Modeling spatial distribution of carbon sequestration, CO2 absorption, and O2 production in an urban area: integrating ground-based data, remote sensing technique, and GWR model

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Abstract

The main purpose of this research is to model the spatial distribution of carbon sequestration, CO_2 absorption, and oxygen production by trees within Isfahan city, Iran, in 2020. To quantify carbon sequestration, we accessed a sample group of trees with measured biophysical attributes. First, we calculated the biomass and carbon sequestration of a tree using the allometric and photosynthesis equations. Then, to model the spatial distribution of carbon sequestration, we used Geographic Weighted Regression (GWR) method. In this model, the amount of calculated carbon sequestration was the dependent variable, whereas the difference between vegetation index of ΔExGR(Excess Green Plant Index minus Excess Red Plant Index)from the Worldview image was the independent variable. Subsequently, the spatial distribution map of CO_2 absorption and oxygen production was generated. The total value of annual carbon sequestration, CO_2 absorption, and O_2 production was about 7704.22, 28274.502, and 20570.16 tons, respectively. The results showed that there was a strong correlation between the ΔExGR index of the canopy with calculated carbon. Integrating the ΔExGR index from a high-resolution image with calculated carbon can contribute to developing a fast, accurate, and low-cost method in estimating carbon sequestration and modeling its spatial distribution in urban areas. In conclusion, the results of this research can be implemented by land use planners in order to integrate urban ecosystem service concept (i.e., carbon sequestration) in planning process towards sustainability of the cities.

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Abstract

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***Key Word*:** Urban Ecosystem Service; Urban Ecology; Climate Regulation Service; Green Infrastructure; Geographic Weighted Regression (GWR);

1. ***Introduction***

Increasing fossil fuel consumption in urban areas due to population growth brings about a large amount of greenhouse gases emission into the atmosphere (Houghton, 2001). Among greenhouse gases, carbon dioxide plays a significant role in global warming (Lal, 2004; Peters, 2001; Petit et al., 1999; Scott et al., 2002). In climate change studies, urban areas attributes to emit a high proportion of carbon dioxide into the atmosphere (Churkina, 2008, Grimm et al., 2008).

Urban green areas (lawns and trees) provide multitude of ecosystem services like climate regulation and air purification. Carbon sequestration service by vegetation cover is a well-recognized urban ecosystem service mitigating the atmosphere's carbon dioxide (Baró et al., 2014, Gómez-Baggethun et al., 2013, Haase et al., 2014, Kiss et al., 2015, Larondelle and Haase, 2013).

Carbon sequestration refers to a process in which the atmospheric carbon dioxide is converted into organic compounds by photosynthesis process in trees, plants, phytoplankton, and algae (Adams et al., 1990, Nanda et al., 2016, NAYAK et al., 2020, Tornquist et al., 2009). Carbon sequestration amount is related to the growth rate, species type, and age of the tree (McPherson 1998). During the photosynthesis process, CO_2 stores in the form of cellulose. Also, the other portion of the carbon transfers to the soil in organic form (Dwivedi et al., 2009, Komiyama et al., 2005, MacFarlane, 2009, Miller et al., 2015, Nowak and Crane, 2002, Nowak and Dwyer, 2007, Rowntree and Nowak, 1991, Tang and Li, 2013, Ward Thompson et al., 2016, Zirkle et al., 2012). The resources of carbon storage in an ecosystem include above-ground and below-ground biomass, litter and plant residues, and soil organic matter (Nowak and Crane, 2002, Sinoga et al., 2012).

Additionally, green spaces are considered as oxygen production resources in urban areas. Oxygen production of plants directly related to the carbon storage process. Estimating produced oxygen and carbon sequestration by vegetation in an urban area is essential in dealing with air pollution (Nowak et al., 2007).

Considering previous literature related to tree biomass estimation and carbon sequestration, they can be divided into two general categories: the first body of research is characterized by ground sampling or measuring biological variables in a laboratory environment. Numerous studies have been done in this area, which included: estimating carbon storage in biomass in a forested area in Chile (Espinosa et al., 2005), biomass estimation and leaf area index in mangrove forests of Japan (Khan et al., 2005), estimating the biomass of ten tree species in temperate forests of China (Wang, 2006), calculating soil biomass of mangrove species in Brazil (Medeiros and Sampaio, 2008), and estimating above-ground biomass and carbon sequestration in rainforests in Thailand (Terakunpisut et al., 2007). Other studies in this field included the research by Aguaron and McPherson, 2012, Bernal et al., 2018, Nowak et al., 2013, Tor-ngern and Leksungnoen, 2020, Townsend - Small and Czimczik, 2010, Velasco et al., 2016. The second class of research is organized based on satellite image and remote sensing techniques to measure the biomass of the plants. For instance, estimating the amount of biomass of Acacia species, silver cypress, berry tree using linear regression model and applying Quick bird data and NDVI and DVI indices in Isfahan, Iran (Hosseini et al., 2015). Mirrajabi and colleagues in 2016 estimated biomass of broadleaf and coniferous species using GeoEye images in Chitgar park, Tehran, Iran (Mirrajabi et al., 2016). Amini and Sadeghi benefitted from ALOS data and multiple regression equations to estimate the amount of forest biomass (Aliabadi and Entezari, 2014). The other research in this category can be found in related papers done by Deng et al., 2011, Günlü et al., 2014, Hall et al., 2006, Raciti et al., 2014, Strunk et al., 2014.

Previous studies show that allometric equations were used to determine the above-ground and below-ground biomass of trees as well as to estimate the amount of carbon storage.

