Article details

Parsa V.A., Salehi E., Yavari A.R. & Bodegom P.M. van (2019), Evaluating the potential contribution of urban ecosystem service to climate change mitigation, Urban Ecosystems 22(5): 989-1006.
DOI: 10.1007/s11252-019-00870-w

Urban Ecosystems (2019) 22:989–1006
https://doi.org/10.1007/s11252-019-00870-w

Evaluating the potential contribution of urban ecosystem service to climate change mitigation

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Published online: 28 June 2019

Abstract

Promoting urban greenery through tree planting strategies has been considered as a measure to mitigate climate change. While it is essential to understand the temporal dynamics of urban forest structure as well as its services and contribution to human wellbeing in cities, it has hardly ever been examined whether the future contributions of these services after different possible planting strategies can comply with climate change policy goals; these are topics rarely discussed in urban planning and management. In this paper, the ecosystem services currently provided by urban trees (through carbon sequestration and storage), as well as those potentially provided in the future, were quantified using the i-Tree Eco model, and their contribution to climate change mitigation was evaluated. As a case study in Tabriz, Iran, we developed four possible scenarios. Synergy (urban temperature regulation by UF) and trade-off (tree water requirements) were also analyzed. Future carbon sequestration and storage potential of urban trees was compared with the estimated future carbon emissions. The current contribution in Tabriz is relatively modest (about 0.2%), but it can be tripled through long-term tree planting strategies. Additionally, the temporal cooling effects and tree water requirements increase as climate change mitigation improves through tree planting. We conclude that urban tree planting has a small impact on carbon mitigation in the study area, most likely because of the young age of trees in Tabriz as well as the fact that the planted trees cannot deliver all their benefits over a 20-years period and need more time. Thus, the use of urban trees serves only as a complementary solution rather than an alternative climate mitigation strategy. Our quantitative approach helps urban environmental policymakers to evaluate how much they can rely on urban forest strategies to achieve climate change mitigation targets.

Keywords Carbon storage and sequestration · Greenhouse gas emissions · Urban forest · I-tree eco · Trade-off · Synergy

Introduction

The global climate is changing rapidly and is predicted to change at an even faster rate in the future (Brandt et al. 2016). Global warming is one of the most significant environmental issues (Crowley 2000; Smith et al. 2007; Liu and Li 2012). The mean surface air temperature has increased by 0.5 °C in the twentieth century and will rise by 1.5 to 4.5 °C by the end of the next century (Romm 2013), which poses a critical threat to the environmental system (McLaughlin 2011). The increase in air temperature is mainly caused by the increasing emissions of greenhouse gases (GHG) (Crank and Jacoby 2015; Shirani-bidabadi et al. 2019). CO_2 is the most significant human-induced contributor to GHG (Olivier et al. 2005). It has played a significant role in capturing and absorbing outward radiation from the earth and is responsible for about half of the greenhouse effect (Rodhe 1990).

Urban areas can be considered both as a hotspot for GHG emissions and a carbon sink (Churkina et al. 2010; Strohbach et al. 2012; Schröder et al. 2013; Stigter et al. 2016). Therefore, cities should be taken into account in global climate change mitigation and adaptation efforts (Romero Lankao 2011; Bulkeley 2013; Haase et al. 2014; Masson et al. 2014; Raciti et al. 2014; Stigter et al. 2016).

Urban trees and shrubs (UF) provide significant climate regulation services through carbon sequestration and storage (Nowak 2000a; Nowak and Crane 2002; Mcpherson et al. 2005; Strohbach and Haase 2012; Andersson et al. 2014; Raciti et al. 2014; Brandt et al. 2016) Given the ability of

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UF to capture and store atmospheric carbon, it can be considered as a useful tool in mitigation of climate change in *micro* (i.e. effect on microclimate of surrounding buildings by shading and reducing energy demand and consequently reducing carbon emissions), *meso* (i.e. at city level, UF can influence solar radiation, humidity and other characteristics of local climate (Gill et al. 2007; Nowak and Dwyer 2007)), and even *macro* (i.e. at the global level, UF can play a role as carbon sink) scale (Jo and McPherson 2001; Escobedo et al. 2010; Chen 2015). The contribution of UF to nationwide carbon storage can also be considerable, especially in countries with low forest cover (Davies et al. 2011; Tanhuanpää et al. 2017).

Urban policymakers mainly focus on technical measures (e.g. energy efficiency) to meet the climate change mitigation targets, whereas various studies have suggested the improvement of UF cover through tree planting actions as a cost-effective strategy beside other – technical – solutions to mitigate the impacts of climate change in cities (Byrne and Jinjun 2009; Bulkeley and Betsill 2013; Elmqvist et al. 2013; Baró et al. 2014; Brandt et al. 2016; Velasco et al. 2016). Valuable potential contribution of urban green infrastructures in achieving these targets is mostly neglected in urban policymaking and planning processes (Escobedo et al. 2010; Baró et al. 2014). More insights in and awareness of the potential of UF and, consequently, the optimization of its future contribution to the achievement of GHG emissions targets can help illustrate the importance of UF for the policymakers. Information on future trends is, however, hardly available.

In order to understand the net long term dynamics of carbon sinks and sources as affected by UF, a detailed knowledge of the UF structure and composition is needed, which again varies over time due to natural and anthropogenic drivers (e.g., trees' growth, death and also management actions) (Nowak et al. 2002a, 2013; Stoffberg et al. 2010; Parsa et al. 2019). An appropriate urban tree planting and management scheme can help optimize the carbon sink function in order to achieve environmental policy targets (e.g., GHG emission reduction targets), particularly when compared with future GHG emissions levels at city scale. Such scenario analyses can help urban policymakers to determine the most appropriate UF strategy for future climate change mitigation at city scale and attract their attention to these vital ecosystem services besides the technical ones.

Additionally, it should be noted that urban tree planting provides a wide range of urban ecosystem services (UES), which are characterized by complicated linkages and interrelations. In other words, improving an important UES (e.g. climate change mitigation in this study) by greening may affect other UES both positively (synergies, e.g. urban temperature regulation) or negatively (trade-offs, e.g. tree water use) (Baró et al. 2015; Grunewald and Bastian 2015). An Analysis of urban tree ecosystem services (ES) and associated costs may provide insights for urban green infrastructure decisionmakers to balance benefits and values and the resource use trade-offs in different tree planting scenarios (Carreiro et al. 2007; Darrel et al. 2011). Greening arid and semi-arid cities – known as water-limited areas – through tree planting provides various UES such as carbon sequestration and storage which comes at the expense of significantly increased water use (McHale et al. 2017; Smith et al. 2017; Zhang et al. 2017). This spatial trade-off (benefits here – costs there) between climate change mitigation UES and water use may restrict the potential of UF to provide services (Darrel et al. 2011; Grunewald and Bastian 2015). With this background in mind, synergies (urban temperature regulation by UF) and the critical tree-water trade-off (the total water required for sustaining current and projected future trees to supply climate change mitigation services) will be assessed.

In Iran, no assessment of carbon storage and sequestration by UF is available and previous research is mostly limited to natural bodies, small areas (e.g. parks), and a few tree species, while it is mainly by laboratory methods (Varamesh et al. 2011; Naghipour et al. 2014; Ostadhashemi et al. 2014; Alizadeh and Verdian 2015; Goodarzi et al. 2016). As a consequence, there is a poor understanding of the contribution of UF to the mitigation of climate change in Iranian cities, and, therefore, the UF measures have not been integrated into climate change mitigation scenarios and targets.

Therefore, this paper focuses on the assessment of the current and, particularly, future potential of urban trees in contributing to the compliance of CO_2 mitigation targets using Tabriz, Iran, as a case study. The objectives are to; 1) quantify carbon sequestration and storage in the current urban forest, 2) elaborate scenarios on urban trees and predict possible future potential of trees in carbon storage and sequestration; 3) predict future GHG emission at city scale, 4) evaluate current and future potential of global climate regulation provided by urban trees to achieve environmental policy targets and 5) analyze synergies and trade-off generated by improved climate change regulation through tree planting programs.

