportion (%)
NW Growth	911.64	34.32	2489.85	37.12	2022.97	44.08
NE Growth	224.08	8.44	391.41	5.84	202.39	4.41
SE Growth	946.86	35.65	1939.16	28.91	1274.11	27.77
SW Growth	573.59	21.59	1886.57	28.13	1089.35	23.74
Shiraz Growth	2656.17	100.00	6706.98	100.00	4588.83	100.00

The development of SMA to the northeast from the past until now has been due to various environmental constraints such as highlands and protected forest areas so it occurred relatively far away from the main city.

Development of the city to the southwest and southeast was 23.74% and 27.77% respectively of the total growth during 06-14, and comparing it with past records showed reduction in the area portion of these sectors Table 3. Due to lack of construction of new residential areas and settlements in these sectors, new development has taken place mainly in the periphery of the rural areas Fig. 4. Growth of surrounding villages on the SE sector of the city located outside its borders was about 545.92 hectares, indicating that it contributed 42.8% of the horizontal growth of the SE. While this ratio was about 19.5% during 96-06. Also, the growth of the surrounding villages on the SW sector located outside its borders was about 476.89 hectares, implying that it contributed 43.77% of the SW growth. This ratio was 16.9% during 96-06.

In fact, after experiencing great urban sprawl, especially on the edge of the main city in the 96-06 period, SMA experienced growth of periphery rural areas beyond

the city borders with high density and poorer facilities for the last ten years. Since there are more expensive urban lands in NW of SMA, the expansion of rural areas on this side has been less severe, accounting for the distribution of the poor towards cheaper areas like the surrounding villages on the SE and SW sectors.

Table 4 Annual growth rate of SMA over various periods (source: Authors).

Period	1986-1996	1996-2006	2006-2014
Annual Growth Rate (%)	1.54	5.89	2.04

Hence, it can be seen that NW of SMA is more attractive than other areas, especially during recent decades. Major growth of SMA over thirty years has been edge-expansion, and almost half of the growth in the southern part of SMA in recent decade occurred in the periphery of the rural areas beyond the city borders, while half of the NW growth of SMA occurred in the periphery of Sadra new town.

Table 5 Land cover changes of rural areas over various periods (source: Authors).

Period	Location	North West		North East		South East		South West	
		Area (hec)	Proportion (%)						
1986-1996	Periphery	41.22	4.52	62.94	28.09	109.26	11.54	25.72	4.48
	Total	911.64	100.00	224.08	100.00	946.86	100.00	573.59	100.00
1996-2006	Periphery	326.62	13.12	191.73	48.98	522.28	26.93	318.93	16.91
	Total	2489.85	100.00	391.41	100.00	1939.16	100.00	1886.57	100.00
2006-2014	Periphery	270.23	13.36	85.14	42.07	618.97	48.58	476.90	43.78
	Total	2022.97	100.00	202.39	100.00	1274.11	100.00	1089.35	100.00

3.2. Urban growth patterns of SMA

All the metrics used in the study measure the rate of aggregation and the compactness or dispersion of urban

patches. Total area (CA) measures the overall growth of built-up area during the various periods. By calculating the Number of Patches (NP), it can be possible to analyze coalescence and diffusion of urban patches. An increase in

the NP represents diffusion of urban patches in urban landscape [3]. The Number of Disjunct Core Areas (NDCA) measures the number of urban cores that are separated from one another (McGarigal et al., 2012), and in this study, an edge depth of a patch of at least 150 cells from each side is indicative of a disjunct core area. As a result, this metric measured the aggregation of urban patches. Mean Euclidean Nearest Neighbor Distance (ENN_MN) measures minimum Euclidean distance between the urban patches, therefore, if a set of urban patches are closer together, they will represent more compact urban area [28-29]. Since the patches consist of 30m×30m pixels, ENN_MN will be at least over 60. A value less than 60 would connect the patches to one another, and this connection is measured by Proximity Index (PROX_AM). As defined by the authors, PROX_AM measures the proximity of urban patches in a radius of 800 m, and increasing the metric represents a more compact urban area.

3.2.1. Total area (CA)

The results showed that at the beginning of the study period, the SE of SMA had the highest built-up area rate, but over time, the NW sector of SMA has grown more rapidly than other sectors during three decades. The built-up area of SMA southwest had similar growth pattern to the SE sector. There was no increase in the built-up area of SMA northeast in considerable scale, this was due to the noted limitations. The process of SMA growth continued at a slower rate during 06-14 compared to 96-06 period, but it seems the growth of NW sector would be much more rapid than other sectors Fig. 5.