These equations consider several parameters like diameter at breast height (DBH), tree height, and wood density to estimate biomass in a single tree unit (Aguaron and McPherson, 2012).

In this research, we used allometric equations to calculate the biomass of a tree. Then to model the spatial distribution of carbon sequestration, we integrated the results of the allometric equation with the spectral data of the satellite image.

Another influential factor in the accuracy of estimating carbon storage is statistical modeling methods. A wide range of methods, including parametric, semi-parametric, and non-parametric methods, have been used to quantify carbon storage using remote sensing (Wu et al., 2016)

In a cumulative body of research, different statistic methods were used to integrate ground data (from the allometric equation) into remotely-sensed data to quantify various characteristic of trees like a canopy, biomass, and carbon storage (Carreiras et al., 2006, Cartus et al., 2012, Cutler et al., 2012, Ghanbari Motlagh et al., 2020, Hamdan et al., 2015, Lucas et al., 2010, Moradi et al., 2018, Mutanga et al., 2012, Raciti et al., 2014, Shataee et al., 2012).

To the best of our knowledge, to estimate carbon sequestration, the previous studies measured several trees as samples in a plot to examine the relationship between ground data and satellite data through the linear regression (Deng et al., 2011, Mirrajabi et al., 2016, Raciti et al., 2014). However, in this study, for the first time, we used geographic weighted regression (GWR) to create a relationship between spectral data of each tree (canopy reflection (drip line)) with the calculated ground biomass. It was assumed that integrating the remotely sensed data with the measured biomass in the GWR model can provide reliable results, contributing to addressing the spatial distribution of carbon sequestration as well as estimating the amount of carbon sequestration.

Considering the background previously discussed, therefore, this article aims to develop a model to analyze the spatial distribution of carbon sequestration, CO_2 absorption, and O_2 production within Isfahan city. To achieve this goal, we pursued the following sub-objectives:

- Calculating the above-ground and below-ground biomass of sampled trees using the allometric equations.

- Estimating carbon sequestration of sampled trees using photosynthesis equation.

- Processing the satellite image with different spectral variables to recognize the most appropriate index.

- Creating a GWR model to integrate the spectral data of each tree with carbon sequestration of the tree.

- Providing the spatial distribution map of carbon sequestration, CO_2 absorption, and oxygen production.

2- Materials and Method

2-1- study area

The study area is Isfahan metropolitan, located in the center of Iran lying between 31° 29' to 33° 1' North latitude and 51° 31' to 53° 12' East longitude (Fig. 1). Air temperature and relative humidity in the city are strongly influenced by the type of surface cover. Isfahan city is characterized by an arid climate according to De Martonne's climatic classification scheme. It enjoyed a high diversity of vegetation surface; from the west reaches to the gardens and forest park of Nazhvan, from the south, reaches to the mountain park of Sofeh, from the north and east are bounded by the desert region. Isfahan city is famous for its abundance of parks and green spaces along the Zayandehrood River.

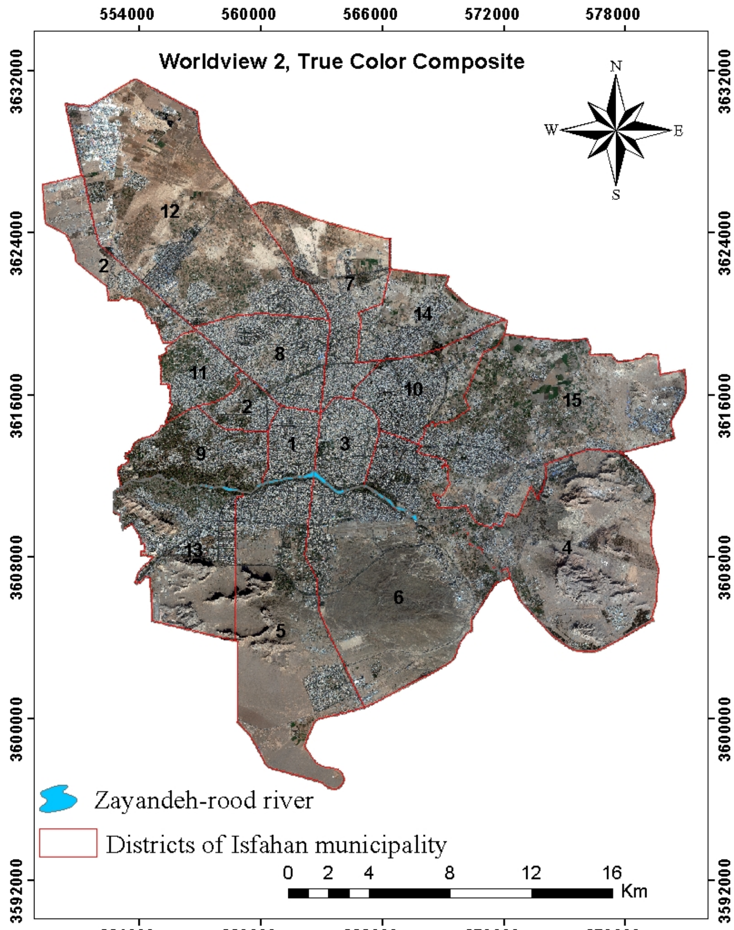

Fig.1. Isfahan city and its municipality districts (the study are)

2-2- Methodology

To avoid ambiguity, we divided the methodology into seven steps which are as follows:

2-2-1- Step1: Data collection

The organization of parks and green space of Isfahan city provided a database of 770561 surveyed trees, in which their biophysical attributes like the height, DBH, health status, and their pest and disease were recorded. In order to estimate the biomass of a single tree, we used biophysical variables of DBH and height of a tree recorded in the survey. Further, we used a topographic map of 1/2000 provided in 2017. Furthermore, it was used Worldview2 satellite image of the region to model carbon sequestration of the trees (the trees that were not surveyed) throughout the study area.