Material and methods

Case study

Iran is one of the main global contributors to CO_2 emissions (EDGAR 2017), and a considerable amount of this emission is associated with urban activities (Olivier et al. 2017). Unfortunately, Iran scored low or very low across almost all categories within Climate Change Performance Index (which measured the success of the Paris Agreement through the implementation of mitigation targets on a national level) (Burck et al. 2018). Iran intends to mitigate its GHG emission by 4% by 2030 (INDC 2015). Establishment of new urban tree planting could complement other technical mitigation and adaptation strategies in reaching this aim (Gómez-Baggethun et al. 2013; Baró et al. 2014).

This paper focused on Tabriz, the capital of East Azerbaijan province, which has a population of 1.56 million people living on 24,479 ha (Statistical Center of Iran 2016). Tabriz is the largest and most populated and industrialized metropolitan area in the northwest and west of Iran (it is known as the commercial and industrial hub of NW Iran). Its climate is commonly classified as semiarid. The city is located at an altitude of 1351 m, and the mean annual precipitation reaches 311.1 mm with an annual mean air temperature of 12 °C. The study area has some large parks, especially outside the city center (e.g. Elgoli), and several small parks. Rapid urbanization and population growth (particularly due to an external population influx) have accelerated the environmental transformations which have led to land use changes and deterioration of the environmental quality (Gorbani et al. 2012; Esmailnejad et al. 2015). Figure 1 shows the location and land use map of Tabriz. The original land use map for 2017 was obtained from the municipality of Tabriz and was reclassified to 7 classes.

Methodology

Data collection

Among the computer-based tools developed to estimate carbon storage and sequestration by urban trees, i-Tree Eco can be considered to be one of the most precise. The i-Tree Eco model has to be adapted for the users outside the U.S and demands the integration and submission to the i-Tree Database of additional data including location information, hourly precipitation, and pollution data for a complete year (i-Tree Eco International Projects 2016).

The trees and shrubs data required by the i-Tree Eco for this research were collected from 330 plots through a field survey conducted from 5th of June to 2nd of October 2017 following i-Tree Eco protocols (i-Tree Eco International Projects 2016; i-Tree Eco User's Manual 2016; i-Tree Field Guide 2016). Pre-stratification helped put more plots in those areas of interest. To obtain the value of interest for each land use class, fifteen academic staff members of the

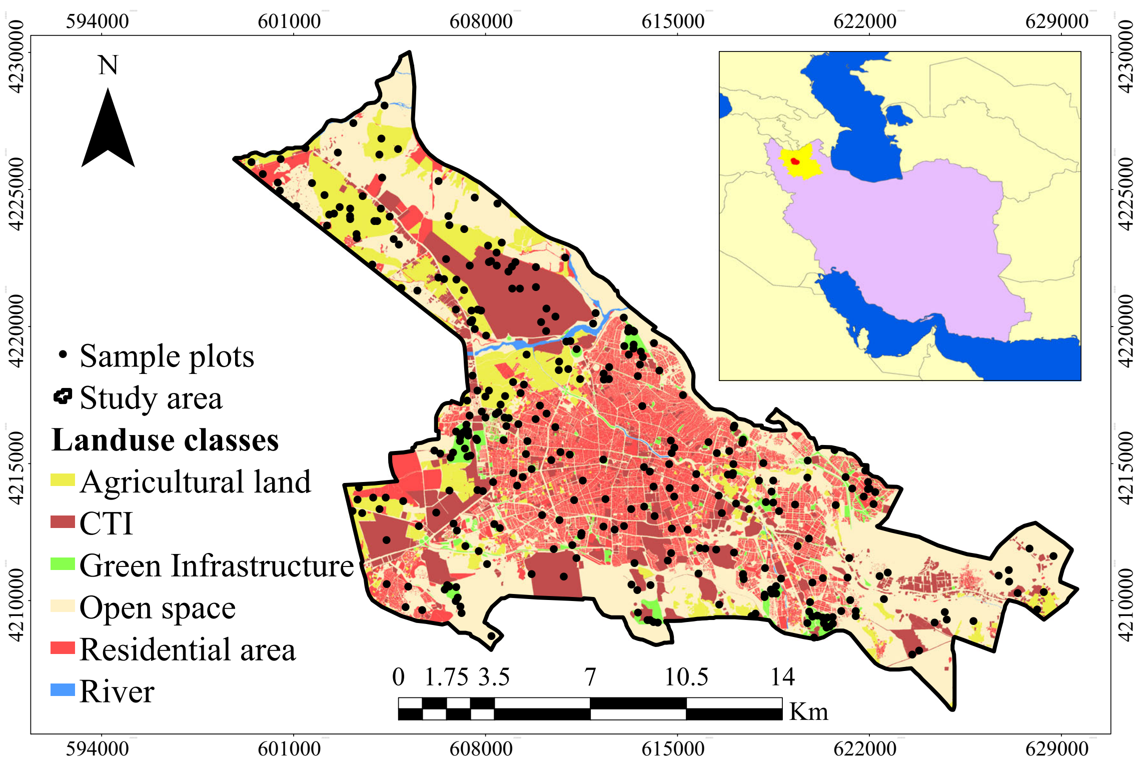


Fig. 1 Location and land use map of the study area and sample plots within the municipality of Tabriz

University of Tabriz, Iran, were asked to weigh each class according to their interest and knowledge about the number of trees in each class (this approach was designed because there was no accurately reliable map or information about the number of trees and their cover in Tabriz prior to this study). The values of interest in combination with the area percentage of each class were used to determine the number of plots for each land use class (Table 1). The Random Points Generator of Arc GIS 10.4.1 was used to randomly distribute 330 circular plots (with a radius of 11.34 m; 0.1 acre) among seven land use classes (Table 1 and Fig. 1). The GPS device and Google Earth were used to precisely locate the plot centers and determine the perimeter.

The field survey gathered three types of data: 1) general information (the date, GPS coordinates of the plot center, tree and shrub cover, the percentage of the plot (%) which could be assessed, actual land use, ground cover, plantable space, reference objects), 2) main data on shrubs (species, average height, percentage of shrub cover, the percentage of shrub volume not occupied by leaves) and 3) main data on trees (species, status, distance and direction to the plot center, land use(s), Diameter at Breast Height (DBH), data on crown (health, width and missing, i.e. the proportion of crown volume not occupied by leaves or branches), Crown Light Exposure (CLE), total and live crown height, crown base height and GPS coordinates). Field data on urban trees (only 5 out of the 330 sample plots were not surveyed because access to them was denied, mainly due to security issues of the military lots). This data was used by i-Tree Eco model to determine the urban forest structure (tree composition and structure). A comprehensive analysis of all the structural characteristics of urban trees is beyond the scope of this paper, but the most relevant ones are explained.

Current carbon storage and annual carbon sequestration

Carbon storage is defined as the stock of tree carbon (t or kg), while its change over time is called carbon sequestration (t or kg year^{-1}) (Nowak and Crane 2002). Urban tree carbon storage was quantified using allometric equations (Henry et al. 2011; Breu et al. 2012).

Measuring above-ground biomass of an urban tree is difficult (Dobbs et al. 2011) but can be estimated based on DBH, tree height and tree condition (Nowak 2019). Predicted above-ground biomass was converted to whole tree biomass based on an assumed root-to-shoot ratio of 0.26 (Cairns et al. 1997). The computed fresh-weight biomass was multiplied by species-specific conversion factors (derived from mean moisture contents of species obtained from literature; 0.48 and 0.56 for conifers and hardwoods respectively) in order to obtain dry-weight biomass and, hence, carbon storage. As open-grown and maintained trees may have less above-ground biomass, adjusted biomass is reached by applying 0.8 factor. Also as the deciduous trees lost their leaves annually, the total stored carbon is estimated by multiplying total tree dry weight biomass by 0.5 (Nowak 2000b; Nowak and Crane 2002). The increase in the biomass determines carbon sequestration. The gross amount of carbon sequestered annually was estimated by adding the average diameter growth (determined by available biomass, length of the growing season) from the appropriate genus, diameter class and the tree condition (including CLE) to the current tree diameter (year x) in order to estimate the tree diameter and carbon storage in year x + 1 (Nowak 2000b; Nowak and Crane 2002). For more details on the assumptions in the i-Tree Eco model to estimate urban trees' carbon storage and sequestration, see (Nowak and Crane 2002).

