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Analyzing spatiotemporal changes in urban green spaces' ecosystem service value and resilience

Sh. Hoseini [1], M.J. Amiri [2,*], Y. Moarrab[3]

[1] *Department of Environmental Planning, Alborz Campus, University of Tehran, Tehran, Iran*

[2] *Department of Environmental planning, Faculty of Environment, University of Tehran, Tehran, Iran*

[3] *Department of Safty, Faculty of Passive Defence, Imam Hossein University, Tehran, Iran*

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ABSTRACT

BACKGROUND AND OBJECTIVES: *Urban ecosystem services are provided by a multitude of habitats, including green and water spaces. Such services are commonly under the control of heavy demand raised by the large number of beneficiaries. In this context, urban green spaces viz. parks and gardens supply these services for city residents. From this perspective, this study is to analyze the spatiotemporal changes in the ecosystem servicevalue of urban green spaces in Districts 1 and 14 (out of 22) of Tehran Municipality, Tehran, Iran. The level of resilience (namely, capacity and adaptability) of these districts, once confronted with climate change and environmental degradation, particularly carbon sequestration, is then investigated. As an innovation, the current study ultimately assesses the ecosystem services value of urban green spaces with higher accuracy to exert more actions to improve these spaces.

METHODS: *This library-based documentation study utilized spatiotemporal modeling with reference to software packages and field visits. In the first step, remote sensing was applied to create land-use maps using ENVI 5.3 software package and its formulas, algorithms, and extensions. In the second step, the InVEST software and model were used to model carbon sequestration in selected districts. To assess carbon sequestration and its changes over time, land-cover maps were generated for three 10-year periods (2003, 2013, and 2023) with 30 m accuracy via Landsat satellite-based program. The maps were classified in ENVI 5.3, and the net carbon sequestration in land, along with the market size of carbon sequestration, was estimated using the InVEST model, incorporating land-use maps, land-cover types, and carbon sequestration in reservoirs. Organic carbon content was determined based on other carbon reservoirs, previous surveys, and available data. Each carbon reservoir unit was valued in dollars, and discount rates and annual changes in carbon value were calculated based on global and local conditions surveys.

FINDINGS: *The study results obtained from land-cover/use maps produced during 2003, 2013, and 2023 in the selected districts, demonstrated a diminishing trend of green spaces and barren lands, while the area of built land has increased over time. The numerous changes in land use in the company of construction in green spaces and barren lands in District 1 from 2003 to 2013 had further led to 191401608 tons of emission, including 179114669 tons of carbon, valued 49056267 and 4636422 million Dollars, respectively. In District 14, the emission during 2003-2023 was also equal to 18.3644 tons of carbon, and that was 3444.14 tons of carbon for the period of 2013-2023, worth 1873871 and 1749769 thousand Dollars, in that order.

CONCLUSION: Indiscriminate construction and development of built-up areas in Tehran have undermined green spaces and barren lands, negating the benefits of green infrastructure efforts. This has resulted in a reduction in urban green spaces, hampering their capacity for carbon absorption and sequestration. Consequently, reduced carbon deposition will contribute to higher temperatures, diminishing the resilience of these urban areas.

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*Corresponding Author:
Email: *mjamiri@ut.ac.ir*
Phone: +989111212352
ORCID: 0000-0003-1748-9036

