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Levan Alpaidze
Ivane Javakhishvili Tbilisi State University

Rocco Pace ((rocco.pace@iret.cnr.it)
National Research Council: Consiglio Nazionale delle Ricerche  https://orcid.org/0000-0002-3126-635X

Research

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Ecosystem services provided by urban forests in the Southern Caucasus region: a modeling study in Tbilisi, Georgia

Levan Alpaidze¹, Rocco Pace²*

¹ Faculty of Social and Political Sciences, Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia
² Institute of Research on Terrestrial Ecosystems (IRET), National Research Council (CNR), Porano (TR), Italy

*corresponding author: rocco.pace@iret.cnr.it
ABSTRACT

Background
All cities globally are growing considerably as they are experiencing an intensive urbanization process resulting in significant economic, social, and environmental challenges. One of the major risks is the deterioration of living environment in urban areas due to the high soil consumption and pollution of environmental components. For this reason, cities are required to adopt measures to reduce air pollution concentration and CO$_2$ emissions, preserve biodiversity and mitigate the urban heat island effect. In this context, tree planting has been suggested as one cost-effective strategy because green infrastructures can provide important environmental and social functions which contribute to the quality of life and health of city dwellers.

Tbilisi is the largest city in Georgia, with a population of over 1,100,000 inhabitants (about 30% of total population of Georgia). The green space availability in Tbilisi (5-6 m$^2$ per inhabitant) is low compared to other European cities, and in recent years the need to increase the amount of urban vegetation has been underlined at planning level.

Results
In our study, we implemented for the first time in an Eastern European city the i-Tree Eco model to quantify the main ecosystem services from common tree species in Southern Caucasus. Two parks, Expo Park (694 trees) and Red Park (1027 trees) in the city of Tbilisi have been measured and a model simulation was performed for the year 2018. These urban forests store large amounts of carbon in their woody tissues (198.4 t for Expo park and 126.5 t for Red park) and each year they remove 4.6 and 4.7 t of CO$_2$ for Expo park and Red park. They also positively contribute to the air quality by removing 119.6 and 90.3 kg of pollutants (CO, NO$_2$, O$_3$, PM$_{2.5}$, SO$_2$), and reducing water runoff of 269.5 and 200.5 m$^3$, respectively.

Conclusions
This analysis highlighted the key role of urban forests in improving the environmental sustainability of the city of Tbilisi and provides important decision support for the tree species selection in this geographic area with the aim of maximizing the benefits trees can supply to cities.

Keywords: urban greenery; nature-based solutions; modeling; Eastern Europe; tree species selection.
BACKGROUND

During ongoing process of an accelerated urbanization, an additional emphasis is given to the proper understanding and assessment of interactions between people and nature, particularly in the urban environment (Kaplan 1983) where green spaces play a decisive role in providing essential services for citizens (Unterweger et al. 2017). Improving the sustainability of cities and mitigating their impact on the environment requires a careful assessment of environmental and closely related social, economic, cultural, and ecological issues (Braun, 2005). Urbanization process has enhanced the detachment of humans from nature and drastically reduced natural areas in cities (Cole at al. 2017), so that in major cities green spaces as urban parks and gardens, tree-lined streets, and the vegetation of cemeteries are typically the only chance for citizens to enjoy and get in touch with nature (Beatley 2009).

The bigger threat for the urbanized areas comes from the climate change, and cities will be among the most affected ecosystems (Breuste at al. 2013). With more than half of global population domiciled in cities and about 60% of mankind, expected to be urbanized in 2030 (World Cities Report, 2020), the social-ecological resilience of cities and ever-growing demand for ecosystem goods and services in the urbanized areas, stay imbalanced and cities produce only a small amount of total ecosystem services (Kampelmann 2014). Currently, the urbanized areas cover only a small portion of the total surface of the planet that approximates varies from 1 to 3% (Liu et al. 2014), though they have a vast share of anthropogenic impact on the biosphere (Gómez-Baggethun E. et al. 2013). The expansion of urban areas has great negative effects on the environment in terms of increased energy consumption, greenhouse emissions and the degradation of natural environment (Knudsen et al. 2020). The remained green infrastructure is destined to compete with other urban infrastructures (roads, buildings, industrial facilities, general technical infrastructure) for resources and space (Andersson et al. 2015).