2-2-2- Step 2: Calculating biomass volume in an individual tree unit using allometric equations

To calculate the above-ground and below-ground biomass of a tree, we used the well-known method developed by Ponce-Hernandez and colleagues in 2014. The method contained several parameters of DBH, height, and wood density (Ponce-Hernandez et al., 2004). To calculate the above-ground biomass (trunk and crown) and below-ground biomass (root) following sub-steps were taken

A) Estimating the above-ground biomass

The above-ground biomass included trunk and crown biomass. Estimating their biomass are as follows:

Calculating trunk biomass: In order to estimate biomass of tree trunk, basal area of a tree was calculated using Eq. 1, their volume was calculated through Eq. 2, and finally, the biomass of a tree was obtained by Eq. 3 in kilogram (Ponce-Hernandez et al., 2004).

$$A_b = \pi \times r^2 \qquad Eq.1$$

$$V = A_b \times H \times K_c \qquad Eq.2$$

$$Biomass = \mathrm{AGB} = V \times WD \times 1000 \qquad Eq.3$$

Where π is 3.14, $A_b$is a basal area (*m²*), r is tree radios(*meter*), H is the height of a tree(*meter)*, WD is tree density (*gr/cm³*), V is the volume of a tree (*cm³*), K_c is a coefficient that depends on the site (In most of the studies associated to the biomass in Northern jungle of Iran, the coefficient was considered 0.54) (Namiranian, 2003, Peichl and Arain, 2006, Ponce-Hernandez et al., 2004).

In equation 3, the variable of dried wood density (*gr/cm³*) was calculated based on the dried weight (*gram*) to the volume (*cm³*); M is weight of dry wood (*gram*) and V is the volume of the wood (*cm³*), and WD stands for dried wood density in term of a gram per cm^3 (Henry et al., 2010, Varamesh et al., 2010).

Since the density of dry wood of trees was not measured in the study area, then for each species in the area, we used the average amount of wood density measured in the previous study (Brown, 1997, McPherson et al., 2016).

***- Calculating crown biomass (tree branches)*:** Crown size is one of the basic variables in allometric equations to estimate the tree biomass. The above-ground biomass is summation of the trunk biomass and crown biomass (leaf and branches). There are different methods to calculate crown biomass in jungle areas (McPherson et al., 2016; (Dong et al., 2016, Negi et al., 1995, Ximenes et al., 2008, Xue et al., 2016) As represented in table 1, previous studies determined the proportion of crown biomass related to the total biomass (root, trunk, and crown) for conifer and broadleaf species (Dong et al., 2016, Negi et al., 1995, Ximenes et al., 2008, Xue et al., 2016).

Table 1: Relative proportion of crown, trunk, and root biomass in coniferous and broad-leafed trees

@ >p(- 8) * >p(- 8) * >p(- 8) * >p(- 8) * >p(- 8) * @ **Reference** & **Crown (Leaf and branches) biomass** & **Trunk biomass** & **Below-ground biomass** & **Species**
(Dong et al., 2016, Negi et al., 1995, Ximenes et al., 2008, Xue et al., 2016) & (17-19)

Average (18) & 57-67

Average (62) & 17-23

Average (20) & **Coniferous**
(Negi et al., 1995, Ximenes et al., 2008, Xue et al., 2016) & 24 & 56 & 20 & **Broadleaf**

B) Calculating below-ground biomass (root biomass)

In order to calculate root biomass, we used equation 4, in which RGB stands for below-ground biomass and AGB stands for above-ground biomass (sum of trunk and crown biomass) (West and West, 2009, Ximenes et al., 2008, Xue et al., 2016).

$$BGB = Volume\ AGB\ \times 0.2 \qquad Eq.4$$

2-2-3- Step 3- Estimating carbon storage in an individual tree unit

Once the biomass of a single tree was calculated using the allometric equations, carbon storage in the above-ground biomass (trunk and crown) and the below-ground (root) was calculated through equation 1 and 2(Aboal et al., 2005, Kirby and Potvin, 2007, Pearson, 2007, Peichl and Arain, 2006)

$$C_{\mathrm{AGB}} = AGB * C\% \qquad Eq.1$$

$$C_{\mathrm{BGB}} = BGB * C\% \qquad Eq.2$$

Where C_{AGB} indicates carbon in the above-ground biomass (*kg*), AGB is the above-ground biomass of tree (*kg*), C_{BGB} is the amount of carbon in below-ground biomass (*kg*), BGB stands for the below-ground biomass(*kg*), and C% is carbon percentage (the amount of carbon storage in biomass or carbon conversion efficient). The results of previous studies showed that the carbon conversion ratio in the biomass of different tree species varies between 44.4% to 55.7%, and usually in most studies, it is equivalent to an average of 50% of the dry mass (Elias and Potvin, 2003; Singh et al., 2011; Zhang et al., 2009; Zhu et al., 2010). While, in this research, to estimate the amount of carbon in the biomass, instead of using the coefficient (50%), we used the photosynthesis chemical equation. The well-known chemical photosynthesis equation is explained as follows (Blankenship, 2014):

$$6CO_2\ (264\ g) + 6H_2\text{O}\ (108\ g) + light \rightarrow C_6H_{12}O_6\ (180\ g) + 6O_2\ (193\ g)\ \rightarrow\ Amylase\ (162\ g)$$