Plausible future carbon storage and sequestration

As the amount of stored carbon in trees depends on the biomass of the trees and the net long-term dynamics of urban trees, the carbon sinks vary over time due to the growth of trees (Nowak et al. 2002a, 2013) and the policies and strategies for increasing the number of trees (Gómez-Baggethun et al. 2013). Therefore, one of the attractive alternatives for climate change mitigation in Iranian cities can be tree-planting

Table 1 Number of plots for each land use class.

Stratum	Area		Number of plots
	Ha	%	
Agricultural land	3026.9	12.37	57
CTI; Commercial, transportation and institutional	4325.55	17.67	51
Green Infrastructure	760.71	3.11	100
Open space	11,119	45.42	63
Residential area	5080.01	20.75	59
River	167.24	0.68	0
Total	24479.4	100	330

programs. To analyze possible planting programs and their potential role in the carbon cycle, a scenario analysis was performed. Four scenarios were developed from the most pessimistic to the most optimistic (the scenario *I*; No tree planting, scenario *II*; Maintaining current tree number, scenario *III*; Implementation of the Tabriz municipal tree planting programs and scenario *IV*; Aiming for 40% urban tree canopy cover). For each scenario, carbon sequestration by trees over the next 20 years was predicted using the Forecast module in the i-Tree Eco model.

The Forecast module provides the tool for projecting the future conditions of UF with various tree covers, compositions, and structures (e.g. tree population density, canopy cover, LAI, DBH, and biomass distribution) and benefits (e.g. carbon storage) based on the current urban forest structure as well as the user-defined options. The user defines the basic options (number of years to forecast, base annual mortality rates, and frost-free period) and trees to plant (applies to stratum, set DBH of new trees, and trees to plant annually) (i-Tree Forecast Model 2016; Nowak 2019). The main components of this module are: 1) *tree mortality*; annual mortality rates based on canopy dieback and user-defined rates based on tree size classes and DBH. The annual mortality rates for healthy trees with 0–49% dieback, sick trees with 50–74%, and dying trees with 75–99% dieback were set at 3, 13.1 and 50%, 2) *tree establishment;* based on the user-defined number of trees planted annually, and 3) *tree growth;* annual DBH growth for the study area estimated as a function of (Nowak 2019):

Length of the growing season

Base growth rate based on length of the growing season was determined by standardizing growth measurement for urban street, park, and forest trees to growth rates for 153 frost-free days (i-Tree Forecast Model 2016; Nowak 2019). To determine the mean difference between standardized growth rates of street, park and forest trees, the growth rates of trees of the same species or genera were also compared. Park and forest growths were 1.78 and 2.26 times less than street tree growth, respectively (Nowak 2019).

Species growth rates

Average standardized growth rates of open-grown trees were set at 0.66, 0.99 and 1.32 and cm $yr.^{-1}$ for slow, moderate and fast growing species class, respectively (Nowak 2019).

Tree competition

Tree competition was represented by using CLE measurements (Table 2). However, the CLE factors were adjusted proportionally to the amount of available green space as the tree canopy cover decreases or increases (Nowak 2019).

Tree condition

Base growth rates are also adjusted with regard to tree condition (based on the percentage of crown dieback) (Table 3).

Tree height

The species growth rates decline as the trees reach the maximum height, so the species growth rates as mentioned above were adjusted according to the ratio between the current height and the average height at maturity. The species height at maturity was estimated based on literature searches. As the height exceeds 80% of the average mature height, the yearly diameter growth proportionally decreases from full growth rate at 80% of height to 50% rate at mature height. Next, this rate (50%) was maintained until the tree is 125% of the maximum height, when the growth rate is then decreased to 0. Then the tree height, LA, and crown width and height were estimated relying on diameter for each year. These parameters were calculated through derived species, genus, order, and family specific equations from measurements from urban tree data. Total canopy cover was estimated by summing the two-dimensional crown area of the individual tree in the population (Nowak 2019).

Moreover, in simulating the annual addition of new trees to the model, the species composition and CLE of new trees were assumed to be proportional to the current species composition. Therefore, the future dominant species will be proportional to the current condition (Nowak 2019).

Then Forecast module projects urban forest population and carbon sequestration and storage (carbon storage is based on the carbon equations and processes from i-Tree Eco) (i-Tree Forecast Model 2016; Nowak 2019).

Current and future contribution of urban trees to climate regulation

The contribution of urban trees to climate change mitigation in Tabriz for 2015 was determined based on the estimated GHG emissions. As there is no GHG emission data specifically for Tabriz, the total GHG emission for the country (Iran; Gt CO_2 eq) was adopted from the PBL Netherlands Environmental Assessment Agency report on trends in global CO_2 and total greenhouse gas emissions (Olivier et al. 2017) and then extracted for Tabriz based on the population ratio. To assess the future contribution, a regression model was used to estimate the projected GHG emissions over the next 20 years based on observed trends on emissions and the population growth rate. The annual GHG emission was compared with the carbon sequestration by urban trees to identify their contribution to climate change mitigation in Tabriz.

Table 2 Base growth due to CLE

CLE	Conditions	Base growth
0–1	Forest	SG* / 2.26
2–3	Park	SG / 1.78
4–5	Open-Grown	SG

* Standardized growth

Analyzing synergies and trade-offs

Cooling effect

To address potential synergies resulting from the improvement of climate change regulation service by the increased tree cover, the provided urban temperature regulation ES was estimated for both the current situation and for the future prospects through elaborated tree planting scenarios. Tree cooling effect is provided by the tree shading effect as well as by evapotranspiration (Bowler et al. 2010). This UES was estimated using a tree shade area (canopy cover) as a proxy indicator, with the assumption that the temperature reduction (cooling effect) occurred mainly under the tree canopy (Bowler et al. 2010; Baró et al. 2015). The tree cover area was estimated using i-Tree composition and structure tool for the current condition and the Forecast module for each scenario.

Tree-water trade-offs

The total amount of irrigation water need of a tree species was estimated using a method localized for Iran and proposed by (Alizadeh 2009), which integrated the FAO for the drip irrigation system and the WUCOILSIII methods. The total amount of water lost by a single tree species (*i*) over a specific timespan through the evapotranspiration process (as an estimation of the amount of water required to be compensated by irrigation) was calculated as follows (Alizadeh 2009; Azari et al. 2018):

$$ET_{c,i} = ET_0 \times K_{s,i} \quad (1)$$

Where $ET_{c,\ i}$ is the evapotranspiration of tree species (*i*) ($^{mm}/_{day}$), ET_0 is the reference evapotranspiration ($^{mm}/_{day}$)

Table 3 adjustment factors for base growth rates due to tree conditions

Dieback (%)	Conditions	Adjustment factors
< 25	Excellent	1
26–50	Poor	0.76
51–75	critical	0.42
76–99	Dying	0.15
100	Dead	0

and $K_{s,\ i}$ is the coefficient of the tree species (*i*). ET_0 was calculated using CROWAT 8.0 software which adopted the FAO Penman-Monteith approach (Clarke et al. 2001). Historical monthly average meteorological data for a period of 30 years (1987–2017), including minimum and maximum temperature (°C), relative humidity (%), wind speed ($^{km}/_{year}$), sunshine – representing the duration of the daylight without clouds ($^{hours/day}$) – were introduced in CROWAT 8.0 model and then the ET_0 was calculated. K_s for each species was adopted from (Costello et al. 2000). The water need of each species (Td_i) was calculated as follows (Azari et al. 2018):

$$Td_i = [ps + 0.15(1-ps)] \times ET_{c,i} \quad (2)$$

Where Td_i is the daily water need of species (*i*) ($^{mm}/_{day}$) and *ps* is the maximum shading percentage. Also, the maximum irrigation period (*day*) was adopted from (Alizadeh 2009; Azari et al. 2018) and was calculated based on the maximum irrigation depth (*mm*), and *Td*. Net water need (In_i) for species (*i*) was estimated as follows (Alizadeh 2009; Azari et al. 2018):