Urban areas are characterized by high-level of air pollution caused by anthropogenic sources such as from the stationary (manufacturing, heating from the houses, energy generation factories, other industrial sources) and mobile sources (automobiles and transport) (Shaddick et al. 2020). In addition to polluted air, the Urban Heat Island Effect (UHI) contributes to the increased temperature in the cities (Yang et al. 2016), further deteriorating the negative results of the global climate change in urbanized areas (McCarthy at al. 2010). Urban green spaces play a key role in the urban fabric providing important environmental and social functions which support to the quality of life and the health of city dwellers (Andreucci et al. 2019). Number of studies from the various disciplines (geography, ecology, urban studies, climatology, other) show that the air samples taken from sites with less greenspace frequently had high concentrations of all fractions of particulates than other sites and the sites with higher density of green spaces had lower particulates, even when vehicular traffic was considered (Irga et al. 2015; Hirabayashi and Nowak 2016; Riondato et al. 2020; Lin et al. 2020).

Trees are considered as one of the most effective solutions to mitigate the air pollution and particulate matter uptake in urban areas (Beckett et al. 2000). Beckett et al. (2000) indicate in their research that some conifers, as P. nigra and C. leylandii were the most effective species, due to their physical features, for capturing fine particles, suspended in the urban air. Some authors state that street vegetation in busy urban transport roads, are able to reduce the concentrations of PM$_{10}$ particles up to 60% (Pugh et al. 2012).
and offer immediate improvement of air quality particularly in the street canyons and contribute to the pollution decrease in streets’ ambient air at the city-scale (Pugh et al. 2012).

Urban green spaces contribute to the absorption of carbon dioxide, remove gaseous pollutants and fine particulate matter from the air (Nowak and Crane 2002), mitigate extreme temperatures (Santamouris and Osmond 2020) and the UHI (Urban heat island) effect by shading and the evapotranspiration (Rahman et al. 2020), slow down soil erosion processes, reduce water run-off and facilitate the filtration process in the soil (Grey et al. 2018), and preserve animal and plant biodiversity, promoting the pollination process with the breeding of various species and the biological control of populations (Dwyer et al. 2003). In addition to environmental services, urban green spaces have an important social function because they are essential recreational and cultural spaces for the city (Andersson et al. 2015), producing positive impacts on human health and wellbeing (Higgins et al. 2019).

Generally, urban vegetation, particularly urban forests, have a great positive impact on the urban air quality (Esposito et al. 2018). To date, we have somewhat limited number of empirical studies on the scale and value of the effects of urban trees on air quality and human health (Szkop 2016). Overall, this is also true towards the less attention, paid to the research of small-scale urban green spaces (as urban parks, squares and gardens, street trees, other small forms) and their role in the resilience and the quality of urban life (Chiesura 2004; Camps-Calvet et al. 2016). It is especially relevant if we speak about the climate, pollution and their implications on the cities of the Southern Caucasus. The integrated research in urban studies, which encompass the urban green infrastructure, urban forests and their influence on air quality and urban ecosystem services is very limited in Georgian, and other Southern Caucasian research institutions.

The history of ecosystems research clearly indicates that most research papers, related to the sustainability science in general, and ecosystems services and human well-being, which were published in the period of 1992 to 2018, came from 119 countries of the world. Most of those scientific articles came from the USA, UK, Australia, Germany, and China (Wang et al. 2021) and were concentrated in countries/territories of North America, Western/Central Europe, East Asia, and Australia. At the same time, the research about the topics of urban ecosystems and sustainability is very rare in the former Soviet states, and especially in the region of the Southern Caucasus what shows the utter necessity of and the attention needed to other regions, which are also experiencing the effects of climate change and urbanization. Consequently, the proper urban green planning in ex-Soviet countries, and particularly in Georgia, at this stage, lack the analysis of changes, caused by the still present rapid construction and land development activities in Tbilisi urban area. The thorough study of natural and manmade landscapes of Tbilisi area, that are very sensitive to any kind of changes, would help to improve the quality of the urban environment for its inhabitants and give city a chance to use this new knowledge for scientifically justified urban planning.