The molecular weight of carbon dioxide is 44.9595 $g\ /\ mol$; therefore, plants absorb six molecules of CO_2, i.e., 264 gram of carbon dioxide, 162 gram of amylase, or dry matter (Blankenship, 2014). Therefore, it can be said that each kilogram of dry matter (produced by trees) absorbs 1.629 kilograms of carbon dioxide Based on this equation, considering that the atomic weight of carbon is 12.01 grams, therefore, for absorbing 6 molecules of carbon dioxide, around 72 grams of carbon is fixed in the biomass. In general, for every kilogram of dry matter produced in a tree, approximately 453 grams of carbon is stored in the biomass of a tree.

2-2-4- Step 4: Estimating CO_2 absorption in an individual tree unit

According to the photosynthesis equation in step 4, I can be concluded that for each unit of carbon storage in the biomass, 3.67 unit of carbon dioxide is absorbed. It means that to calculate CO_2 absorption in an individual tree unit, the amount of carbon storage in the biomass should be multiplied by 3.67.

2-2-5- Step 5: Estimating annual carbon sequestration in an individual tree unit

The absorption of atmospheric carbon or carbon sequestration is the amount of fixed carbon in tree biomass in a given time. Generally, carbon sequestration is measured within a year and is based on a kilogram or gram per year.

In order to calculate the average amount of the annual carbon storage, we assumed that the average diameter growth is 0.61 cm per year based on the previous evidence (table 2). Also, since most of the trees were categorized in the moderate and old class, therefore, the average annual growth of their height was considered 15 cm per year.

Table 2 the average annual diameter growth and average annual height growth

Reference	Estimated amou
(Aguaron and McPherson, 2012, De Vries, 1987, Nowak et al., 2007	0.61 cm
(Aguaron and McPherson, 2012, McPherson, 1994, McPherson, 1998, Nowak et al., 2007	15 cm

Thus, to calculate the annual carbon sequestration, we added the average annual diameter growth (*0.61 cm*) and the average height growth (*15 cm*) to all trees. The above-ground and below-ground biomass of the trees were calculated using the equations in step. 2. The amount of tree biomass that converted to the sequestrated carbon was estimated per year by using the equations in step 3. Finally, the results of this step (annual carbon sequestration in above-ground and below-ground biomass) were subtracted from the value in step 3. The result value is the amount of annual carbon sequestration in each tree

2-2-6- Step 6: Modeling the spatial distribution of carbon sequestration and CO_2 absorption across the city

To model the spatial distribution of carbon sequestration within the city, we created a regression relationship between the spectral values of the Worldview2 satellite image with calculated carbon sequestration (described in the previous steps) in a single tree unit.

In this step, first, we needed to do image pre-processing and processing, and then created a regression model that is as follows:

- ***Image Preprocessing***

Image preprocessing included georeferencing and atmospheric corrections. We used the removal haze tool for atmospheric correction. In this study, to ensure the accuracy of the geometric correction of the image, a topographic map (1/1000) was used. The exact matching of the road layer from the topographic map with the image showed the geometric accuracy of the image.

- ***Image processing***

To investigate the regression relationships between the spectral variables o with the calculated carbon in a tree, the processes were applied on the spectral bands. Then, the most important spectral variables were extracted from the image to estimate the amount of carbon. The processes that applied to the satellite imagery in this study can be classified into three groups. The first group included spectral ratios obtained from the three red, green, and blue bands. The second group consisted of three plant indices, including the Excess Green Plant Index (ExG), the Excess Red Plant Index (ExR), and the difference between these indices (ΔExGR). Their equations are expressed in relations 1 to 3, respectively (Meyer and Neto, 2008).

Also, in the third group, texture analysis was separately performed on each band (blue (B), green (G), and red (R) bands).

$$ExG = (2 * G) - R - B \qquad Eq.1$$

$$ExR = (1.4 * R) - G \qquad Eq.2$$

$$\Delta\text{ExGR} = ExG - ExR \qquad Eq.3$$

- ***Creating a GWR to model the relationship between calculated carbon sequestration and spectral variables***

In this section, we modeled the relationship between the spectral variables of the satellite image with the amount of carbon that was measured for a tree unit. To do so, first, a buffer around the tree with a radius of the drip line (approximate radius of the canopy) was defined. Dripline is the area, which is located completely below the outer perimeter of the tree branches saying that its area is approximately equal to the area of the canopy. To determine the actual radius of the critical root protection zone (drip line), first, the perimeter of the tree trunk was measured at the height of 1.3 meters above the ground. Then the perimeter of the trunk was divided by the pi constant (3.14) to calculate the DBH. Finally, the DBH was multiplied by 12. The general rule of this method is that for every 1 cm of tree trunk diameter, the radius of the critical root protection zone increases by 12 cm (Council, 2013, Design et al., 2019, Limited, 2009, Matheny and Clark, 1998, Moore, 2018, Roloff, 2016, Rust, 2015, Standard, Suchocka, et al., 2019).

In this study, the drip line was used as a buffer for each sampled tree. Then 70% of these drip lines (vectors layers) that their DBH were 5 cm or larger than 5 cm randomly selected. After that, we used the zonal statistics tool to derive the pixel value of the spectral variables (bands, vegetation indices, and texture analysis) for each sampled tree.