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INTRODUCTION

Modern urbanization and high urban growth rates have brought about loads of challenges, including the destruction of natural ecosystems (Moarrab *et al.*, 2022). As cities and natural environment systems are highly interconnected, they form socio-ecological systems. The interactions between the public and ecosystems are accordingly associated with the dependency of humans on natural environments for receiving vital Ecosystem Services (ES) (Torres *et al*., 2023). In this sense, such services have been generally explained as the benefits obtained by people from ecosystems that contain provisioning (e.g., food, water, and fiber), regulating (such as, climate regulation and pollination), cultural (like spiritual, aesthetic, and recreational values), and supporting (including, soil formation) services. In other words, rapid urbanization and the high rate of unplanned constructions have converted Urban Green Spaces (UGS) into the most vulnerable natural ecosystems in cities. In the era of global climate change caused by human activities, the loss of UGS has further led to an upsurge in temperature in these regions (Kong *et al*., 2016). As a result, urban heat stress has negatively affected the quality of life of city residents. As Schröter *et al*. (2017) state, the Greenhouse Gas (GHG) emissions per capita in North American cities were 25-50 times higher than those in low-income nations. As well, Livesley *et al*. (2016) and Sun, (2017) argued that urban resilience had reduced due to the destruction of wetlands and UGS, followed by a fall in thermal comfort and a rise in energy consumption for cooling purposes. As evidenced in previous studies, the heat wave in 2003 in many European cities could be partly attributed to insufficient UGS (Campbell, 2018). The rapid conversion of barren lands and parks into residential buildings along with commercialization in urban peripheries might further intensify temperature and produce Urban Heat Islands (UHIs) (De Luca, 2021; Amlor and Alidza, 2016). Of note, the survival of one-fifth of the world's population is contingent on the services provided by ecosystems and green spaces within rural and urban landscapes (Puplampu and Boafo, 2021). ES means the benefits that people take from ecosystems, and their main goal is to establish a connection with human well-being, placed in the four categories. Provisioning, regulating, supporting, and cultural services (Abdollahi, 2023). In this respect, the benefits resulting from natural ecosystem regulation processes are labelled as regulating services, such as climate regulation (Makovníková *et al*., 2023). By removing GHGs, such as Carbon Dioxide (CO_2), from the atmosphere, ecosystems accordingly contribute to climate regulation as an ES. In fact, forests, pastures, and other dryland ecosystems store carbon four times more than that observed in the atmosphere (IPCC, 2006). Dry carbon storage and Carbon Sequestration (CS) have been thus introduced among the uppermost services, and studies have shown that the value of one ton of carbon stored has been equal to the damage avoided from not releasing one ton of carbon to the atmosphere (Stern, 2007; Balist *et al*., 2022). CS includes biophysical assessment tools and economic valuation (Lusardi *et al*., 2020). The carbon stored in a piece of land thus depends largely on four reservoirs, viz., above-ground biomass, below-ground biomass, soil, and Nonliving Organic Matter (NLOM). Dead carbon also consists of the soil layer and the standing dead wood. In this vein, one of the main regulating services with a leading role in maintaining an ecosystem and its functions is CS. Thanks to the removal of GHGs, such as CO_2, from the atmosphere; UGS thus play a vital role in climate regulation as an ecosystem-related service (IPCC, 2006). Among the major providers of regulating services are UGS and landscapes as human-environmental networks that meet diverse and valuable service needs of city residents (Mengist *et al*., 2020; Sinha *et al*., 2020). The World Health Organization (WHO) also introduces parks, sports fields, wetlands, forests, and pastures as examples of UGS, and considers them a vital part of urban ecosystems. Moreover, such spaces have been defined as any vegetation in urban environments, including parks, outdoor spaces, residential gardens, or street trees (Kabisch and Haase, 2013). According to Lindley *et al*. (2018), human activities, like land-use change, have significantly converted land cover on a global scale, with 25% of land use on the Earth's surface transformed which hase also been noted by Pielke *et al*. (2011). Managing urban ecosystems for the resilient delivery of urban ES, such as maintaining resilience to respond to shifting demands, is thus part of sustainable urban ES. Despite this, socio-ecological ES seems to be context-dependent, which requires addressing the inherent complexity of not only ecological dynamics, but also human perceptions, values, and cultural traditions affecting their supply and demand (Biggs *et al.,* 2012). To boost the resilience of the supply of ES on multiple spatial scales, it is of utmost importance to first better understand the manifold values of urban ES, and then recognize the context-dependent nature of ES, including sociocultural and ecological aspects (McPhearson *et al.,* 2015). Notably, not just disasters or climate change events, such as storm surges or heat waves, are likely to shape resilience in cities, but this is correlated with a larger set of urban ES that bring benefits to urban livelihoods and well-being (Sutikno *et al.,* 2023). All the more so, the aesthetic benefits of urban green infrastructure may alter the level of resilience to socioeconomic and ecological changes (Sanders *et al.,* 2015; Troy and Grove, 2008). Otherwise stated, urban resilience is the degree to which cities can stand change before being reorganized into a new collection of structures and processes (Qian *et al*., 2023; Alberti *et al.,* 2004). UGS is accordingly a strategic issue to the extent that it can be regarded as one of the indicators of urban development and basic economy. With respect to multiple reasons, mainly the economic aspects, UGS have been changed into other uses, particularly more profitable residential ones. Of note, the process of changing the use of UGS within the city boundaries is common, so destroying UGS and changing their uses have given rise to excessive physical expansions (Golchubi Diva *et al*., 2018). Among the key regulating services with an influential role in maintaining ecosystems and their functions is CS. Ecosystems accordingly contribute to regulating climate as an ES by adding and removing GHGs, such as CO_2 from the atmosphere (IPCC, 2006). The improper exploitation and destruction of UGS and barren lands has thus led to a quantitative and qualitative reduction of weather conditions, and subsequently lowered such services in cities. Therefore, the interactions between ES and CS should be taken into account and city managers need to be encouraged to develop UGS to make the most of their services. Tehran, one of the central provinces of Iran as the political-economic capital, has the largest population of city residents due to its important role. Every year, UGS in this city is being destroyed for various reasons, such as the development of industrial towns and the expansion of this megacity. During the past years, the urban population has further grown along with the area of Tehran. Unfortunately, the rising trend in the population has not been accompanied by the development of UGS, that is, they have remained at a low rate as that in previous years (Safari & Sharifi, 2021). In view of population growth and the increasing number of vehicles, air pollution in Tehran has become one of the big challenges. Cars and factories are now the leading sources of air pollution, and the emissions of GHGs and air pollutants caused by fossil fuels, such as gasoline and diesel, are posing many problems, such as redoubling the concentrations of CO_2, Nitrogen Oxide (NO_x), and suspended particles in the air, which are remarkably evident in the cold seasons of the year (Ogunkunle and Ahmad, 2021), because the phenomenon of heat transfer between the air layers is weaker, and blocking airflow multiplies the pollutants in the air. As mentioned, the depletion of UGS is another important challenge facing Tehran. Following the increase in population and urban development, many green spaces, viz. parks, gardens, and lawns, have been reduced and replaced by buildings. For that reason, there is a lack of resources, such as oxygen, no biodiversity, and disturbance in climate regulation, which are directly and indirectly affecting quality of life of city residents. In this respect, CS, as one of the main components to protect the environment and combat climate change, has high economic values, help in sustainable economic development, and minimize the environmental impacts associated with climate change. Thus, investing in environmental protection and resilience measures and then diminishing GHG emissions are of great importance. Against this background, the present study is to analyze the spatiotemporal changes in the ES Value (ESV) of UGS in Districts 1 and 14 of Tehran Municipality, Tehran, Iran, and determine the effects of these spaces on urban resilience by calculating and analyzing CS. Here, urban resilience means the city's readiness and resistance in facing problems and events caused by climate change and air pollution. In this study, the relationship between UGS and urban resilience is accordingly investigated, and much focus is laid on the ESV of UGS, which plays an important role in evaluating the benefits and costs associated with the preservation and development of such spaces in the urban economy. These two components can further help city planners and officials in making effective decisions, among the innovations of this study.