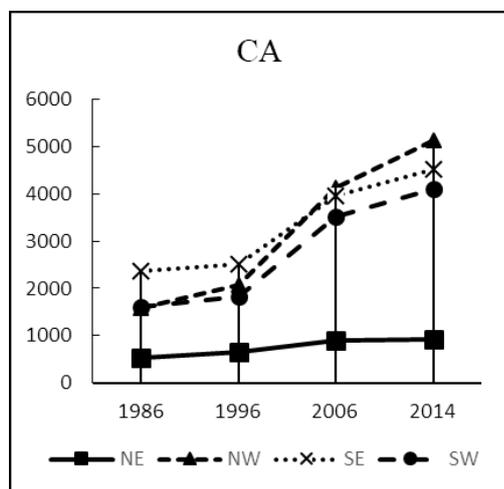


Fig. 5 Changes of CA index for four sectors (source: Authors)

3.2.2. Number of patches (NP)

During 1986-1996, the number of patches of the metropolitan area, especially in SE, implied a coalescence process of the urban patches and an increase in the compactness of SMA [3, 20]. This trend continued in the next decade for the NE, SE and SW, while the built-up area of these sides still grew, resulting in more compactness of SMA. An increase in the number of

patches on NW sector during 96-06 indicated that SMA was dispersed on this side. The process of NW growth continued over the next decade, which reflected the ongoing dispersion in the northwest of SMA. The number of patches of other sectors remained relatively constant due to the attractiveness of the northwest and ecological limitations that have prevented discontinuous growth of SMA in the NE, SE and SW areas Fig. 6.

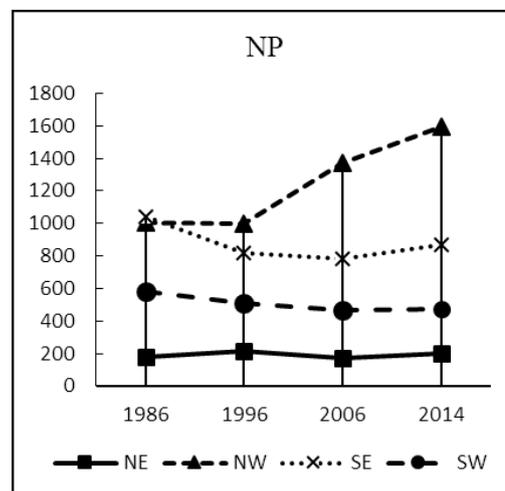


Fig. 6 Changes of NP index for four sectors (source: Authors).

3.2.3. Number of disjunct core areas (NDCA)

Unnoticeable changes of this metric indicate a lack of large-scale formation of new urban areas and continuous growth of existing urban patches over the first decade. But the major change of the metric which is affected by the construction of new settlements and neighborhoods in different areas indicates discontinuous and horizontal expansion of SMA during 96-06. During 2006-2014, the growth increase of NDCA in the Western areas stopped, indicating a lack of formation of new core areas in these areas. An increase in the number of core areas in the Southeast region is attributed to a significant growth of the surrounding villages in this sector that have been transformed from rural areas to urban areas, while the SW villages grew with less compactness than the SE villages Fig. 7.

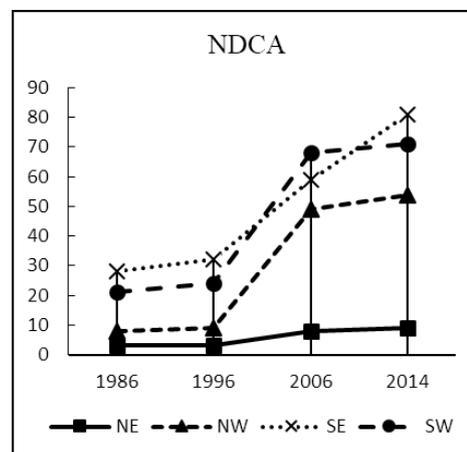


Fig. 7 Changes of NDCA index for four sectors (source: Authors)

3.2.4. Mean euclidean nearest neighbor distance (ENN-MN)

During 1986 and 1996, there was continuous growth of urban areas around the main axes. This kind of development led to an increase in the Euclidean distance of patches from one another during the first period. There was a decrease in this distance in the next decades due to filling of the unbuilt areas, especially in southern areas. This index in 2014 is indicative of a more dispersed NW sector than other sectors of SMA Fig. 8.

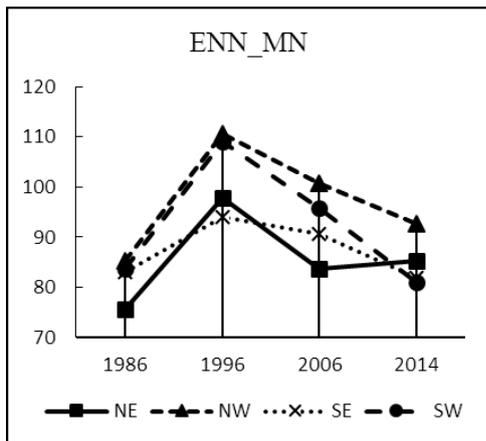


Fig. 8 Changes of ENN_MN index for four sectors (source: Authors)

3.2.5. Area weighted mean Proximity Index (PROX-AM)

This index represents the vicinity of patches with one another in an 800-meter radius. During 86-96 the NW of SMA experienced adjacent development as a result of the commencement of the construction of new neighborhood which had their core originally built in close proximity to one another. But during the next decades, the discontinuous growth of NW and scattered development of new settlements and neighborhoods, especially Sadra new town, led to a downward trend in the metric. An important point to note is a significant increase of the index within the period 2006-2014 for the southern areas which was as a result of the filling of the unbuilt areas and the lack of sufficient urban lands to be developed Fig. 9.