Finally, the amount of calculated carbon sequestration for a sampled tree was considered as a dependent variable, whereas the spectral values (image bands, plant indices, and image texture analysis results) were regarded as an independent variable. The independent and dependent values entered into the GWR model.

GWR is a statistical technique that is used to model the spatial heterogeneous processes. It has high accuracy in analyzing location-affected relationships (Fotheringham et al., 2001). This model is a generalized version of the ordinary least square regression method in which the spatial pattern of relationships between variables is examined in the sample space (Gao and Li, 2011). Instead of calibrating a single regression equation, this method produces a separate regression equation for each observation (for more information, see the references: Brunsdon et al., 1996, Fotheringham et al., 2001, Gao and Li, 2011; Tu and Xia, 2008, Zhao et al., 2018).

After evaluating different models with different arrangements of independent variables, the best significant model was selected, and its weight matrix was determined. Then, the model was implemented using a significant independent variable on the entire study area. After that, the amount of carbon sequestration in the tree biomass was estimated for the whole green space of the study area.

2-2-7- Step 7: Estimating Oxygen production by trees in the study area

Oxygen is produced through photosynthesis process:

$$6CO_2\,(264\,g)+6H_2\text{O}\ (108\,g)+light\rightarrow C_6H_{12}O_6\,(180\,g)+6O_2\,(193\,g)\ \rightarrow\ Amylase\,(162\,g)$$

Respiration :$(CH_2O)n+nO_2\rightarrow n(CO_2)+n(H_2O)$+energy

As shown in the photosynthesis equation, plants absorb 264 grams of CO_2 to produce 193 grams of O_2 and 162 grams of dry matter in the form of fiber and starch (Blankenship, 2014). On the other hand, plants respiration process consumes some produced oxygen in the photosynthetic process according to the chemical equation of respiration; therefore, the net production of oxygen by trees is a function of producing oxygen during photosynthesis minus the amount of oxygen consumed during respiration (Nowak et al., 2007)

Also, since the net oxygen production by a tree over a year is directly related to the amount of carbon released by the tree, the amount of oxygen produced is tied to the accumulation of tree biomass. Therefore, if the amount of carbon dioxide absorbed during photosynthesis exceeds the carbon dioxide due to respiration during the year, it accumulates in carbon trees (carbon sequestration). Thus, a tree that has a net carbon accumulation during a year, it also produces net oxygen (Nowak et al., 2007)

The net annual amount of oxygen produced is estimated according to Equation (-) (Nowak et al., 2007). According to the relation (1), the amount of oxygen production (O_2) in kilograms per year is calculated by multiplying the net precipitation of carbon (C) (in kilograms or grams) by the ratio of the atomic weight of oxygen to carbon (32/12=2.67).

$$\mathbf{O_2 = C * 2.67\ \ Eq.1}$$

1. ***Results***

3-1- Determining tree diversity and their dominance within the city

We accessed the database of 770561 trees surveyed by the green space organization. Approximately 34 percent of the trees were conifer species, while 66 percent were categorized as broad-leaved species. The dominant species of trees are represented in table 3.

Table 3 Dominant tree species in Isfahan green space

Species	Scientific name	Percent	Annual carbon sequestration
Pinus	Pius Eldarica	19	22.7
Mulberry	Morus Alba	14.34	11.27
Cypress	Cupressus Arizonica	12.55	2.78
Elm	Ulmus Minor	12.23	20.45

Species	Scientific name	Percent	Annual carbon sequestration
Ash	Fraxinus Excelsior	10.15	5.44
Plane	Platanus Orientalis	8.78	25.42
Melia	Melia Azedarach	3.13	1
Acacia	Robinia Pseudoacacia	2.51	1.34
Weeping willow	Salix Alba	1.5	2.16
Juniper	Ailanthus Altissima	1.4	1.04
Pomegranate	Punica Granatum	1.1	0.13

3-2- DBH classification

The DBH parameter of surveyed trees was classified into 11 classes (table 4). The DBH of about 83 percent of the trees was less than 23 centimeters. The smaller diameter, the younger the trees (Millward and Sabir, 2010) So, the majority of trees are attributed to the young groups.

Table 4 Classification of trees based on DBH

DBH (cm)	(percent)
7.6	33.67
7.7-15.2	27.446
15.3-22.9	23.346
23-30.5	4.927
30.6-38.1	7.773
38.2-45.7	2.119
45.8-53.3	0.393
53.4-61	0.17
61.1-68.7	0.022
68.7-76.3	0.0623
76.3	0.0624

3-3- Biomass volume, carbon sequestration, and carbon absorption in an individual tree unit

Based on all the equations described in the first four steps, the total annual gross carbon sequestration in the surveyed trees was about 1563.32 tons per year. Carbon sequestration was different between various species. The percentage of carbon sequestration by the dominant species (coniferous and broad leave) in the study area is given in Table 5.

The results revealed that plane trees had the highest carbon sequestration, accounting for 25.42% of the sequestered carbon by sampled trees within Isfahan parks. Also, the amount of tree biomass, annual carbon sequestration, and annual carbon dioxide absorption in the roots, trunk, and canopy of conifer and broad-leaved species were calculated and represented in Table5.