Literature Review

Regarding previous research in this field, Zhang *et al*. (2023) investigated the impact of CS via terrestrial vegetation on economic growth based on satellite data in China and found that such services had a significant positive effect on economic growth in Northeast, Central, South, and Southwest China, but not in North, East, or Northwest parts. Following stability testing, this effect remained constant. CS using terrestrial vegetation had thus influenced economic growth, mainly through the improvement of industrial structures, resource allocation, and vegetation. This statistical model further elucidated the empirical evidence provided by CS for high-quality economic development and economic impacts on forestry and environmental protection. Smith *et al.* (2002) examined the CS potential of UGS in an urban area, using Remote Sensing data and field measurements to estimate the carbon storage capacity of various UGS, providing valuable insights into the importance of UGS for carbon reduction. As well, Han *et al.* (2018) identified urban ES; especially those produced by UGS and quantified their spatiotemporal changes on the regional scale in the southern part of Seoul, South Korea. At first, the changes in UGS were categorized, then a CS-related factor was selected as a trial case, and its spatial pattern was investigated using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. The study results showed that the total CS potential decreased by 41.2% from 1975 to 2015, due to the reduction in the area of green and natural spaces. In addition, the drastic decline in the extent of urban forests and agricultural areas was introduced as one of the main reasons for the loss of CS. Moreover, Ariluoma *et al*. (2021) reflected on the role of CS and the potential of UGS in residential areas, and established that the simultaneous presence of trees and biochar (viz., charcoal from plant biomass and agricultural waste) in the environment could significantly increase CS. The CS potential of the study area was also 520 kg of CO_2 for each resident for 50 years. As well, biochar and tree biomass constituted 65% and 35% of the capacity, which could lead to the storage of 330,000 tons of CO_2 over 50 years, on a city scale. The findings additionally showed that green planning could help mitigate climate change by encouraging the use of biochar and tree planting, and further ensure optimal growing conditions. In 2019, Jonsson *et al.,* investigated the potential of CS for different land uses as nature-based solutions (NBS) to increase carbon storage and/or reduce GHGs. They concluded that most of the CS potential had occurred in conifer-broadleaf forests, covering approximately 60% of green infrastructure. Besides, the annual carbon storage potential would be thus lost with the rapid reduction of UGS due to the future land-use development from 2020 to 2040. By preventing development in areas with high CS potential, the losses could be accordingly reduced by 64.5%. Gharibi *et al*. (2021) correspondingly investigated the capability of UGS in providing ES for CS and confirmed that the largest area of green infrastructure was related to agricultural fields, gardens, parks, and abandoned lands, respectively. The highest CS potential in the city of Hamedan, Iran, was also soil (312047 tons), tree and shrub cover (90266 tons), grass cover (8383 tons), and litter (771 tons), in that order. In general, the results revealed that most CS could be met by the soil in the park use compared with other uses, so the development of UGS could be an option to reduce carbon in the atmosphere. Pourtoosi *et al*. (2017) studied the economic valuation of the ES of parks in the city of Mashhad, Iran, wherein the amount of gross carbon storage of trees was 9.2337 tons per hectare each year, and the major part was related to plantain species. The production of oxygen was also 1.0387 tons per hectare annually and the carbon storage in the urban parks was calculated as 761.22 tons per hectare. The removal of pollutants in one year and per hectare was further reported as 249.2 tons, and the value of regulating services (i.e., sequestration, oxygen production, and purification of urban pollutants) in parks in this city was shown as 4 million Dollars per hectare per year. The carbon reservoir of the parks in Mashhad was also valued at 1643 Dollars per hectare. Since the atmosphere was a huge reservoir of oxygen, this gas was not included in the Dollars valuation. The present study is to analyze the spatiotemporal changes in the ESV of UGS (here, CS) in Districts 1 and 14 of Tehran Municipality, Tehran, Iran. District 1, with a population of 480 thousand people has a green space area of 3799 thousand m^2 and the per capita of 10 m^2, as one of the districts rich in terms of UGS in this megacity. Given the population growth, indiscriminate construction has seriously threatened the UGS in this district, resulting in the reduction of green space ES and CS. Also, District 14, with a population of 333,484 thousand people, has a green space with an area of

2100 thousand m^2 and the per capita of 4 m^2, which is little as compared with other districts of Tehran Municipality. The construction in this district has been excessive since the past, UGS have faced much destruction, and this process continues.

The current study has been carried out in Tehran-Iran in 2023.

MATERIALS AND METHODS

Districts 1 and 14 of Tehran Municipality

Tehran, as the most populous city and the capital of Iran, is the first city of Tehran Province, with a population of 9,039,000 people according to the 2022 estimates and the 34th most populated city in the world and West Asia, as declared in 2018 by the United Nations (UN). The city of Tehran is divided into 22 districts and 122 urban areas. District 1 is located in the northeastern part of the city, as the northernmost district. It is bounded by the Alborz Mountain range from the north, the Evin neighborhood on the west, Shahid Chamran, Modares, and Shahid Sadr highways from the south, and Lavasanat on the eastern part. District 14 as the most densely populated one in the city of Tehran is also in the eastern-southeastern end parts of the city of Tehran, adjacent to District 12 from the west, District 13 on the north, and District 15 from the south. A region of study is shown in the Fig. 1:

The research process included two general steps, first, the preparation and processing of satellite-based images, and then, the modeling of CS using the InVEST suite. The land-use map was further created utilizing satellite images. For this purpose, the images captured on June 2003, 2013, and 2023 were obtained from the Landsat satellite program, and then classified with reference to the Maximum likelihood estimation algorithm (Balist *et al*., 2022; Lu and Weng, 2007), as one of the common methods for controlled classification in RS. Within this algorithm, the unknown pixels could be assigned to the most probable class with the assumption that the distribution of the training data of each class was normal. In the first step, based on the training samples of the classes, the mean value and the covariance table for the bands utilized during the classification were thus calculated. In the second step, the probability of the pixels belonging to each class was computed, and the pixels were classified and allocated to different classes at the highest probability. Statistical models based on normal distribution were further exploited to calculate the probability of each pixel belonging to each class, and then the pixels were assigned to the most likely ones (Jahandari *et al.,* 2022; Samimi and Nouri, 2023). Upon classifying the images and determining the land cover and use in each district, the accuracy of the results was checked, typically by comparing the reference map (land reality map) or the images with high spatial accuracy or the map

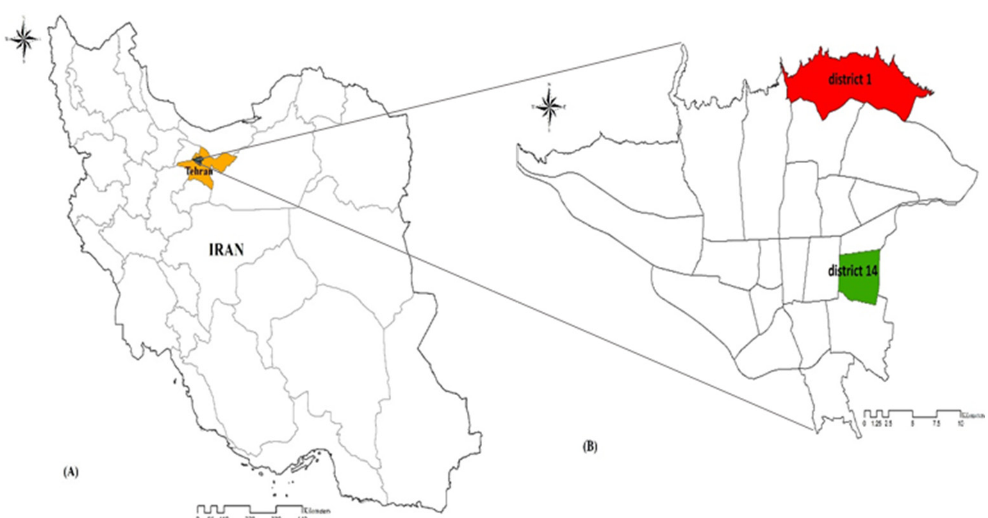

Fig. 1: Study area: (A) Iran and Tehran Province, (B) the city of Tehran and Districts 1 and 14