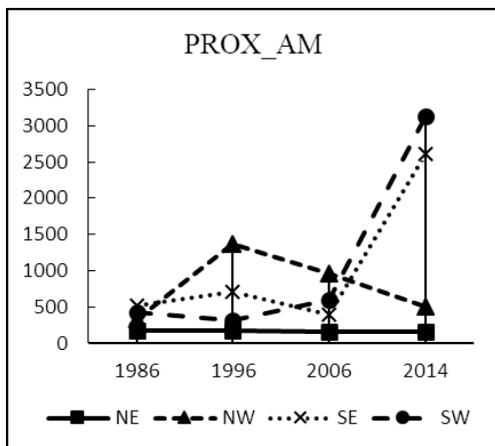


Fig. 9 Changes of PROX_AM index for four sectors (source: Authors).

The growth patterns of NE, SE and SW are likely to be more compact while NW is going to be more dispersed in the coming years. Owing to the fact that this area serves as the lifeline of SMA from an ecological point of view, adoption of appropriate policies for this area seems essential. During the various periods, there was observed difference in the growth pattern between the four sectors according to the indices. The NE sector did not experience any major changes although there was more compactness in the recent decades. There was continuous traditional growth until 2006 in the SE sector which is the original core of the city but during 2006-2014, rather than having a continuous development of existing urban areas, an intensive and extensive development of surrounding villages in this sector occurred. The NW sector being the most attractive area of SMA experienced major changes. The growth pattern of this sector was dispersed, having no signs of compactness. The existence of potential urban lands in this sector gives room for a continuous urban sprawl. On the contrary, there was no remarkable potential urban land in SW, and the growth of surrounding villages behind the highlands on this side would have the highest portion of SMA expansion on this sector.

4. CONCLUSION

Since the identification of process of changes in the spatial configuration of urban areas as well as analysis of urban growth patterns could help planners and decision makers to plan and decide for the urban areas, the aim of this study was to investigate the pattern and process of SMA expansion during the last three decades. Over the years, many researchers have tried to identify spatial configurations of metropolitan areas, and the analysis of compactness or dispersion of urban areas has been one of the most important topics of urban studies in recent decades. Remotely sensed images are one of the efficient tools which have been significantly used in urban studies in recent years. These data could be very useful in examining the land cover changes, especially when detailed information is not available. Therefore, a study of temporal developments of land use changes makes it possible to explain these changes and to describe their patterns. In this study, changes of spatiotemporal patterns of SMA expansion during the last three decades were analyzed by using satellite imagery and landscape metrics. The results demonstrated more attractiveness of NW than other sectors of SMA. Horizontal expansion or urban sprawl has been the main characteristic of SMA growth over the past three decades. Apart from being good natural barriers against floods, forests and gardens of the northwest of SMA are good source of fresh air in the city. Therefore, while the development of the city to the northwest is inevitable, the quality of this development has created a great deal of sensitivity. By raising the built-up area of SMA to the thresholds of the city on its eastern and southern regions, the development of the metropolitan area, as well as maintaining its ecological heritage has become a critical issue.

The accuracy of the results of such research,

particularly the effectiveness of landscape metrics majorly depends on resolution of satellite imagery and process of preparing the data, like image classification. In fact, low resolution of images or low accuracy of image classification may have significant effects on size and number of patches. Another point is to note here is the lack of a defined set of landscape metrics among many metrics which could be used in urban studies. It could be concluded that as long as an appropriate definition of useful landscape metrics for urban studies has not been introduced, the use of these metrics to compare the changes of spatial configurations of a defined urban area through time or comparing spatial configurations of some urban areas with one another, would have the best possible performance.

In conclusion, the results indicate SMA has faced massive changes during last three decades and according to landscape metrics it is most likely to continue this growing trend so it may be best for future studies to predict the future growth of this trend and investigate the impact it is going to have on the northwest part of SMA which is the most important part of the metropolitan area from an ecological point of view.

NOTE

1. $CA = \sum_{j=1}^n a_{ij} \left(\frac{1}{10000}\right)$ a_{ij} = area (m) of patch ij .
2. $NP = N_i$ n_i = number of patches in the landscape of patch type (class) i .
3. $NDCA = \sum_{j=1}^n n_{ij}^c$ n_{ij}^c = number of disjunct core areas in patch ij based on specified edge depths (m).
4. $EMN_MN = \frac{\sum_{j=1}^n h_{ij}}{n_i}$ h_{ij} = distance (m) from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center.
5. $PROX_AM = \sum_{s=1}^n \frac{a_{ijs}}{h_{ijs}^2} a_{ijs}$ = area (m) of patch ijs within specified neighborhood (m) of patch ij .
 h_{ijs} = distance (m) between patch ijs and patch ij , based on patch edge-to-edge distance, computed from cell center to cell center.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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