Table 5 – total biomass, annual carbon sequestration and annual CO_2 absorption by surveyed tree

Tree species	**Root**			**Trunk**			**Crown**		
	Biomass	**Carbon sequestration**	**Annual CO_2 absorption**	**Biomass**	**Carbon sequestration**	**Annual CO_2 absorption**	**Biomass**	**Carbon sequestration**	**Annual CO_2 absorption**
Conifer	2152.47	87.26	320.24	7788.7	270.52	992.8	2261.23	78.54	288.23
Broad-leaved	7709.98	225.4	827.22	21587.96	631.12	2316.21	9251.98	270.5	992.7

As represented in table 5, the total annual carbon sequestration in the root, trunk, and crown biomass by coniferous and broadleaf species were about 436.32 and 1127 ton, respectively. Overall, approximately 5737.5 tons of carbon dioxide from the atmosphere were absorbed by all the sampled trees across the city. The trunk biomass participated the most in the carbon sequestration of an individual tree unit.

1. ***Modeling the spatial distribution of carbon sequestration across the city***

3-4-1- Preprocessing and processing of the image

After preprocessing the image through the removal haze, the appropriate processes were done (see the methodology). The results of GWR showed that amongst different spectral variables (i.e., band analysis, vegetation indices, and texture analysis) difference between Excess Red Plant Index (ExR) and Excess Green Plant Index (ExG), which was indicated by ΔExGR had a significant correlation with the annual carbon sequestration. Figure 2 shows the result of applying the ΔExGR index on worldview image to extract tree canopy.


562700
562800
562900
563000
563100
563200
3613500
3613400
3613300
3613200
3613100
3613000
3612900
3612800

Fig. 2. (A) The location of two sample areas to show (B) The canopy of trees in Hasht Behesht Garden derived by applying ΔExGR index on the Worldview image C)The canopy of trees around Zayandeh-rood river derived by ΔExGR index on the worldview image.

1. ***Analyzing the relationship between calculated carbon sequestration and vegetation index using the GWR model***

   Table 6 represents the results of the relationship between ΔExGR as an independent variable with dependent variables (carbon sequestration) in GWR model

   The results of the GWR regression modeling (Table 6) show that Residual Squares (R2) was 0.91, indicating what percentage of the changes in the dependent variable was explained by the independent variables. Also, the amount of adjusted residual squares (Adjusted R2) was 0.64. Using adjusted R2 is useful when we have more than one independent variable in the regression model. In this research, considering only one independent variable, we used R2 to investigate the relationship between vegetation index and carbon sequestration: there was a significant positive relationship between them

   As it can be shown in table 6, the Sigma parameter (i.e., second root of the normalized Residual Square) was also used to show the relationship between dependent and independent variables. The less sigma value, the better relationship. In this analysis the sigma value was 0.0399. Another parameter was the Corrected Akaike Information Criterion (AICc). The AICc is a mathematical method for evaluating how well a model fits the data it was generated from.

   Table 6- the relationship between calculated carbon sequestration and vegetation index using GWR model

Dependent variable	Independent variable	Parameters	Value
Annual Carbon Sequestration	ΔExGR Vegetation index	Sigma	0.0399
		AICc	441316
		R^2	0.915
		Adjusted R2	0.64

1. ***Mapping Spatial distribution of carbon sequestration, Co_2 absorption, and Oxygen Production***

GWR model determines intercept value and the coefficient for each sampled tree. Then using the relation of $y_i = 0 + 1x$ ΔExGR, the spatial distribution of annual carbon sequestration was estimated and mapped (Fig. 3).

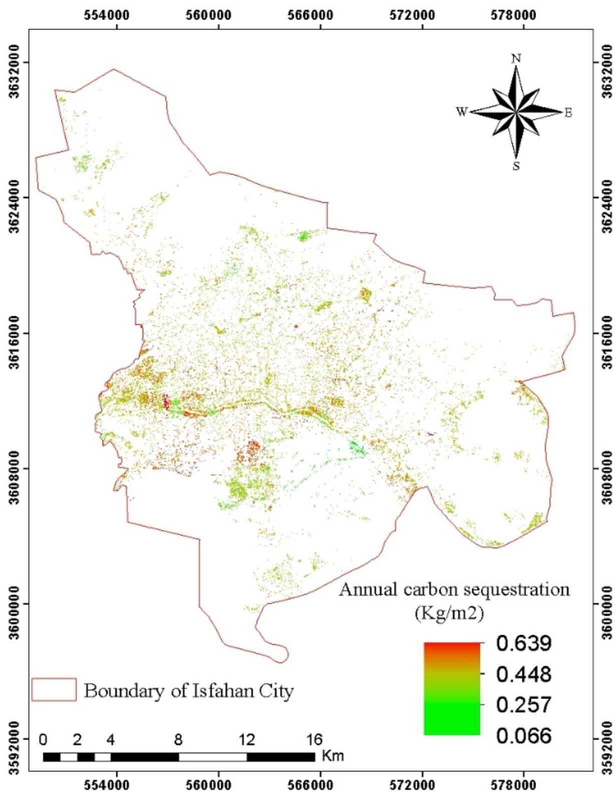

Fig.3. (A) Annual carbon sequestration (Kg/m^2) in Isfahan city based on the GWR model; (B)Zooming in on the picture(A): Annual carbon sequestration (Kg/m^2) in green space around Zayandeh-rood river

To determine the spatial distribution of annual CO_2 absorption, the calculated value for carbon sequestration is multiplied by a coefficient of 3.67(refer to photosynthesis equation). Since based on the photosynthesis equation, for every unit of carbon storage, 3.67 units of carbon dioxide are absorbed by the tree. The maps obtained from the GWR model for CO_2 absorption are shown in Fig 4