resulting from different classification methods and error matrix generation, though there were other methods for this purpose. A certain threshold of the correct classification probability was then respected. Afterward, random sampling was fulfilled by the Environment for Visualizing Images (ENVI) 5.3 software package, and the correctness of the classification was measured by Cohen's kappa coefficient to summarize the information obtained from the error matrix, recruiting all the elements of the error matrix to calculate the accuracy of the classification. This type of coefficient was a classification evaluation method to find the accuracy of the classification compared with a completely random one, indicating how different the classification was from chance, and the comparison showed agreement with the ground reality with no influence of randomness (Jahandari *et al*., 2022; Balist *et al*., 2022). The second step is comprised of modeling carbon storage and CS, using biophysical assessment tools and economic valuation (Jahandari *et al.,* 2022). In this step, the InVEST 3.7.0 model was operated to estimate the effect of land-use changes on CS spatially on the urban land scale. In fact, this model could help calculate the total amount of carbon stored in four reservoirs, including above-ground biomass (tree leaves, branches, and trunks), under-ground biomass (e.g., plant roots), soil (soil organic carbon in the mineral horizon), and NLOM (leaf carcasses and branches) (Zhang *et al*., 2010). In this model, the inputs from land-use maps downloaded through the Landsat satellite program during the previous steps, were processed in the ENVI 5.3 software package, and prepared in the Geographic Information System (GIS) software, and then the amount of carbon stored in the mentioned reservoirs and the net amount of carbon stored in each area of land was estimated over time (of note, the amount of the fixed inputs of CS related to each land use per hectare had been previously determined by the researchers according to Table 2). The model outputs were further expressed as megagrams of carbon in cell grids or pixels. The land-use/land-cover (LU/LC) substrate for each pixel was each unique integer as a land-use class, indicating different land covers. For each LU/LC type, the model needed to estimate the amount of carbon in at least one of the four mentioned reservoirs, because the modeling results would be more complete if the data were available for more than one reservoir. This model applies carbon estimates for each type of land cover and use to produce the maps of carbon storage in the existing reservoirs. If the current and future land cover and use maps were provided, the net changes of carbon storage over time (absorption and release) and its economic value could be calculated. To estimate the changes in CS over time, the model was simply applied to the existing maps and a projected future landscape, and then the difference in carbon storage between the pixels was calculated. If several future scenarios were available, the differences between the current scenario and each future one could be thus compared (Aalde *et al*., 2006). The calculations of the model were accordingly based on the application of the general equations of carbon measurement. CS could further occur when there was carbon storage over time. Based on this, if the carbon storage changes were positive, that is, from time t to T in the pixels examined, CS had occurred, and if they were negative, carbon had been lost between the two time periods, t and T (Mohaghegh *et al*., 2020). Employing land-use maps, land-cover types, and the amount of carbon stored in the reservoirs, the net amount of CS in a piece of land in Districts 1 and 14 of Tehran Municipality, during 2003, 2013, and 2023, as well as the market size of carbon stored in the remaining inventory were estimated via this model. Among the limitations of the model were an oversimplified carbon cycle, an assumed linear change in CS over time, and potentially wrong discount rates. The main biophysical conditions for CS, such as photosynthesis rate and the presence of active soil organisms, were not included in the model. This model could map carbon storage density to the LU/LC rasters, containing types, such as forests, pastures, or agricultural fields. It further summarized the results in the storage, separation, valuation, and total sum raster outputs. For each LU/LC type, the model needed to estimate the amount of carbon in at least one of the four main reservoirs introduced above. The modeling results would be thus more complete if the data were available for more than one reservoir. This model simply applied these estimates to the LU/LC map to create that of carbon storage in the existing reservoirs. If both current and future LU/LC maps were presented, the net change in carbon storage over time (sequestration and loss) and its social value could be calculated. To estimate this change in CS over time, the model was basically applied to the current

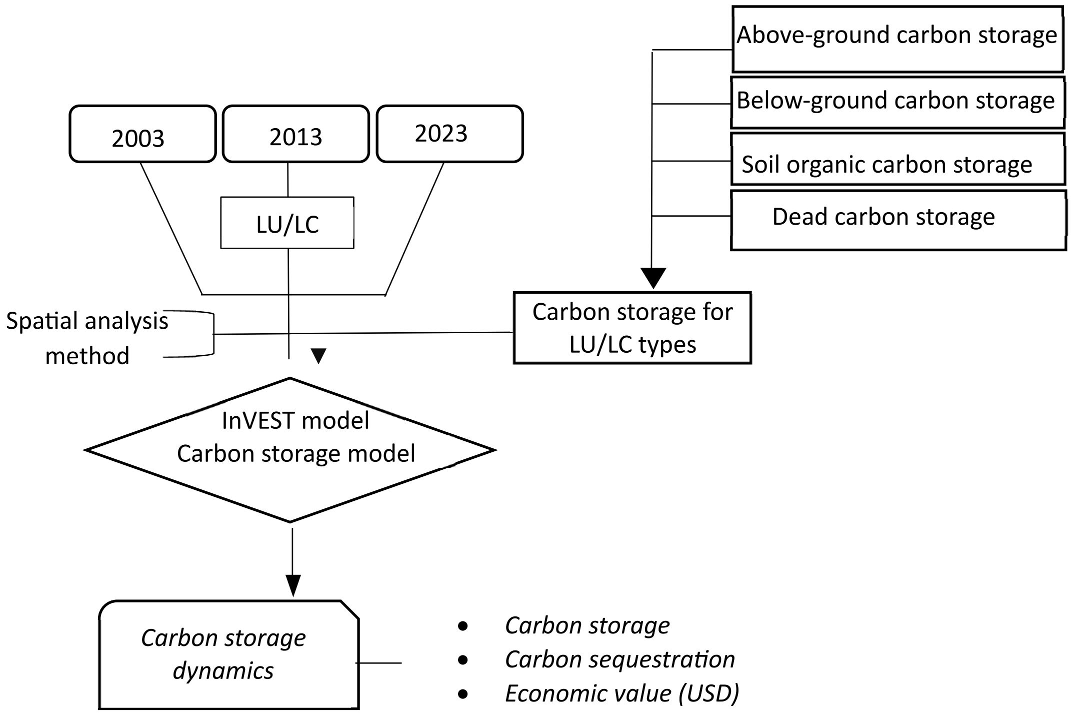

Fig. 2: Recearch Process

and the projected future landscapes, and the pixel-by-pixel storage difference was computed. If several future scenarios were available, the differences between the current scenario and each future one could be accordingly compared. The social value of one ton of separated carbon was social damage that could be avoided by not releasing each ton of carbon into the atmosphere. For the economic valuation of ES of CS, the value of each ton of carbon was considered equivalent to 35 USD with a discount rate of 3% and the annual changes of 2% of the carbon credit worth. The research process is illustrated in Fig. 2.