Unfortunately, the lack of appropriate knowledge and the awareness of the environmental and social benefits of ecosystem services, the disrupted communication between various urban stakeholders (public and private sectors, civil society, communities and governments) and the weak communication between various sectors of economy, society and city governance structures, result in various types of challenges
for sustainable urban development and pose unanticipated risks and threats to the resilience of cities and their inhabitants (Filho et al. 2020).

Tbilisi has experienced several phases of its urban development and expansion, during the last two centuries, transforming from a strategically located trading town into the city of over a million, with its distinctive and diverse culture and important socio-economic role in the Caucasus. Along with the processes of economic downfall, nationalism and the dramatic changes of social fabric, characteristic to post-Soviet transition process (in the states of former USSR), Tbilisi as a modern globalizing metropolis, has brought contradictions, such as undermining the city's heritage, contributing to socio-spatial polarization (Salukvadze and Golubchikov 2016). During the Soviet Era (1921-1991) started the expansion of Tbilisi territory and an intensive urbanization has occurred, when the city increased ten times in terms of territory, and six times as population (Salukvadze and Golubchikov 2016).

According to the Environmental Standards document of Tbilisi Municipality from 2019 (Tbilisi Municipality, Green and Recreational Space Standard 2019), the green areas (men-made and natural, both) of Tbilisi comprise about 145 sq.km, within Tbilisi municipality limits, what is about 28.9% of the total area of Tbilisi Municipality (502 sq. km) (Tbilisi in figures 2018). The green zones of Tbilisi are already hung behind the area of built, impervious (aka, urbanized) zones (158 sq. km, i.e., 31.47% of the total) (Tbilisi Municipality, Green and Recreational Space Standard 2019). However, the major concern, related to the green areas, is that they are located near the city limits, far from the “real city” contour. The natural vegetation (mainly forests) is located in the suburbs and in places with complex topography. The biggest parks, as Mtatsminda Park, Lisi Lake Park and Tbilisi Sea Park (officially named as Tbilisi Dendrological Park), are located far from the residential zones and are difficult to access for the population on daily basis (Tbilisi City Municipal Assembly, Resolution 2015). The urban green spaces of Tbilisi are mainly represented by man-made and naturally grown green zones – parks, public gardens, tree-lined streets, and various places with artificially planted and decorative vegetation (Tbilisi City Municipal Assembly, Resolution 2015).

The impact of climate change in Georgia and Tbilisi was recently discussed by the United Nations Framework Convention on Climate Change (UNFCCC), reporting a 1.3 °C increase in average temperature and 60 mm in annual precipitation over the past 25 years (1990-2015) (Georgia’s Second Biennial Update Report 2019). The highest greenhouse gas emitting categories in Georgia are transport (38%), other Sectors (18%), oil and natural gas (17%), energy industries (15%), manufacturing industries and construction (10%) (Georgia’s Second Biennial Update Report 2019). The transport sector is also a major air polluter in Tbilisi, the main hub of social and economic activities in Georgia (51.2 % of Gross Domestic Product (GDP) of Georgia (National accounts of Georgia, 2019). An increasing number of second-hand passenger vehicles manufactured before year 2000 (48% of approx. 1.4 vehicles, registered in country) (Automobile fleet, Georgia, 2019) have been registered, which has further aggravated the air quality. According to air pollution data of 2017 (Annual Report of the pollution of atmospheric air, Georgia, 2017), the average annual concentration of particulate matter in some locations of Tbilisi exceeded, in given periods, the EU standard norm for PM$_{2.5}$ and PM$_{10}$ in ambient air (0.025 mg/m$^3$ and 0.04 mg/m$^3$, respectively), particularly near the construction sites (1.5 of the standard norm) and busy urban road intersections (Air Quality in Tbilisi, Thematic Inquiry, 2019).
Research on urban ecology and ecosystem services of Tbilisi and other Southern Caucasus cities is missing in the literature, and thus a thorough assessment of the multiple environmental benefits provided by green infrastructure is essential for planning and managing urban green spaces and contributing to the improvement of citizens' quality of life.