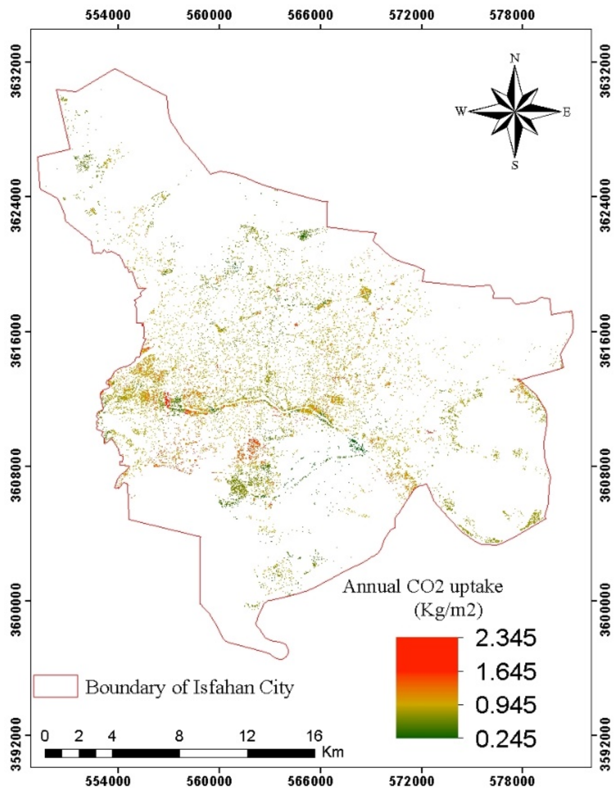

Fig.4. (A) Annual CO_2 absorption (Kg/m^2) based on the GWR model in Isfahan city; (B) Zooming in on the picture (A): Annual CO_2 absorption (Kg/m^2) in Hasht Behesht garden palace in Isfahan.

The spatial distribution map obtained from the GWR model for the annual oxygen production is represented in Figure 5. The results of annual carbon sequestration multiplied by 2.67(based on the photosynthesis equation for every unit of sequestrated carbon, 2.67 units of oxygen is produced).

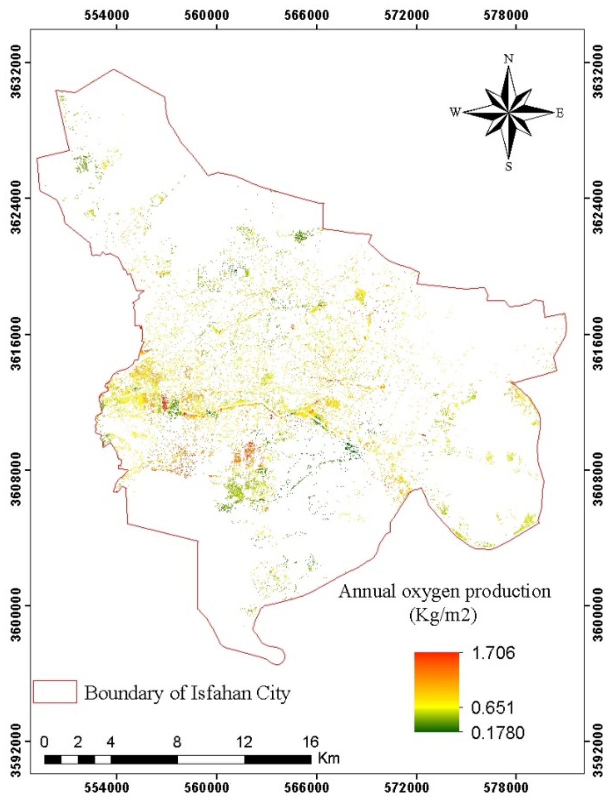

Fig5. Annual oxygen production (Kg/m2) based on the GWR model in Isfahan city

1. ***Estimating the total amount of carbon sequestration, CO_2 absorption, and Oxygen production***

The results obtained from the spatial distribution map showed that the biomass of all trees within the city sequestrated about 7704.22 tons of carbon. This amount of carbon absorbs a total of 28274.502 tons of carbon dioxide Accordingly, 20570.16 tons of oxygen is produced by all trees across the city per year.

1. ***Discussion***

Regarding the calculation of above-ground and below-ground biomass, previous studies used allometric equations using biophysical parameters like DBH, height, and wood density (Aboal et al., 2005, Basuki et al., 2009, Bond-Lamberty et al., 2002, Cai et al., 2013, Djomo et al., 2010, Henry et al., 2010, Joosten et al., 2004, Segura and Kanninen, 2005). Similarly, in this study, to calculate the biomass in an individual unit, we used the allometric equations that were developed by Ponce-Hernandez and colleagues in 2004.

In terms of calculating carbon sequestration, in this study, we used a photosynthesis equation to estimate carbon storage in the biomass. While previous studies used a constant to convert the biomass into carbon storage. In different species, it varies between 44.4 to 55.7 percent. Generally, in most of the studies, an average of 50 percent of the weight of the dried biomass is considered as a constant to convert biomass into carbon storage (Elias and Potvin, 2003, Singh et al., 2011, Zhang et al., 2009, Zhu et al., 2010).

Applying different processes to extract the trees' canopy, we used different spectral variables, included band analysis, vegetation index, and texture analysis. The vegetation indices included the Excess Green Plant Index (ExG), the Excess Red Plant Index (ExR), and the difference between these indices (ΔExGR) (Meyer and Neto, 2008). Amongst all the variables the ΔExGR index showed a significant relationship with carbon sequestration.