RESULTS AND DISCUSSION

The land-use changes in Districts 1 and 14 of Tehran Municipality were as follows. As mentioned in the research methods, the land-use map of these districts was first created using RS and satellite-based images. Figs. 3 to 8 show the land use maps of Districts 1 and 14 of Tehran Municipality for three time periods, 2003, 2013, and 2023. The land uses in these districts were further divided into four types, and classified according to field surveys and the knowledge of each district. These uses included waters spaces not available in District 1, very few water spaces between 2003 and 2013 in District 14, and water spaces in District 14 that will be removed in 2023. Green spaces, including parks, boulevards, and areas with vegetation and trees as spotted in the images, built-up uses, such as buildings, impervious surfaces, e.g., asphalt pavements, road networks, and areas manipulated by humans with no natural cover, and barren lands, namely, areas having no vegetation and construction, but bare soil.

District 1 of Tehran municipality with an area of 4661.2 hectares, was characterized by 26.55% of the area covered with green spaces, along with 56.24% and 17.21% of built-up lands and barren lands, respectively, in 2023. As well, District 14 with an area of 1455 hectares in 2023 also had water spaces, but green spaces, built-up lands, and barren lands accounted for 16.1%, 56.16%, and 27.57%, respectively. Table 1 shows the percentage of each land use in Districts 1 and 14 of Tehran Municipality from 2003 to 2023.

Carbon Storage and CS and their changes

To model carbon sequestration and storage, carbon reservoirs, which include 4 types of reservoirs on the ground, underground reservoirs, dead carbon reservoirs, and soil organic carbon reservoirs, were extracted and the data were introduced to the model

Fig. 3: Land use in District 14 of Tehran Municipality in 2003

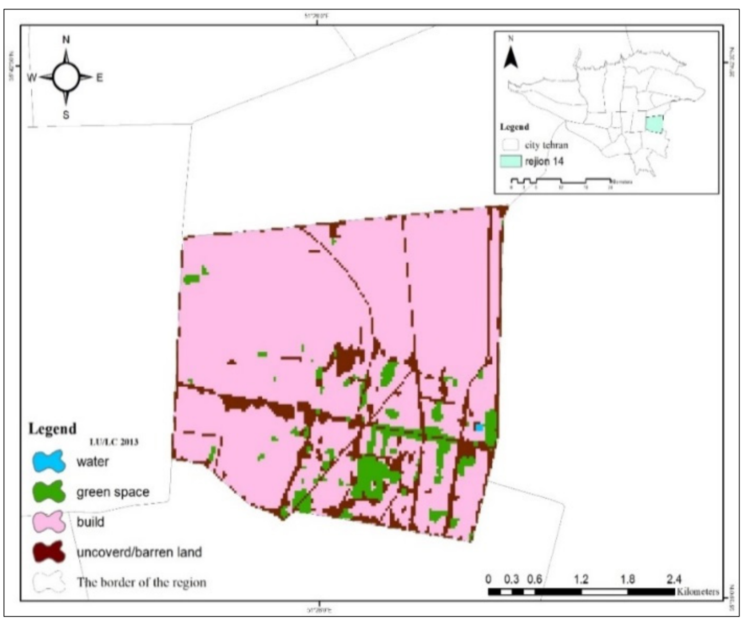

Fig. 4: Land use in District 14 of Tehran Municipality in 2013

Fig. 5: Land use in District 14 of Tehran Municipality in 2023

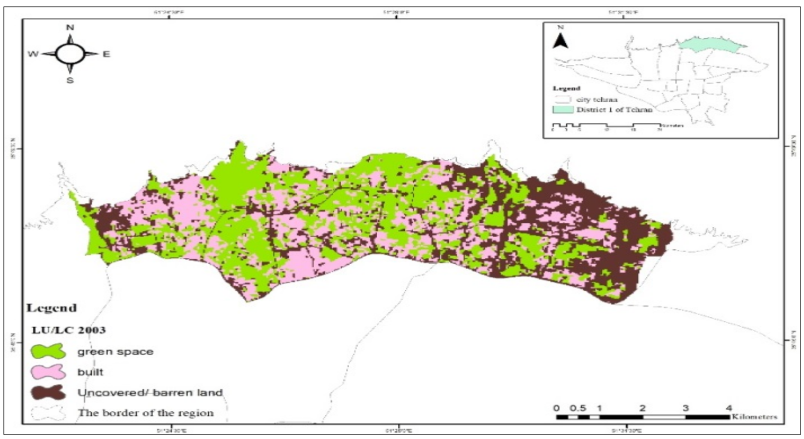

Fig. 6: Land use in District 1 of Tehran Municipality in 2003

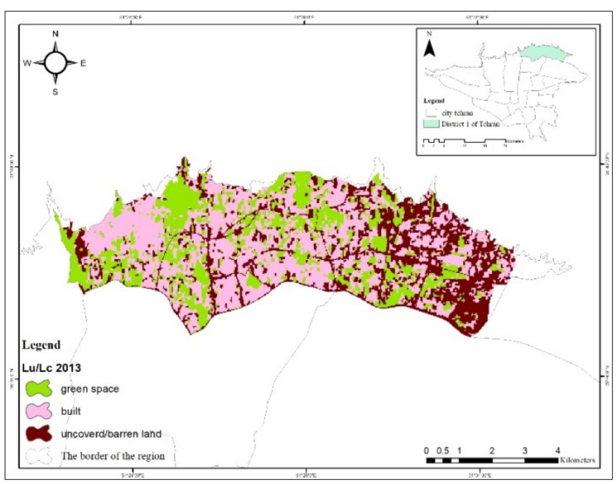

Fig. 7: Land use in District 1 of Tehran Municipality in 2013

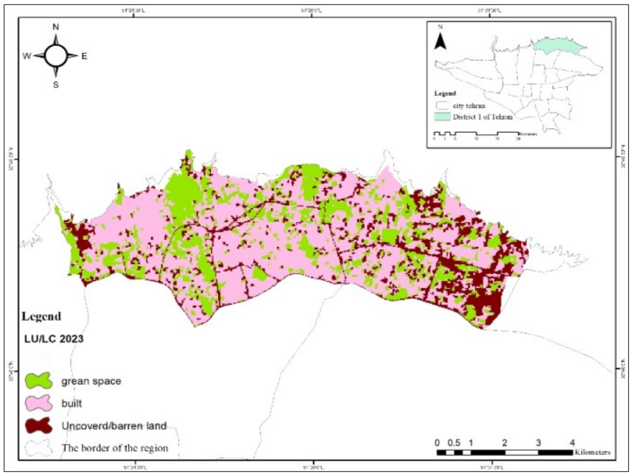

Fig. 8: Land use in District 1 of Tehran Municipality in 2023

Table 1: Percentage of land use in Districts 1 and 14 of Tehran Municipality from 2003 to 2023