This study aims to evaluate the air quality and climate-related ecosystem services of two Tbilisi’s public parks. The analysis has been carried out using the i-Tree Eco model, which for the first time has been applied in a scientific study of urban ecosystem services in the South Caucasus. Based on these results, the most common trees species in Southern Caucasus cities were evaluated and compared for more detailed and specific selection in future urban forestation programs.
METHODS

Study area

The city of Tbilisi presents a stretched (from North to South-East), longish geographical layout, with the major built-up area squeezed between mountains. In 2019, Tbilisi Municipality had a population of 1.171 million inhabitants (total population of Georgia, in 2019 was 3.723 million) (National Statistics Office of Georgia, 2019), what makes a rough 31.45% of the total population of Georgia (National statistics Office of Georgia, 2019). Additionally, the change of Tbilisi administrative borders in 2007 (that time Tbilisi spanned only to 365 sq. km) (Resolution of the Parliament of Georgia, 2007), which incorporated the lands of surrounding outskirts (villages of Tabakhmela, Kojori, Tskneti, Shindisi, Tsavkisi, Kiketi, Betania, Akhaldaba, other), had resulted in the new development and construction activities on mostly wooded, recreational, and generally, green areas. By 2016, the portion on built-up areas of Tbilisi increased from 23% (in 1987) to 37.53% (Gadrani et al. 2018).

Tbilisi is situated in the terraces of the valley of river Mtkvari (Kura) on the elevations of 410-370 m a.s.l (above sea level). River Mtkvari divides the city in two distinct parts – the left and right banks, surrounded by the mountain gorges. On the right bank the Trialeti Range (770 m, part of the Lesser Caucasus Mountains) sharply descents to the river valley, forming higher part of the city, and the left bank is limited with Makhata mountain (630 m), forming the wider part of the river valley.

Tbilisi has a humid subtropical climate (Köppen climate classification: Cfa) with considerable continental and semi-arid influences. The average annual temperature is 12.7 °C, with average temperature of 0.9 °C in January, and 24.4 °C in July. The absolute minimum and maximum temperatures, recorded were -23 °C, and + 40 °C. The annual precipitation varies from 400 to 560 mm. The rainiest month is May (90 mm), and the driest month - January (about 20 mm). The snowfalls may happen for 15-25 days a year, without forming a stable snow cover. Northwesterly winds dominate in most parts of Tbilisi throughout the year, but southeasterly winds are common as well. Generally, given the proximity of The Greater Caucasus Mountains Range (further to the north), which prevents the intrusion of cold air masses from Russian planes, Tbilisi experiences a mild and pleasant climate.

The study areas, consisting two urban parks – Vaso Godziashvili Park (also known as a ‘Red Park’) with total area of approx. 3.3 hectares (the right bank of riv. Kura, 455 m above sea level), and Expo Georgia Park (total area: approx. 3.2 hectares, the left bank of riv. Kura, 418 m, founded in 1958), are located in the central parts of Tbilisi – the capital of Georgia (see Fig. 1), 2.7 km apart from each other.

These two urban parks had been designed in 50-60-ies of XX century. RED Park is a typical public urban park, built in densely populated neighborhood of Saburtalo district of Tbilisi, and it is used as a leisure and sports activities park. EXPO Park, is a part of Georgia EXPO - an exhibition space, located in Didube District of Tbilisi, owned by the private company (with free access for general public). EXPO Georgia’s territory is a combination of buildings, the pavilions for the exhibition activities, and the park, built for the exhibition space during in 1958 in Soviet period (Expo Georgia, 2021).
Figure 1. Vaso Godziashvili and Expo Georgia parks, Tbilisi aerial photograph (designed by Giorgi Kirkitadze and Levan Alpaidze, 2020)
Tree inventory

The field work, conducted in August-September of 2019, was designed according to the i-Tree Eco v6 field manual (i-Tee Eco, field guide v6.0, 2020). The analyses of collected data are based on fieldwork conducted in the two research sites in Tbilisi, for complete tree inventory of trees in both parks (Vaso Godziashvili Park, aka “RED PARK”, and EXPO Georgia Park). Tree sampling was conducted during the ‘leaf-on’ season (July-September) of 2019.

The general information collected from the field data included, with other parameters: the identification of species (scientific names), tree diameter at breast height (DBH), height of the tree, height to base of live crown, crown base, crown width, percentage of canopy missing (relative to crown volume), percentage canopy dieback, and light exposure of the crown (Nowak et al, 2008). Listed data were taken for each tree in the study area with DBH greater than 5 cm.