$$In_i = Td_i - EF \times F \quad (3)$$

Where EF is the effective rainfall ($^{mm}/_{day}$) and is calculated based on a 30-year historical monthly average rainfall data ($^{mm}/_{month}$), using CROWAT 8.0 which applied the fixed percentage method (Clarke et al. 2001). F is the scheduled irrigation period (day) and is adopted from (Alizadeh 2009) for each month throughout the year. The gross water need (Ig) for each species is estimated as follows (Alizadeh 2009; Azari et al. 2018):

$$Ig_i = {}^{In_i}/_{Ea} \quad (4)$$

Where *Ea* is the irrigation efficiency (%) (the value adopted from (Alizadeh 2009)). Finally, the volume of water need ($^{V:litre}/_{day}$) was estimated based on Ig_i, *Sp* (the distance between the rows; the standard value is 3 m) and *Sr* (the distance between trees in a row; the standard value is 3 m) (Alizadeh 2009; Azari et al. 2018):

$$V_i = Ig_i \times Sp \times Sr \quad (5)$$

Where V_i is the volume of water need for a single tree, so the total volume of water need for all trees of the same species ($V_{total,\ i}$: *litre/year*) was estimated as:

$$V_{total,i} = V_i \times n_i \times t \quad (6)$$

Where n_i is the number of specified tree species, and *t* is the timespan the irrigation is applied (*day*). The i-Tree Eco composition and structure tool was used to estimate the n_i values for the current condition and for each scenario using the Forecast module. The overall volume of water need for all trees ($V_{overall}$: *litre/year*) was estimated as the sum of $V_{total,\ i}$ for all species:

$$V_{overall} = \sum V_{total,i} \quad (7)$$

Results

Structural characteristics of the urban trees

A total of 48 species were identified within 325 inventoried plots. Most of the species were exotic (80%), and the dominant tree species include *Robinia pseudoacacia* (12.5%), *Fraxinus excelsior* (9.8%), and *Elaeagnus angustifolia* (8%). Tabriz had 1.928 million trees with an overall tree density of 79 trees per hectare (trees ha^{-1}), with the highest occurrence in green spaces (455 (trees ha^{-1})) followed by the residential area (100 (trees ha^{-1})) and open spaces (63 (trees ha^{-1})). The total leaf biomass was 5767.5 tons, which is one of the most influential indicators of the carbon sequestration and storage assessment (Moser et al. 2015). Also, a considerable number of the trees were recently planted, and about 80% of them had DBH smaller than 15.2 cm. About 95% (±0.9) of the trees were in excellent conditions, and only 2.4% (±0.6) were dead (Fig. 2).

Ecosystem Service of Climate Regulation

Existing urban trees in Tabriz were estimated to have stored 2.238 tha^{-1} (54,420 t) of carbon over the year 2015. A comparison between the amount of stored carbon among the land use classes shows that the green spaces had the highest amount, followed by residential areas. As with the carbon storage, the majority of carbon was sequestered by these two land use classes at a total of 2102 kg CO_2eq per hectare over 2015 (71% of the total amount) (Table 4). This pattern is likely to be associated with the tree coverage and leaf area in each class (Fig. 3)

The amount of carbon stored and sequestrated varies among the species. Robinia pseudoacacia is the most important species in carbon storage and sequestration in Tabriz by virtue of its relative abundance and size. The top 10 tree species contributing to carbon storage and annual net carbon sequestration (Table 5) were responsible for 75 and 49.4% of total carbon storage and annual net carbon sequestration, while they respectively constitute 64.7, 73.3, 75.4 and 75% of the total number of trees, leaf area, leaf biomass and tree dry weight biomass (Fig. 4). These results may help to provide better recommendations for landscape designers and urban managers to select appropriate tree species to mitigate climate change.

Future potential of urban trees in carbon sequestration and storage

The projected structural characteristics in the 20th years of each scenario was summarized in Fig. 5. Also, the future pattern of some characteristics of UF by the end of the simulated year was showed in Fig. 6. The future potential of urban trees to sequester and store urban carbon for the four scenarios is projected using the Forecast module in the i-Tree Eco model. In the scenario *I* (no tree planting), Tabriz will lose 629,350 trees, store 564,568 t C and sequester about 48,196 t Cyr^{-1} at the end of the 20th year. Planting 40,000 trees per year maintain the current urban tree number, stores 539,840 t C and sequesters 43,812 t Cyr^{-1} in the last projected year (Scenario *II*). 638,813 t of carbon will be stored in urban trees over the next 20 years if the municipality of Tabriz implements its tree planting program (Scenario *III*). The 40% urban tree canopy goal for Tabriz can be achieved at the end of the simulated timespan by planting 150,000 trees per year, which yields a final amount of 675,964 t C stored and 65,054 t $yr.^{-1}$ sequestered carbon (Scenario IV). The estimated total net carbon sequestration shows an increase in all scenarios, even in the scenario *I* (Fig. 7). This may be since the majority of trees in

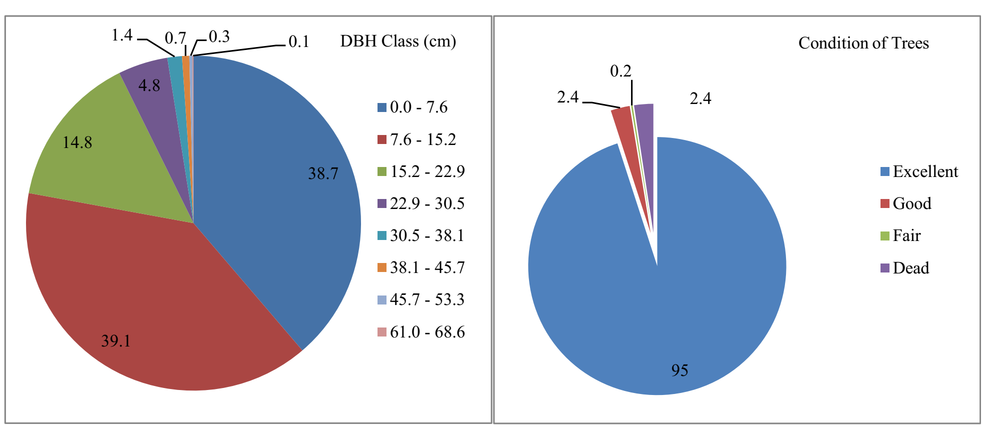


Fig. 2 DBH and condition class distribution of the studied population

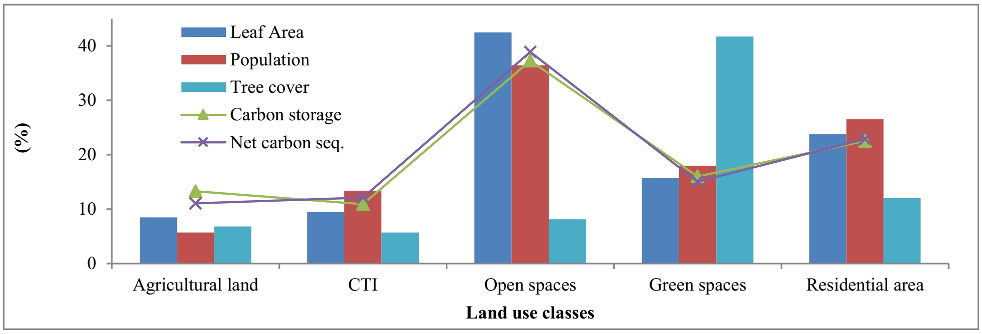


Fig. 3 Comparing the characteristics of the urban trees and the carbon storage and sequestration among the strata (all value in percentage)

Tabriz were in the early stage. Such young urban trees, however, require more careful maintenance (Liu and Li 2012).

The contribution of current and future urban trees to climate change mitigation

The relative contribution of urban trees to climate change mitigation in Tabriz for the year 2015 (considered as the current situation) was determined based on data and projections of GHG emissions (Fig. 8). The estimation suggests that the total GHG emission will increase by about $3.73 * 10^7$ (t year^1).

The results show that the contribution of urban trees to climate change mitigation is meager and accounts for about 0.2% of the overall GHG emissions. The maximum contribution in 2035 will be yielded through scenario *IV*, equalling 0.623%. The dynamic annual contribution of urban trees to climate change mitigation is shown in Fig. 9.