Districts	Uses	2003 (percentage)	2013 (percentage)	2023 (percentage)
District 1	Green spaces	31	19.12	10.58
	Built-up lands	34.1	50.3	65.32
	Barren lands	34.9	30.58	24.1
District 2	Water spaces	0.1	0.055	0
	Green spaces	8	6.31	6.8
	Built-up lands	79	81.07	83
	Barren lands	12.97	12.55	12

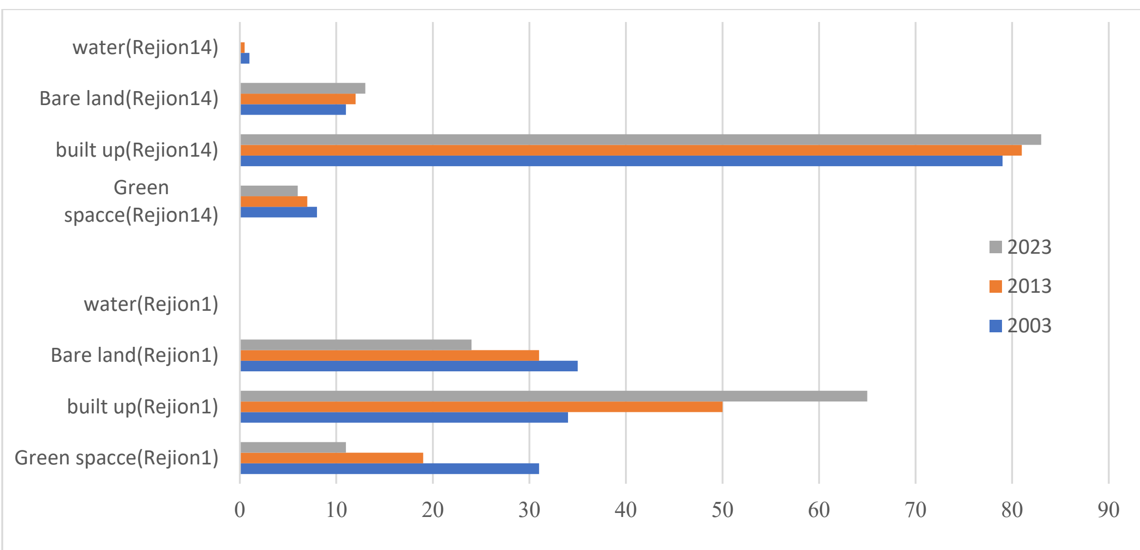

Fig. 9: Changes in land use in Districts 1 and 14 of Tehran Municipality during 2003-2023

Table 2: Carbon storage reservoirs in the city of Tehran (based on megagrams per hectare) (Mohaghegh *et al*., 2020)

Uses / Carbon	Above-ground carbon	Under-ground carbon	Soil carbon	Dead carbon
Water spaces	0	5	0	0
Green spaces	10	2	62	1.1
Built-up lands	4	5	15	1
Barren lands	0.4	0.83	60	0

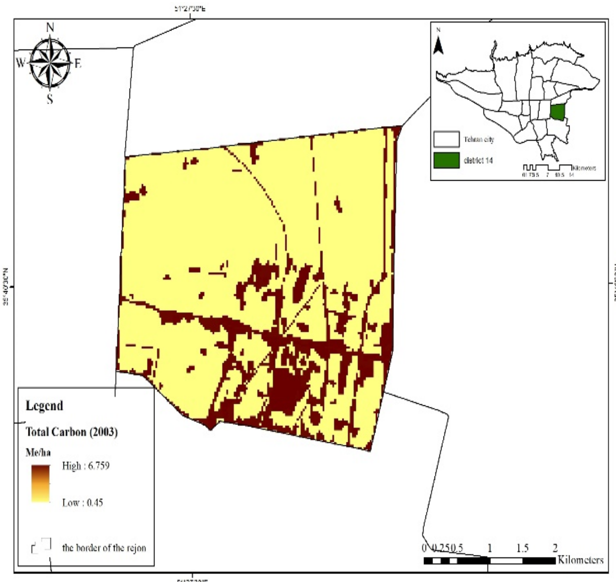

Fig. 10: Map of CS amount in District 14 of Tehran Municipality in 2003

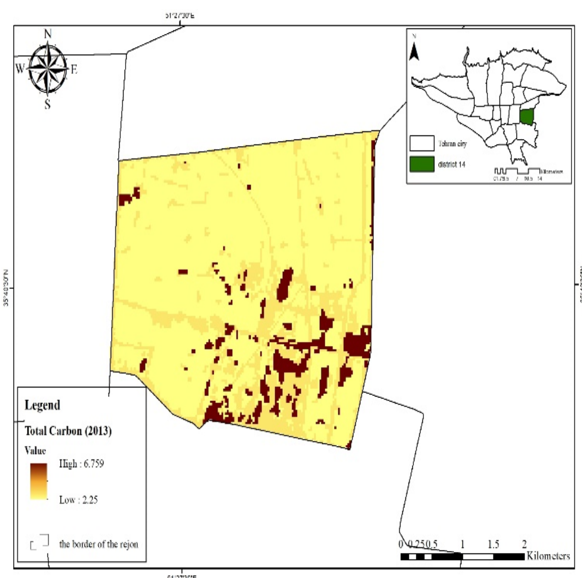

Fig. 11: Map of CS amount in District 14 of Tehran Municipality in 2013

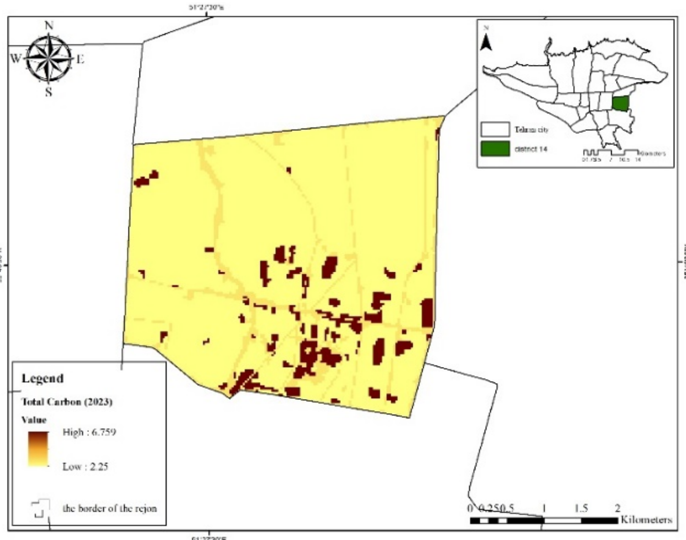

Fig. 12: Map of CS amount in District 14 of Tehran Municipality in 2023

Table 3. Amount of carbon storage in Districts 1 and 14 of Tehran Municipality during 2003, 2013, and 2023

Districts	Years	Minimum carbon storage (Tons per cell)	Maximum carbon storage (Tons per cell)	Total carbon storage (Tons per cell)
District 1	2003	0.45	6.759	21156415.4
	2013	0.45	6.759	19754807.7
	2023	0.45	6.759	18430138.5
District 14	2003	0.45	6.759	55006.68
	2013	0.45	6.759	51362.5
	2023	0.45	6.759	47918.36

Table 4: Changes in carbon storage in Districts 1 and 14 of Tehran Municipality during 2003, 2013, and 2023

Districts	Periods	Changes in carbon storage
District 1	2003-2013	-191401608
	2013-2023	-179114669
District 14	2003-2013	-3644.18
	2013-2023	-48229.8

in the form of a table with a specific format. Of note, the carbon reservoirs used in this study were extracted based on the review of previous research in this field in the city of Tehran and its surrounding environment. In this line, the carbon reservoirs were extracted for each class of use, and imported into the model.