Model settings

The model simulation was performed for 2018, the latest year available in i-Tree Eco, using hourly meteorological data (air temperature, radiation, wind speed) registered at the Tbilisi Airport weather station (Tbilisi/Lochini Airport) and precipitation provided by the National Environmental Agency (NEA) of Georgia.

The hourly air pollution concentration data (2018) had been provided by NEA, from the operational monitoring station at Kazbegi Avenue in Tbilisi. The station is located in the entrance of the Red park, ensuring accurate data for air pollution concentration, which included: $O_3$, $NO_2$, $SO_2$, $PM_{10}$ and $PM_{2.5}$ (fine particulate matter that is 10 microns and with a diameter equal or less than 2.5 microns). After completing data collection, the field data of urban trees, air pollution, and meteorological data were processed using i-Tree Eco software, i-Tree Eco V6.

These two sets of data have been used to analyze the effects of park trees in sequestering and storing the carbon, improving the air quality (pollution removal), and avoid rainwater runoff.
RESULTS

Weather and pollution data

In 2018 in Tbilisi the average daily temperature was 15.3 °C with a minimum at the end of December (-0.6 °C) and a maximum in July (31.2 °C). The mean Photosynthetically Active Radiation (PAR) was 330.1 W m\(^{-2}\), with a lowest value in December (77.5 W m\(^{-2}\)) and highest in June (572.5 W m\(^{-2}\)). Precipitation was distributed relatively evenly (a monthly average of 33 mm) though having seasonal features, with maximums in June, August, and November (73.2, 64.4, 63 mm, respectively), and a lower value in February (6.2 mm) (Fig. 2).

Figure 2. Weather data used for model simulation of Tbilisi in 2018. From top to bottom: daily average photosynthetically active radiation (PAR), daily average air temperature, and total monthly precipitation.
The average CO concentration in 2018 was 388 µg m⁻³ with higher values in winter months (max value = 1712.5 µg m⁻³). SO₂ shows average values of 7 µg m⁻³ with frequent peaks during the year up to 30.4 µg m⁻³. The concentration of PM₂.₅ and PM₁₀ was relatively constant throughout the year (15.8 and 40.3 µg m⁻³ on average, respectively) with highest values in December (70.8 and 196.9 µg m⁻³, respectively). Also, another peak (177.9 µg m⁻³) was registered for PM₁₀ on July 27th due to the spread of dusty air masses from the South in all Eastern Georgia including Tbilisi (NEA, Georgia). O₃ annual mean was 33.8 µg m⁻³ with higher values in spring and summer (max value = 78.8 µg m⁻³). On the other hand, NO₂ shows an opposite trend with higher values in winter months (75.7 µg m⁻³) and an annual average of 34.5 µg m⁻³. A peak (108.8 µg m⁻³), as with PM₁₀, was recorded for NO₂ on July 27th (Fig. 3).

Figure 3. Daily average pollution concentration of CO, SO₂, PM₂.₅, PM₁₀, O₃, and NO₂ in Tbilisi (year: 2018).
Urban forests

For the evaluation of ecosystem services provided by urban forests, we have analyzed their structural characteristics. A total of 1,030 trees (tree cover: 1.5 ha) for the Vaso Godziashvili Park (i.e. RED PARK) (Tab. 1), and 694 trees (tree cover: 1.8 ha) for the EXPO Georgia Park (Tab. 2) were measured.

**Table 1. Dominant species in Red Park with a relative number, canopy cover, leaf area, and basal area greater or equal to 1%, 300 m², 1000 m², and 0.3 m².**