Analyzing synergies and trade-offs

Cooling effect

An assessment of the tree cover percentages as proxy indicators for urban temperature regulation from the current conditions to the next 20 years in each scenario showed incremental trends (Fig. 10) similar to those of carbon sequestration (Fig. 7). This means there is a positive relationship (synergy) between the improvement of the climate change mitigation ES and the provision of urban temperature regulation.

Tree-water trade-offs

The results show that the average total water need for a tree was about 9 m^3 per year. It was estimated that about 17.2 million m^3/year of water was required to maintain the current number of urban trees in order to sustain the provision of climate change regulation ES. If no tree is planted for the next 20 years (Scenario *I*), the overall water requirement decreases by 11.5 million m^3/year in the 20th year. Through scenarios *III* and *IV*, which aim at increasing tree cover by planting tree annually, the overall water needs increase respectively to 26.3 and 33.7 million m^3/year at the end of the 20th year (Fig. 11). The results indicate that as the climate change mitigation ES improves by tree planting, the amount of water use also increases (tree-water trade-offs).

Discussion

In order to correctly understand and manage the potential of urban trees for urban climate change mitigation, it is necessary to have verifiable and accurate estimations of the current

Table 4 Carbon storage and annual net carbon sequestration delivered by the trees for each land use class

Strata	Carbon storage					Annual net carbon sequestration			
	By class			Per unit area		By class		Per unit area	
	(t)	(%)	CO_2eq (t)	(kg ha^{-1})	CO_2eq (kg ha^{-1})	(tyr^{-1})	CO_2eq (tyr^{-1})	Density (kg $yr.^{-1}$ ha^{-1})	CO_2eq (kg $yr.^{-1}$ ha^{-1})
Agricultural land	7250	13.3	26586	2395.2	8783.2	982.9	3604.3	324.7	1190.8
CTI	5907	10.9	21661.7	1365.7	5007.9	1075.7	3944.7	248.7	912.0
Open spaces	20,307	37.3	74466.7	1826.4	6697.2	3450.9	12654.4	310.4	1138.1
Green spaces	8707	16	31927.2	11445.3	41970.1	1335.0	4895.5	1755.0	6435.4
Residential area	12,248	22.5	44914.8	2411.1	8841.5	2033.0	7455.0	400.2	1467.5
Total	54,420	100	199556.4	2238.4	8208.1	8877.6	32554.0	365.2	1339.0

Table 5 Tree structure summary and carbon storage and sequestration by the top 10 species

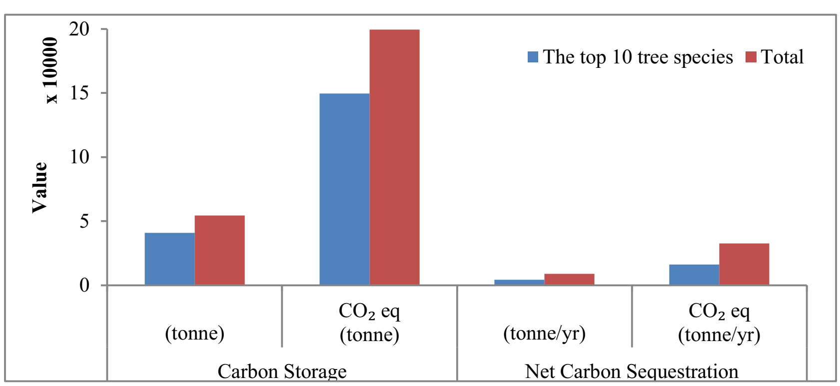
Species	Carbon storage		Net carbon sequestration		Structure summary by species			
	(t)	Co2eq (t)	(ty^{-1})	Co2eq (ty^{-1})	Tree Number	Leaf Area (ha)	Leaf Biomass (t)	Dry Weight Biomass (t)
Robinia pseudoacacia	7947	29142	248	909	240590	1100	592	15894
Fraxinus excelsior	5654	20734	849	3114	188821	742	789	11309
Morus alba	5307	19461	633	2321	63579	409	299	10614
Populus alba	4339	15911	141	517	49695	628	546	8678
Ulmus carpinifolia Hollandica	3249	11915	394	1445	128342	354	241	6499
Ulmus minor	3136	11499	121	444	51038	487	332	6272
Elaeagnus angustifolia	3054	11197	713	2615	153675	635	476	6107
Cupressus arizonica	2418	8867	293	1075	130009	730	1143	4836
Acer negundo	2282	8367	296	1085	39574	295	270	4563
Ailanthus altissima	1749	6413	416	1526	107713	269	201	3498
Pinus nigra	1681	6165	283	1036	94402	491	473	3363
Total	40816	149673	4386	16085	1247438	6140	5362	81632

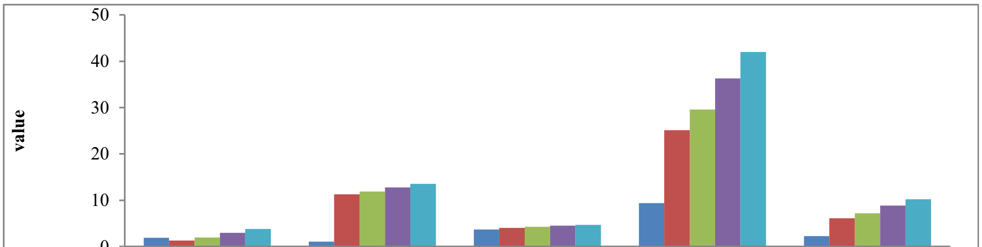
carbon sequestration and storage delivered by trees (Liu and Li 2012; McPherson et al. 2013; Pasher et al. 2014) and the future potential of this ES (Stoffberg et al. 2010), as well as an analysis of synergies and trade-offs. Urban trees are one of the several potential solutions –a complementary and temporary solution rather than an alternative one – to mitigate the problem of climate change.

Future urban trees carbon accounting has not received much attention so far. This paper attempted to quantify the existing and particularly the potential future contributions of urban trees to climate change mitigation at city scale. Our findings on the contribution of the urban trees of Tabriz to climate change mitigation show a very modest contribution compared with other cities (Pataki et al. 2009; Liu and Li 2012; Baró et al. 2014). The reasons can be attributed to the low level of urban trees and green spaces, the local biophysical conditions, the young age of trees (discussed below) and the relatively high emissions in Tabriz. Concerning the biophysical conditions, Byrne and Jinjun (2009) showed that the site contamination and the vegetation characteristics are among the critical biophysical factors which constrain the ability and utility of urban trees to combat climate change. They also indicated that the urban morphology, along with other factors, determines the scope and scale of ES provided by UF. Therefore, the morphology of the case study – in this case, a bowl-shaped valley surrounded by mountains which act as the trap for pollutants (Gorbani et al. 2012; Esmailnejad et al. 2015) – can be one of the reasons for the low contribution.

As the urban tree's carbon storage and sequestration are a function of the total amount of urban tree cover (Nowak et al. 2013), this ecosystem service can be improved by urban tree planting. Among the four different scenarios, scenario *IV* sequesters and stores more carbon compared with other scenarios especially with the realistic one (*III*). Comparing the future amount of carbon sequestration by urban forests with the predicted GHG emission at city scale showed that the maximum contribution of urban trees to climate change mitigation at the end of the next 20 years will be 0.623% (in scenario *IV*) which is three times more than the current conditions, but is still very

Fig. 4 Share of the top ten species in total carbon sequestration and storage





	Number of Trees (million)	Total Tree Biomass (100 thousands tons)	LAI	Tree Cover (%)	Total Tree Cover (thousands ha)
Current	1.928	1.09	3.68	9.4	2.27
I	1.299	11.29	4.04	25.1	6.10
II	1.958	11.89	4.28	29.6	7.19
III	2.948	12.78	4.53	36.3	8.84
IV	3.773	13.52	4.68	42	10.21

Fig. 5 Comparison between the current structural conditions and the values in the 20th year in each scenario

low. The present study also shows that while carbon sequestration potential is small compared with the emissions, the current amount of carbon stored by these trees is large. Hence, it is essential at least to maintain the current UF. Losing the existing trees without any replacement may act as a net carbon source to the atmosphere. This indicates that future urban tree planting will have to maintain the current carbon storage. Locating individual trees more properly and selecting appropriate tree species may allow the UF to become a more significant sink for carbon (Lal and Augustin 2012; Liu and Li 2012). It can also improve the biodiversity of the UF and consequently increase the resilience and resistance of trees to adverse shocks (e.g. diseases), thus improving other environmental benefits delivered by urban trees (e.g. air purification) (Pataki et al. 2011b). More research is needed to determine which urban tree species and traits create the most substantial benefit for carbon sequestration and other ecosystem services.