Tables 3 and 4 displays carbon storage in the three time periods of this study, as well as the amount of changes in each period, compared with the previous one. In District 1, the equivalent of 21156415 megagrams of carbon was thus stored in 2003, and this value reached 19754807 megagrams in 2013, with a decrease of 191401608 megagrams. In 2023, 179114669 megagrams of stored carbon have been released, as compared with the value in 2013. Figs. 10 to 12 present the amount of CS. In District 14, there were 55006 megagrams of carbon storage in 2003, which dropped to 51362 megagrams in 2013, that is, 3644.18 megagrams of carbon was lost over 10

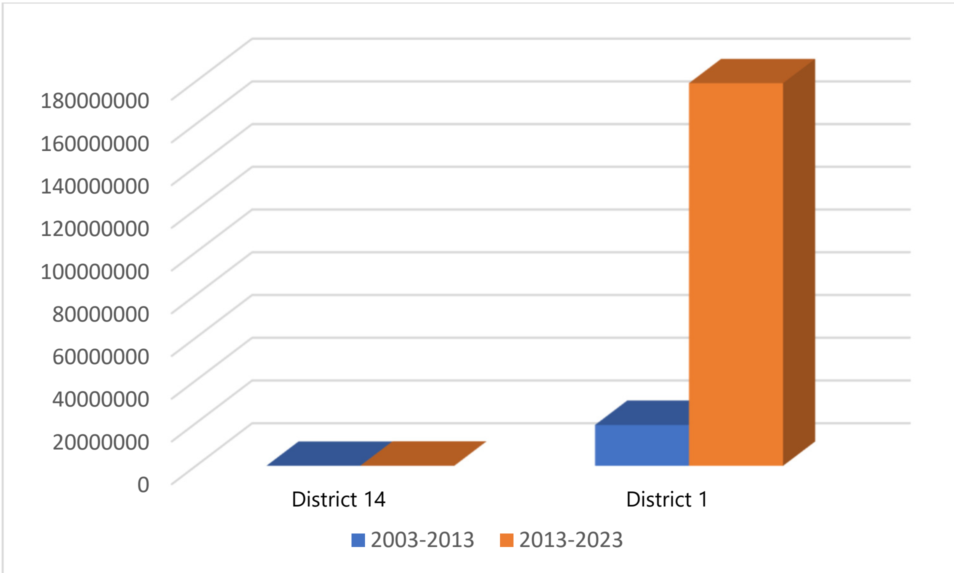

Fig. 13: Changes in carbon storage

years. In 2023, there has been 47918.36 megagrams of carbon storage in this district, namely, 47918.36 megagrams of carbon lost in comparison with the value in 2013.

Changes in Carbon Economic Value

According to the research methods, the value of each ton of carbon was considered to be 35 USD based on regional conditions and global references (Council, 2013). The discount rate of 2% and the annual carbon value change of 3% were also considered. As evidenced, different land-use changes in District 1 of Tehran Municipality resulted in the emission of 1401607.65 tons of carbon during 2003-2023, worth 49056267 USD, and 1324669.2 tons of carbon from 2003-2023, valued 46363422 USD. In District 14, various land-use changes also resulted in the release of 3644.18 tons of carbon in the period of 2003-2013, worth 1873871 USD, and 3444.14 tons of carbon during 2013-2023, valued 1749769 USD. Therefore, the unsystematic construction and development of built-up areas at the cost of destroying green spaces and barren lands, despite much effort and planning to develop UGS in this megacity overwhelmed the relative benefits of green infrastructure there, thereby making the resilience of ES of UGS unstable.

Natural-structural resilience has been documented among the main dimensions of urban land-use resilience, accounting for various structural-natural capacities of a city to prevent destruction and quickly back to the original state following threats and demolition. Without structural-natural resilience, urban lands have a very low environmental quality and seem to be in a weak position to disasters. In comparison with domestic research in this field, the present study made it possible to examine and archive the changes in land use during 2003-2023, via the InVEST model, visualize the changes of CS on a regional scale, and represent its impacts on urban resilience. It also valued the amount of ES of CS in the study areas. In this line, Joneidi Jafari *et al*. (2015) had investigated the effect of changing the use of pastures in Eyvanki, Semnan, Iran, in terms of carbon storage and sublimation, and put emphasis on the sensitivity of the carbon storage of these lands to the effect of land-use change. In another study, Asadollahi *et al*. (2017) had further explored the impact of land-use change on CS, and reported that the role of green space coverage and CS was diminishing. Human activities in the form of land-use change have thus significantly transformed land cover on a global scale. With the growing recognition of ES, there is a need for the development of software packages and models to provide decision-makers with the required