| Species | Number trees (N°) | Canopy Cover (m²) | Leaf area (m²) | Basal area (m²) |
|---------|------------------|------------------|----------------|-----------------|
| Italian cypress (*Cupressus sempervirens* L.) | 125 | 2265.5 | 9496.2 | 6.3 |
| Oriental arborvitae (*Platycladus orientalis* (L.) Franco) | 79 | 406.5 | 1105.1 | 0.4 |
| Deodar cedar (*Cedrus deodara* (Roxb.) G. Don) | 61 | 2327.2 | 10895.5 | 10.7 |
| European ash (*Fraxinus excelsior* L.) | 60 | 595.1 | 1749.2 | 1.1 |
| White ash (*Fraxinus americana* L.) | 41 | 475.4 | 1631.4 | 0.3 |
| Bigleaf linden (*Tilia platyphyllos* Scop.) | 32 | 306.5 | 1028.3 | 0.4 |
| Japanese pagoda tree (*Styphnolobium japonicum* (L.) Schott) | 30 | 844.5 | 2679.2 | 2.2 |
| Oriental planetree (*Platanus orientalis* L.) | 23 | 1462.4 | 8757.8 | 3.3 |
| White mulberry (*Morus alba* L.) | 17 | 475.4 | 1631.4 | 0.3 |
| White poplar (*Populus alba* L.) | 15 | 1478.1 | 6942.2 | 5.6 |

**TOT urban forest** | **1030** | **14625** | **55917.6** | **32.7** |

**TOT dominant species** | **483** | **10773.6** | **47053.3** | **31.5** |

**Relative number of dominant species (%)** | **46.9** | **73.7** | **84.1** | **96.3** |

**Table 2. Dominant species in Expo Georgia park with a relative number, canopy cover, leaf area, and basal area at least 1%, 300 m², 1000 m², and 0.3 m², respectively.**

| Species | Number trees (N°) | Canopy Cover (m²) | Leaf area (m²) | Basal area (m²) |
|---------|------------------|------------------|----------------|-----------------|
| Italian cypress (*Cupressus sempervirens* L.) | 116 | 3311.3 | 17373.0 | 10.3 |
| Deodar cedar (*Cedrus deodara* (Roxb.) G. Don) | 58 | 3726.7 | 14477.1 | 20.9 |
| Horse chestnut (*Aesculus hippocastanum* L.) | 54 | 1090.5 | 5883.6 | 1.3 |
| Japanese privet (*Ligustrum japonicum* Thunb.) | 47 | 909.3 | 3307.8 | 0.6 |
| Oriental planetree (*Platanus orientalis* L.) | 23 | 1142.3 | 6913.0 | 2.9 |
| Blue spruce (*Picea pungens* Engelm.) | 13 | 297.0 | 1930.8 | 0.9 |
| White ash (*Fraxinus americana* L.) | 12 | 616.5 | 4454.9 | 1.3 |
| White mulberry (*Morus alba* L.) | 11 | 399.9 | 1629.4 | 0.9 |
| Littleleaf linden (*Tilia cordata* Mill.) | 11 | 621.4 | 3401.2 | 1.6 |
| European ash (*Fraxinus excelsior* L.) | 7 | 713.9 | 2983.2 | 3 |

**TOT urban forest** | **694** | **17866.4** | **79992.2** | **53.6** |

**TOT dominant species** | **352** | **12828.8** | **62354** | **43.7** |

**TOT (%)** | **50.7** | **71.8** | **78.0** | **81.5** |
In the Red Park, there are 50 different tree species, from the most common such as *Cupressus sempervirens* (12.1% of total tree population), *Punica granatum* (7.9 % of total), *Cupressus arizonica* (7.7%) and *Platycladus orientalis* (7.7%). The overall tree density in RED Park is 312 trees/ha with a tree cover of 44.3%. Dominant species in terms of canopy cover, leaf area, and basal area are deodar cedar (*Cedrus deodara*), Italian cypress (*Cupressus sempervirens*), white poplar (*Populus alba*), and oriental planetree (*Platanus orientalis*) (Tab. 1).

The Expo Georgia Park encompass 62 different species. The most dominant species of the Expo Georgia Park are *Cupressus sempervirens* (16.7% of total), *Cedrus deodara* (8.4%), and *Aesculus hippocastanum* (7.8%). The overall tree density in Expo Park is about 217 trees/ha with a tree cover of 55.8%. Dominant species in terms of canopy cover, leaf area, and basal area are deodar cedar (*Cedrus deodara*), Italian cypress (*Cupressus sempervirens*), oriental planetree (*Platanus orientalis*), and horse chestnut (*Aesculus hippocastanum*) (Tab. 2).
Carbon storage and sequestration

Trees are estimated to store 126.5 and 198.4 t of carbon in Red and Expo park, respectively. *Cedrus deodara* (27%), *Cupressus sempervirens* (24.6%), and *Populus alba* (15.8%) are the species that accumulated the most carbon in Red park. In Expo park *Cedrus deodara* (33.8%) and *Cupressus sempervirens* (20%) store more than half of the total carbon (Fig. 4).