The most important factor in the capacity of individual urban trees to sequester and store carbon might be the tree species and the DBH distribution (Nowak 1993). Large trees generally provide benefits 44% more than small trees (Armour et al. 2012) and small trees store 1000 times less carbon than large trees (Nowak 1994). In other words, the greatest quality and quantity of ES are given by large, healthy trees (McPherson and Peper 2012; Silvera Seamans 2013; Moser et al. 2015). Our results showed that 77.9% of the current trees are not large enough to provide substantial carbon sequestration. The proposed planted trees are also young, and the twenty-year timespan is simply too short for the trees to become large enough, and urban tree lifespan is a key attribute in maximizing the carbon sequestration (Matthews et al. 2015). This means even investing substantially in future tree planting does not provide a reliable contribution to climate change over the next twenty-year period. Therefore, it is possible to reap the maximum benefit of tree planting for climate change mitigation through carbon sequestration only after a very long period. Such long-term benefits may be difficult to attain, given the fact that the shorter term benefits are minor and meanwhile those young urban trees need careful management and maintenance and thus come with costs.

It should also be noted that the long-time dynamics of net carbon source and sink of urban forest change throughout the lifespan of a tree (growth, death, and decay) (Nowak and Crane 2002; Nowak et al. 2002b, 2013). During the growth period, the net annual carbon sequestration is positive, but the

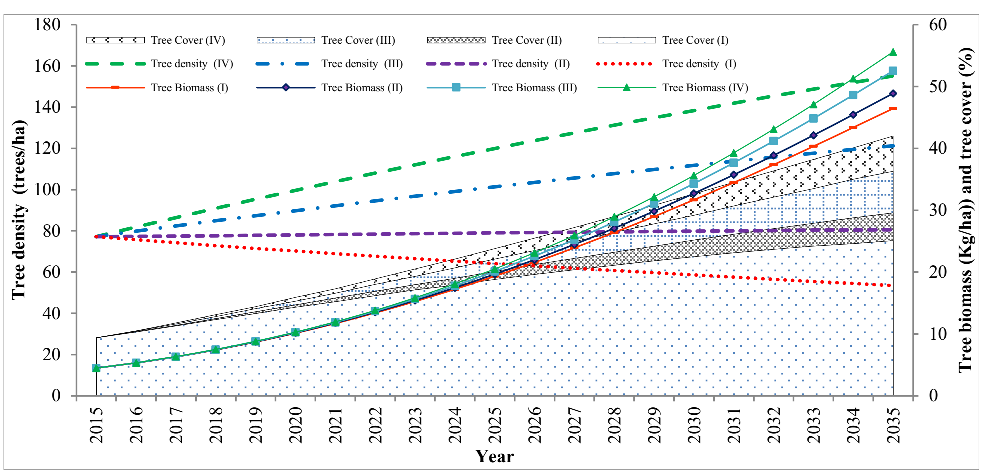


Fig. 6 Dynamic pattern of tree biomass (kg ha^{-1}), cover (%) and density (tree ha^{-1}) in next 20 years lifetime

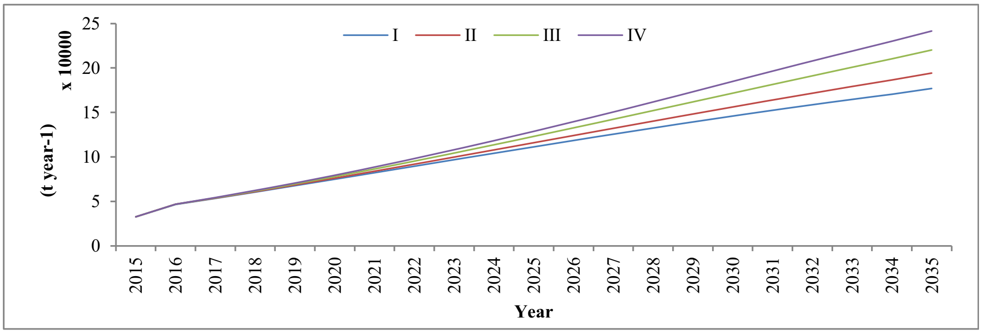


Fig. 7 Estimated total net carbon sequestration (CO_2 eq) in scenarios I to IV

rate diminishes as the urban trees mature; because, in the growing and young trees, the biomass adding rate is faster than in older and mature trees, which leads to faster carbon sequestration compared with mature trees (Nowak and Crane 2002; Lehtonen 2005; Moser et al. 2015). As the tree matures, homeostasis is reached, meaning the amount of carbon absorbed through photosynthesis would be similar to that lost through respiration and decay (Nowak and Crane 2002). The assessment of the relationship between carbon sequestration and tree ages showed that the CO_2 sequestration increases slowly in the initial period of life; then the incremental rate declines dramatically by the maturation time and stabilizes after maturity (Unwin and Kriedemann 2000; de Villiers et al. 2014). Though young and fast-growing species store carbon faster than old and slow-growing species, mature and healthy trees store carbon longer, and, some species (e.g. *Platanus x acerifolia*) sustain reliable and long term carbon stock (Nowak and Crane 2002; Ruiz-Peinado Gertrudix et al. 2012; Koeser et al. 2016). Also, maintaining older senescent urban trees may provide habitat for local fauna (Harper et al. 2005; Isaac et al. 2014).

The net value of carbon sequestration by urban trees, considered as a carbon source, may turn negative if the carbon released from the trees (as a result of maintenance activities and decomposition of dead trees) exceeds the carbon assimilated by them (Nowak and Crane 2002). Urban trees are different from natural and semi-natural forests and often require intensive management practices subsequently (Fares et al. 2017). These tree maintenance activities influence the carbon source and sink dynamics of urban trees and may emit carbon back to the urban ecosystems via carbon emission through machinery maintenance activities by fossil fuel combustion (e.g. from saws and chippers), transferring and removing deadwood and leaves, and pruned or trimmed branches to the urban soil. Therefore, UF may eventually turn to net emitters. A comprehensive assessment should take into account the carbon releasing of urban trees associated with these tree management practices (Velasco et al. 2016). Net carbon sequestration was normally about 75% of the gross value (Nowak and Crane 2002). However, in Tabriz, it was around 96% in the current condition. The difference was due to the relatively low share of dead trees (2.4%) and small DBH in Tabriz' UF (77.9% of trees with DBH less than 15.2 cm).

Strohbach et al. 2012 showed that the amount of sequestrated carbon can be much larger than that emitted from construction and maintenance if the design and maintenance plan aims to minimize the use of oil-based machinery. It should also be noted that increasing tree cover may require the creation of new green spaces which emits carbon. Therefore, at least some trees have to be planted to offset the emission from construction and maintenance. These issues make the accurate assessment of the carbon balances related to UF challenging; thus, the life cycle approach and carbon footprint analysis has been proposed to elucidate the net carbon balance of urban forests (Strohbach et al. 2012).