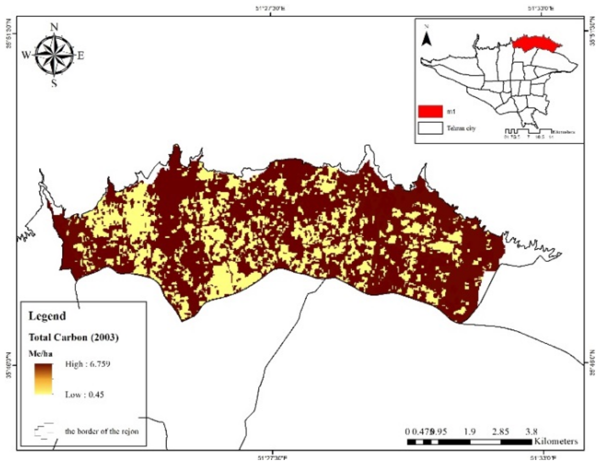

Fig. 14: CS amount in District 1 of Tehran Municipality in 2003

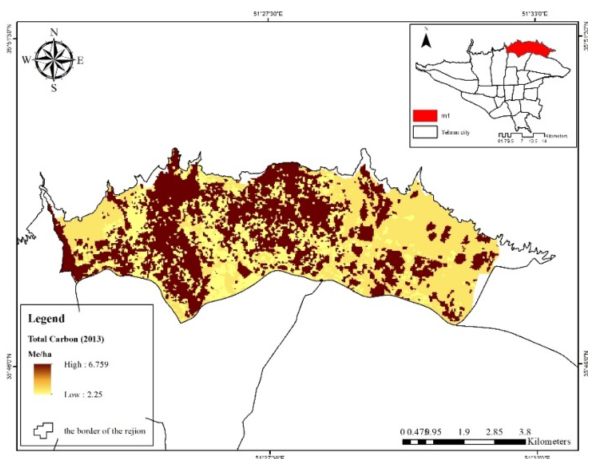

Fig. 15: CS amount in District 1 of Tehran Municipality in 2013

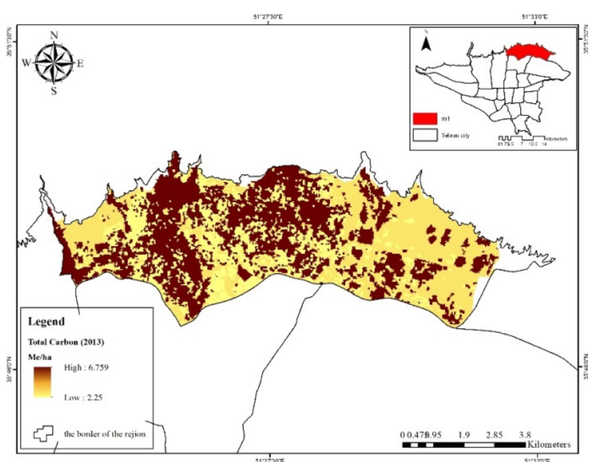

Fig. 16: CS amount in District 1 of Tehran Municipality in 2023

Table 5: Economic value of CS

Districts	Periods	Total CS (Mg* of carbon)	Periods	Change in carbon (Mg of carbon)	Net present value (USD)
District 1	2003	21156415.4	2003-2013	-1401607.65	-49056267.8
	2013	19754807.7			
	2023	18430138.5	2003-2013	-1324669.2	-46363422
District 14	2003	555006.68	2003-2013	-3644.18	-1873871.3
	2013	51362.5			
	2023	47918.36	2003-2013	-3444.14	-1749769.14

*Miligram

information on the supply of ES and examine the effects of land-use management on such services. To model the effect of UGS on CS, as well as the change of use on the change of carbon content, the InVEST model was applied, and its environmental benefits and losses were further delineated. To create land-use maps within the time periods of 2003, 2013, and 2023 in Districts 1 and 14 of Tehran Municipality, RS was recruited. As the results showed, the area of UGS and barren lands decreased over time in this megacity. However, the speed of this change in use was not constant during the 30 years of the study, and it was faster in the first two 10-year periods, implying the speed of population growth in Districts 1 and 14 from 2003 to 2023. A large area of barren lands has also undergone changes during these 20 years (particularly during the first 10 years) due to the increase in population and migration to the city along with subsequent demand for more lands to build residential areas and facilities. The speed of these changes eventually decreased for various reasons, including no capacity to load more constructions over the last 10 years of the study, as compared with the previous 20 years. CS among the most important regulatory services could thus reduce or adjust the speed of climate change through climate regulation from the local to the global macro-scales.

This study was thus an analysis of urban ES provided by multiple types of habitats, including green and water spaces. Such services are commonly under the control of heavy demand in cities raised by the large number of local beneficiaries. UGS, including parks and gardens, can thus provide various ES for city residents.

CONCLUSION

Urban ecosystem services are provided by various habitats such as green spaces and water bodies. Such services are typically in strong demand from many service recipients. In this connection, urban green spaces, i.e. parks and gardens, provide these services to urban dwellers. The main objective in this study was to analyze the spatiotemporal changes in the ESV of UGS in two districts out of 22 municipal districts in Tehran, Iran. For this purpose, there were attempts to evaluate the resilience of these districts in the face of climate change and environmental degradation, especially the amount of CS. This study further provided an innovative tool to improve the ESV of UGS and take suitable measures to enhance such spaces, recruiting library and documentation studies, spatial analysis, modeling, software packages, and field visits. In the first step, land-use maps in the present and past were created using RS. In the second step, different software packages and models were utilized to model CS in the study areas. Upon analyzing the land use and cover maps, using different models, the amount of CS and their changes during three time periods were estimated. The study results showed that the indiscriminate construction and development of built-up areas had led to the depletion of UGS, and as a result, the reduction of their ecosystem resilience. Moreover, reduced CS and changes in land use could have a destructive effect on the ES of UGS, specifically in terms of resilience against climate change and temperature rise. This study was in line with previous research, except for examining the effect of CS of UGS on the economic and environmental issues of CS by vegetation and green spaces. In addition, it was implemented in various environments and laid focus on various aspects, including the significant positive effect of CS based on terrestrial vegetation on economic growth in urban areas, as one of the significant outcomes. Besides, the ESV of UGS as a resilience factor was considered. Other studies had correspondingly evaluated the ecosystem effects of UGS on carbon reduction, but this study in a supplementary manner surveyed the effects of ecosystem on economic growth and spatiotemporal changes in the ESV of such spaces. The main goal was to evaluate the resilience of the study areas against climate change and environmental degradation, particularly CS. To achieve this goal, various steps were taken, and the findings revealed that CS in UGS decreased, and even vanished over time. This might be due to the changes in natural landscapes and the analysis of UGS. The study results can thus help city planners and officials in terms of proper planning and management of UGS. Creating and maintaining UGS not only helps in CS, but also brings other economic and environmental values, such as oxygen production, pollutant removal, and higher levels of resilience. These findings can further aid urban decision-makers to take advantage of the strengths and potential of carbon reduction in the design and development of UGS.

AUTHOR CONTRIBUTIONS

Sh. Hoseini performed the literature review, design, analyzed and interpreted the data, M.J. Amiri as the corresponding author, compiled the data and manuscript preparation. Y. Moarrab performed some of the remaining experiments and data.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication, falsification, double publication, submission, and redundancy, have been entirely witnessed by the authors.

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ABBREVIATIONS

CO_2	Carbon dioxide
CS	Carbon sequestration
ES	Ecosystem services
ENVI	Environment for visualizing images
ESV	Ecosystem services value
GIS	Geographic Information System
InVEST	Integrated valuation of ecosystem services and trade offs
LU/LC	land-use/land-cover
NLOM	Nonliving organic matter
NO_x	Nitrogen oxide
NBS	Nature based solution
RS	Remote sensing
WHO	World health organization

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