The gross sequestration is about 4.7 and 4.6 t of carbon per year for Red and Expo park, respectively. As for carbon storage, *Cedrus deodara* (23.4%), *Cupressus sempervirens* (19.1%), and *Populus alba* (11.3%) in Red park, *Cupressus sempervirens* (29%) and *Cedrus deodara* (25.6%) in Expo park, are the species that sequester more than half of the total carbon per year (Fig. 4).

*Figure 4. Species that store (carbon storage) and sequester (carbon sequestration) the most carbon in Expo and Red park.*
Pollution removal

Red park and Expo park in 2018 remove 90.3 and 119.6 kg of pollutants, respectively. Ozone (O$_3$) is the most removed pollutant from trees (48.9 kg in Red Park and 63.8 kg in Expo Park), particularly in summer with a maximum in June (7.7 kg in Red Park and about 10 kg in Expo Park). Nitrogen dioxide (NO$_2$) removal is nearly constant during the year with an average of 2.1±0.4 kg (in total 24.6 kg) for Red Park and 2.8±0.5 kg (in total 33.1 kg) for Expo park. The annual amount of total fine particulate matter (PM$_{2.5}$) removed is 6.6 kg for Red Park and 9.5 kg for Expo Park with highest values in June, March, and December (1, 0.8, 0.7 kg for Red Park and 1.5, 1.1, 1.2 kg for Expo Park). Also, trees remove 8.2 and 10.8 kg of sulfur dioxide (SO$_2$) in Red Park and Expo Park, respectively, with highest values in February, March, April, and October. Finally, carbon monoxide (CO) is mostly removed during the growing season of trees (in total 2 kg in Red Park and 2.4 kg Expo Park) with a peak in October.

**Figure 5.** Monthly pollution removal of CO, NO$_2$, O$_3$, PM$_{2.5}$, and SO$_2$ from Expo and Red Park of Tbilisi in 2018.
In 2018, trees emitted an estimated 69.9 (45.9 kg of isoprene and 24 kg of monoterpenes) and 55.7 kg (20 kg of isoprene and 35.7 kg of monoterpenes) of volatile organic compounds (VOCs) in Red and Expo park, respectively. About half of the urban forests’ emissions were from *Populus alba, Cedrus deodara* in Red Park, and *Cupressus sempervirens* and *Cedrus deodara* in Expo Park.

**Figure 6.** Monthly isoprene and monoterpenes emitted by Expo and Red park of Tbilisi in 2018.

**Hydrology effects**

Trees in Red and Expo park in 2018 transpired 3039.6 and 3334.2 m$^3$ of water, respectively, with highest values in July (651.8 m$^3$ for Red Park and 715.6 m$^3$ for Expo Park). The annual avoided runoff was 200.5 m$^3$ in Red Park and 269.5 m$^3$ in Expo Park with highest values in summer, in particular June (28.6 and 37.5 m$^3$ for Red and Expo Park, respectively).

**Figure 7.** Monthly transpiration and avoided runoff by trees in Expo and Red Park of Tbilisi in 2018.
DISCUSSION

Urban forest structure and ecosystem services provision

Our modeling analysis shows that Red and Expo Park supply important environmental services to the city of Tbilisi. These urban forests are located in the urban fabric and have a similar size (3.3 ha for Red Park vs 3.2 ha for Expo Park) but have a different number of trees (1030 for Red Park vs 694 for Expo Park).

There are more species in the Expo Park (62) than the Red Park (52), although with only a few trees each, and about half (≈ 47%) are evergreen in both urban forests, with some conifers dominating such as *Cupressus sempervirens* and *Cedrus deodara*.