The growth behavior of the urban tree (tree biomass and canopy cover) is a function of cultural activities (e.g. pruning and trimming) which may lead to the poor growth of trees (Nowak et al. 1990; Frelich 1992; McPherson et al. 2001; Peper et al. 2001; Larsen and Kristoffersen 2002). Pruning

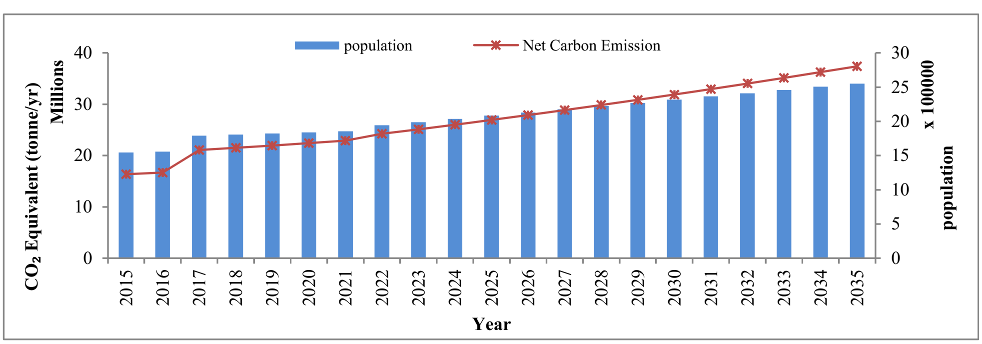


Fig. 8 Predicted GHG emission and population for Tabriz

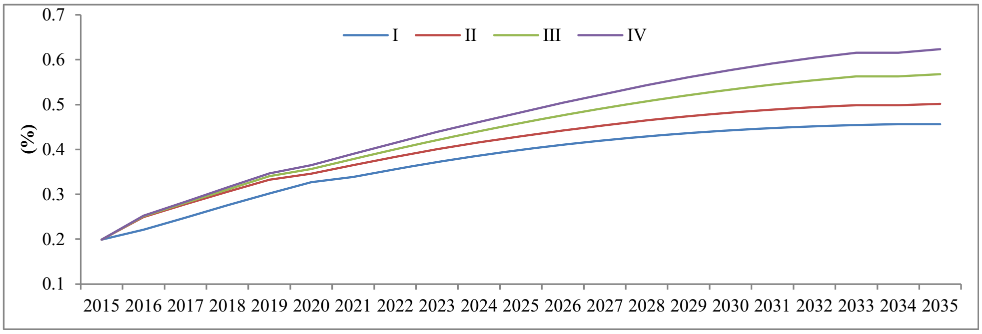


Fig. 9 Contribution of the current and future urban trees to climate change mitigation for the four scenarios (numbered I – IV)

and trimming diminish the tree biomass through cutting and also prevent the crown of the tree from reaching its potential size (Stabler et al. 2005; Alexandrov 2007; Stoffberg et al. 2008, 2009; Semenzato et al. 2011; McPherson et al. 2016; Vaz Monteiro et al. 2016). The tree size at maturity, as well as its lifespan, are the major factors in carbon sequestration and storage (Nowak et al. 2002b; Lal and Augustin 2012). Therefore, pruning and trimming practices may reduce the carbon storage amount (Fini et al. 2015). It may even return and release the carbon residing in trees. On the other hand, if the management practices increase the lifespan, they can have a positive effect on the carbon budget (Nowak et al. 2002b). It should be noted that pruning and trimming may be the best thing that can be done for trees; they are inevitable because they ensure urban trees' health (Badrulhisham and Othman 2016).

Decaying as a common issue occurring with different frequencies and severities may increase as the urban tree matures, and exacerbates the urban tree vitality (Terho et al. 2007; Luley et al. 2009; Koeser et al. 2016). As the tree decays, the above ground biomass diminishes, and the stored carbon reduces. Therefore, decayed tree acts as a carbon source by emitting back the stored carbon (Brazee et al. 2011; Aguilar et al. 2018). The estimated carbon storage by urban trees needs to be adjusted for decay losses (Aguilar et al. 2018). However, the quantitative knowledge about the amount of the biomass loss through decaying is limited (Brazee et al. 2011) and the existing models to quantify carbon storage in urban trees have not accounted for decay losses (Hutyra et al. 2011; Koeser et al. 2016; Aguilar et al. 2018).

In conclusion, the capacity of urban trees to sequester and store carbon may be either improved or restricted by maintenance activities as well as by the site conditions. Therefore, improving growth rates of early aged and young trees and also monitoring the overall health of older individuals to delay their senescence may better sustain the ES provided by UF (McPherson et al. 2013; Mullaney et al. 2015; Davies et al. 2017; Pretzsch et al. 2017).

i-Tree Eco converts biomass accumulation to carbon, assuming no net change in biomass and C storage at maturity. The model does limit carbon sequestration by having a diameter cut-off and also by estimating gross sequestration alongside net sequestration. The gross sequestration accounts for the fact that trees are decaying in place and have some chance of dying within the next year. i-Tree Eco compensates for pruning, etc. in urban settings by applying a 0.8 multiplier to the trees growing on land uses which are typically managed (i.e. all but the vacant and wetland land uses) (Nowak 2019).

Focusing on a single ES isolated from the other ES can frequently cause policy failures (Elmqvist and Tuvendal 2013), and emphasizing multiple ES and benefits is a key element of the "capital" concept of UF (Matthews et al. 2015). As the results show, focusing on one single service (climate change mitigation) alone is insufficient to justify tree planting strategies. Nevertheless, urban tree planting should not be overlooked because of its low contribution to climate change mitigation, since tree planting could be important in supplying other environmental and economic benefits (e.g. air quality improvement, noise pollution reduction, floods controlling (stormwater retention), cooling effects through

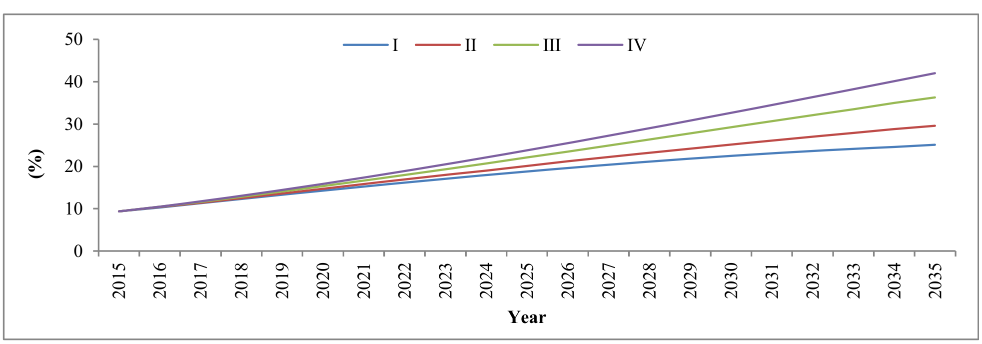


Fig. 10 Estimated urban temperature regulation in the scenarios *I* to *IV*

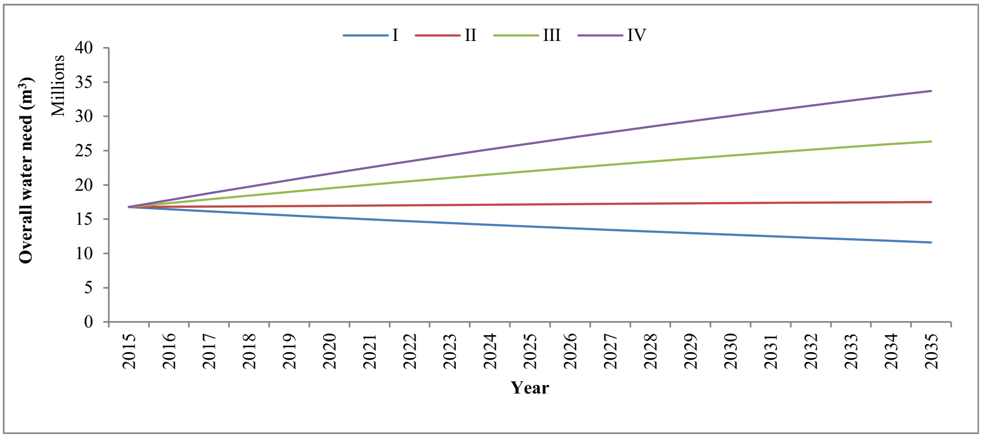


Fig. 11 Overall water need to maintain climate change mitigation ES in the scenarios *I* to *IV*

shading and transpiration, soil erosion reduction, aesthetic benefits, wildlife habitat, etc.) (Carreiro 2008; Stabler 2008; Wu 2008). As with carbon sequestration, many of these ecosystem services and disservices increase as the LAI or canopy cover increases (Davies et al. 2017). In other words, synergies may exist. To address this issue, we examined the synergy between climate change regulation and urban temperature regulation through tree planting scenarios. The results show that as the climate change regulation increases, the provision of cooling effect improves. This may prove that several UES (e.g. air quality improvement, climate change regulation, urban temperature regulation, etc.) synergistically increase via tree planting in the future. Identifying such synergies (which allow for the simultaneous improvement of more than one ES) and trade-offs help policymakers to make better choices to increase human well-being (Haase et al. 2012), for instance, through tree planting strategies.