Regarding carbon sequestration and CO_2 absorption by green areas in the urban ecosystem, the results of this study are in line with previous studies that emphasized the role of the green area to absorb CO_2 in cities (Dwivedi et al., 2009, Groffman et al., 2006, Nowak et al., 2013, Qing-Biao et al., 2009, Raciti et al., 2014, Tor-ngern and Leksungnoen, 2020, Townsend-Small and Czimczik, 2010, Velasco et al., 2016, Zirkle et al., 2012; Schlesinger and Lichter, 2001).

The green infrastructure of Isfahan city with a high diversity of tree species can provide climate regulation services. Addressing the monetary valuation can highlight the importance of the carbon sequestration service. Simply, previous studies have shown that the cost of separating carbon dioxide (CO_2) from major point sources such as fossil fuel power plants and transporting to a storage site, and ultimately storing in an underground natural reservoir cost about 100 to $ 300 per ton of carbon (Bui et al., 2018, EASAC, 2019, Rubin and De Coninck, 2005). The results showed that the trees in Isfahan store 28274.502 tons of carbon in their biomass per year. If the average cost of carbon sequestration is assumed $ 200 per ton, then the annual value of carbon sequestration by trees will be $ 5654,900.

In addition, the results of the study confirm that the GWR method contributes to high accuracy in modeling a spatially heterogeneous pattern (i.e., carbon sequestration distribution pattern) within the city (in this research R^2 was 0.915). Because the GWR method provides a separate regression equation for each observation rather than calibrating only a single regression equation for the whole statement (Fotheringham et al., 2001). The result of this study is congruent with findings from other studies, arguing that the GWR method possesses a better potential to address the spatial distribution of parameters like primary production, land surface temperature, and fire density (Li et al., 2017, Oliveira et al., 2014, Wong and Lee, 2005).

Moreover, the results of this study indicated that determining the drip line radius (approximate radius of the canopy) plays an important role in matching the ground data of each tree and the spectral data of the satellite image. Because the surface of tree canopies in an urban area usually is not homogeneous and uniform in comparison with the canopies in a forest. Then, using plots in sampling to measure the variables is not recommended. Also, the drip line (approximate radius of the canopy) is calculated based on the trunk diameter for each single tree. So, the drip line can be more appropriate than the plot in establishing a regression relationship between the ground-collected information of every sample tree and image data related to the canopy of each sample tree.

Acknowledging the limitations in this study, in order to calculate the annual carbon sequestration, we used the annual diameter growth rate and the height growth rate which was obtained by previous research (i.e., these parameters are not the same in all trees, so it leads to error in carbon sequestration calculation). In addition, parameters like wood density can be different not only among species but also among trees of the same species (Domec and Gartner, 2002). In this study, we divided the trees into two categories: coniferous and broad leave. Therefore this generalisation with using average densities brings about errors in allometric formulas. Weighing the biomass in the field may solve these kinds of issues and subsequently may contribute to high accuracy. But field measurement is considered a costly method and is just applicable in small areas. Besides, in this study, due to the high cost of worldview image, we just access red, green, and blue bands. We did not have a near-infrared band which may assess the green area better than other bands.

The results of this research can be implemented by urban land-use planners and decision -makers, because there is a growing need to integrate urban ecosystem service concept (i.e., carbon sequestration) into impact assessment, urban planning processes towards sustainability, livability, and resilience (Cortinovis and Geneletti, 2018, Gómez-Baggethun et al., 2013, Haase et al., 2014). In this way, for instance, the distribution map of CO_2 absorption can help the planners to better understand which neighborhood needs to be planted to mitigate CO_2 concentration.

1. ***Conclusion***

Increasing concern with the climate change has led to the research which focusing on the green areas impacts in mitigating CO_2 concentration. However, the potential effect of urban forests on air quality and climate change mitigation remains an object of debate, mainly due to a lack of reliable data. In this research we proposed a modeling to contribute to estimating carbon sequestration and its spatial distribution within Isfahan city. Therefore, we developed a GWR model in which calculated carbon sequestration was the dependent variable, while the vegetation index of ΔExGR was regarded as the independent variable.

In general, it can be concluded that integrating high-resolution data with allometric calculations can make a contribution to analyze carbon sequestration and its spatial distribution efficiently and economically.

As a recommendation for future research, this research can be coupled with a study that analyze carbon emission and addresses its spatial variation within the city. The combination of these two approaches can give an insight, for instance, to recognize which sites need more planting strategy or whether there is a balance between CO_2 emission and carbon sequestration in different places of the city.

Data Availability Statement & Software Citation

The Worldview2 satellite image of the region purchased by Isfahan Municipality from the European Space Agency in 2018(https://earth.esa.int/eogateway/missions/worldview-2). The topographic map of 1/2000 provided by Iran National Cartographic Center in 2017(https://www.ncc.gov.ir/). The ground-based data (sample group of trees with measured biophysical attributes), it has been collected by the Land Assessment & Planning Laboratory of Isfahan University of Technology and the Isfahan green space organization in 2015-2018. Currently all of the data available in the Land Assessment and Planning Laboratory at the Department of Natural Resources, Isfahan University of Technology (IUT) (https://natres.iut.ac.ir/fa/lab/3313). The director of Land Assessment and Planning Laboratory is Dr. Saeed Pourmanafi, that one of the authors of the article.(email: `spourmanafi@cc.iut.ac.ir`: **Phone:** +98 31 3391 3566).

In this research, A Free and Open Source Geographic Information System(QGIS) software has been used for modeling and preparing maps(https://qgis.org/en/site/).

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