Considering trade-off for the UES and resource use (e.g. water) provides useful information for urban decisionmakers (Darrel et al. 2011), particularly regarding the balance between water loss and carbon sequestration (Pataki et al. 2011c). The amount of irrigation water the urban trees require during the low-precipitation months in order to sustain carbon sequestration (tree-water trade-off), especially in water-limited regions such as Tabriz, may restrict the sustainability of the long-term potential of UF in mitigating climate change; therefore, it may be considered as a disservice or cost (Stabler and Martin 2004; Jackson et al. 2008; Lyytimäki et al. 2008; Pataki et al. 2011c). This study analyzed the temporal urban trees' water requirements to provide climate change mitigation ES. The total water need for a single tree in Tabriz is almost the same as that of other Iranian cities (Zehtabian and Farshi 1999; Azari et al. 2018). The results showed that about 1854 (m^3) of water was needed to sequester a ton of carbon, annually. The amount of water requirement increases as the climate change mitigation ES improves through tree planting. This means more water is required to sustain the potential of UF to sequester carbon in developed scenarios (*III* and *IV*), which puts more pressure on limited urban water resources. It is recommended to schedule the irrigation practice according to the species' water requirement and growth stage (Stabler and Martin 2000) as well as to introduce trees with low water requirement in arid and semi-arid regions like Tabriz (Pataki et al. 2011c). Using a lower amount of water than the tree requires leads to a reduced ES production (e.g. carbon sequestration), especially by small trees (Pataki et al. 2011a, c).

Tracking such synergies and trade-offs and considering all the benefits and costs resulting from UF can provide a more comprehensive understanding of the delivered ES process (Fisher et al. 2009; Bodnaruk et al. 2017). Unfortunately, there is still a lack of comprehensive understanding of synergies and trade-offs among different ES (Rodríguez et al. 2006).

Moreover, increasing tree cover may aggravate disservices such as emitting BVOCs (biogenic volatile organic compounds) (Peñuelas and Llusià 2003; Peñuelas and Staudt 2010), health and pollutant issues from wind-pollinated pollen (Gómez-Baggethun et al. 2013), damage to urban infrastructure (Escobedo et al. 2011), and blockage of light, views, and heat (Gómez-Baggethun et al. 2013; Davies et al. 2017). More studies are required to understand synergies, trade-offs, and disservices by considering several ES and disservices at the same time and in the same system (Howe et al. 2014).

Another important issue in applying urban forestry approach to mitigate future urban carbon is the limitation of available spaces to plant new trees (Strohbach et al. 2012). The i-Tree Eco results showed that about 34% of Tabriz (8266.2 ha) could be considered as plantable space (leading to more carbon mitigation). On the other hand, though, these same vacant spaces (plantable area) are usually considered for future urbanization projects (i.e. industrial, commercial, and residential purposes) by urban planners (De Sousa 2003). This competition is more critical in developing cities facing expansion. This is another issue which needs scenario analyses – as provided in this study – to examine the future ecosystem services so as to increase the awareness and to persuade urban planners to assign the area for urban greenery as well.

The current results, for instance, suggest that spatial planning regarding UF should mainly focus on responding to climate change through adaptation (Matthews et al. 2015), e.g. using UF to combat the urban heat island effect through its shading and transpiration (Byrne and Jinjun 2009; Pearlmutter et al. 2017).

Despite the comprehensive quantitative approach sought in this study, there are various uncertainties in the contribution to climate change mitigation: 1) This study disregarded the indirect effect of UF on climate change mitigation. For instance, urban trees can decrease carbon emissions in cities e.g. by reducing energy use of buildings through shading and evaporation and the consequent reduction of the urban heat island effect. It has been claimed that the potential indirect effects on carbon mitigation were four times higher than the direct carbon sequestration rate (Nowak 1993). Therefore, these effects have to be incorporated in carbon storage and sequestration estimations of urban trees so as to have a more accurate examination of the role of urban trees in climate change mitigation in cities (Nowak et al. 2013), 2) GHG emission estimations were uncertain as they were adopted from nationwide estimations, which included several emission sectors not located in Tabriz. This may have caused an overestimation of the city-based emission values and, consequently, an underestimation of the contribution of UF to climate change mitigation at city-scale, 3) there were limitations and caveats to the model; the number of available allometric equations for urban trees is limited (Aguaron and Mcpherson 2012) and tends not to account for the strong dependence of root-to-shoot allometry on tree size (Poorter et al. 2015), which might lead to a stronger increase in storage than calculated now. Moreover, most existing urban-based biomass equations were established for the USA (Weissert et al. 2014) and have uncertain conversion ratios and biomass equations and provide less reliable estimations (Nowak et al. 2008; McPherson and Peper 2012). For example, the 0.8 generalized adjustment factor for open-growth tree, which is widely applied by many authors across all the species of urban forest (Liu and Li 2012; Vaccari et al. 2013; Timilsina et al. 2014; Zhao et al. 2016), was developed from and for US urban forest (Nowak and Crane 2002). This is critical since it was suggested to apply a species-decay factor (at least for *Ulmus procera trees*), rather than a standard factor, for a more accurate calculation of stored carbon in urban forests (Aguilar et al. 2018). Therefore, their application is quite limited to IRAN's climatic conditions, 4) The growth rates used in Forecast module to simulate the future tree growth are estimations, since there is a lack of measured data on urban tree growth for slow, moderate or fast-growing urban tree species, and 5) this study disregarded the impacts of climate change and urban conditions on future tree growth, which is an essential issue in sustainable UF management (Moser et al. 2017; Nitschke et al. 2017; Pretzsch et al. 2017). Therefore, the model outputs in this paper represent an approximation rather than a precise and accurate quantification of carbon storage and sequestration. Future research is needed to help overcome these limitations.

Iran has been identified as a country with comparatively high GHG emissions, where urban activities constitute one of the most important emission sources (Mirzaei and Bekri 2017; Olivier et al. 2017). Iran has planned to achieve the mitigation goal especially through technical strategies such as the development of combined cycle power plants, renewable energies, and utilizing low-carbon fuels (INDC 2015). This means the government focuses only on technical measures, which have met no success yet (Burck et al. 2018). The potential of urban trees to achieve this goal was not taken into account, and the small potential shown in this paper should be considered by the policymakers as a complementary measure in contributing to the achievement of the goal, especially at a city scale. Hence, UF is only part of the solution beside the principal solutions such as increased energy usage efficiency.

Conclusions

This paper proposes an approach to analyzing possible future contribution of urban trees in mitigating climate change at city scale, which can help urban planners to understand the current and future tree resources. The approach can be used as a tool by the environmental policymakers to find out how much they can rely on urban trees to achieve the environmental targets (such as the GHG emission targets). Our assessment of the contribution of urban trees to climate change mitigation through their regulating ecosystem services revealed the potential of urban trees in carbon storage and sequestration. The contribution of urban trees in Tabriz is relatively low (about 0.2%) and can be increased to about 0.63% through tree planting over the next 20 years. Hence, the urban tree planting at city scale has only a limited effect on climate change mitigation. It is, therefore, recommended to consider it as a complementary solution beside other mitigation strategies. Moreover, the planting of trees to improve climate change mitigation also enhances the urban temperature regulation (as well as many other ES such as air purification) at the expense of more resource use, especially water. Simultaneous analysis of such synergies and trade-offs between a specific ES and others generates considerable information for sustainable urban green infrastructure management.

Acknowledgments Much gratitude is also owed to Mr. Babak Chalabiyani who participated in the field survey. We would like to thank two anonymous reviewers whose valuable comments significantly improved this paper. We sincerely thank Dr. David Nowak from USDA Forest Service for advice, Dr. Jason Henning and Erika Teach from i-Tree team for their assistance in data processing, and Mr. Alireza Derakhshan and Ms. Fatemeh Adeli for species identification. We are also grateful to numerous people and organizations involved in the field survey. The Iranian National Science Foundation partially supported this research (No. 96000398).

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