Despite the different tree density (312 trees/ha for Red Park vs 217 trees/ha for Expo park), tree cover in Expo Park (1.8 ha) is greater than Red Park (1.5 ha) because there are larger trees as shown by basal area (32.7 m² for Red Park vs 53.6 m² for Expo Park) and this clearly affects the amount of carbon stored by the forests (126.5 t for Red Park and 198.4 t for Expo Park) (Nowak and Crane, 2002). However, Red park's annual carbon sequestration (4.7 t) is slightly higher than Expo Park (4.6 t). This result is mainly due to a higher number of trees in open light conditions (Crown light exposure (CLE) 4-5) which have a larger growth base (Nowak et al. 2008) (Red park – CLE 0-1: 125, CLE 2-3: 535, CLE 4-5: 370 vs Expo park – CLE 0-1: 98, CLE 2-3: 338, CLE 4-5: 258). Despite the higher tree density, the smaller size of the trees reduces the competition for light which promotes growth in diameter and thus carbon sequestration.

The total pollution removal rate was 6.1 and 6.7 g m⁻² for Red and Expo Park, respectively. The highest removal rate was for O₃ (3.3 g m⁻² for Red Park and 3.6 g m⁻² for Expo Park), then NO₂ (1.7 g m⁻² for Red Park and 1.9 g m⁻² for Expo Park), SO₂ (0.6 g m⁻²), PM₂.⁵ (0.5 g m⁻²), and CO (0.1 g m⁻²). Comparing these values with other modeling studies, the total removal rate per unit tree cover is higher than other European cities, such as Munich (5.3 g m⁻²) (Pace et al. 2018) or Strasbourg (5.1 g m⁻²) (Selmi et al. 2016), but lower than London (8.7 g m⁻²) (Rogers et al. 2015) or the calculated average for the US cities (7.5 g m⁻²) (Nowak et al. 2006) considering the PM₂.⁵ removal rate instead of PM₁₀ (Nowak et al. 2013). Regarding VOC emissions from trees, it is interesting to note that the two parks, which have similar composition, differ greatly in isoprene emissions (20 vs 45.9 kg) due to the presence of *Populus alba* in Red Park as dominant species which is a high emitter (Fitzky et al. 2019).

Trees in Red and Expo Park also provide a beneficial cooling effect by transpiring in the warmer months up to 1.7 l m⁻² day⁻¹ in July. Similar results have been modeled (Rötzer et al. 2019) and measured (Rahman et al. 2017) in Germany on broadleaves showing an energy reduction through cooling and shading of 75
kW m$^{-2}$ and an air temperature reduction up to 3° within the canopies (Rahman et al. 2017). Furthermore, the presence of these green infrastructures within the city allows to promote the infiltration in the soil and reduce the water runoff (Berland et al. 2017) (35.9 and 33.7 m$^3$ ha$^{-1}$ yr$^{-1}$ per unit of leaf area in Red and Expo park, respectively). These values are high in terms of efficiency considering the total precipitation of 397.6 mm in 2018 and in the same range of London (32.6 m$^3$ ha$^{-1}$ yr$^{-1}$) (Rogers et al. 2015), but lower than Kyoto (130.3 m$^3$ ha$^{-1}$ yr$^{-1}$) (Tan et al. 2021) where the amount of precipitation is also higher.

**Urban green planning in Tbilisi and future prospective**

In Georgia’s reality, until the very recent years, the urban green infrastructure, as an essential part of the city’s complex and diverse fabric, was not considered as a part of the agenda for urban spatial planning, design and/or as a necessary instrument for city’s resilience. But there are some positive developments in the urban policies of Tbilisi as well: in 2018, after long and protracted process of designing of General Land Use Plan of Tbilisi, the Plan had been approved and the priorities for development of urban green infrastructure had been well defined (Tbilisi land use concept, 2017).

The Tbilisi Land Use Plan envisages the protection of natural and man-made landscapes, supporting their protective and restorative functions, enhancing measures for protecting biodiversity and the minimization of natural and industry-born risks, increase and development of new green recreational areas along the river and in densely populated residential zones. Tbilisi City Hall in the beginning of 2018, had adopted a list of “recommended tree species, best suited for Tbilisi municipal territory’s landscape and the climate” (Tbilisi city hall, 2018). As the City government order states, the Department of Environment and Green spaces, during the planned green infrastructure works, will use the approved species list as a guidance. The list comprises species marked as a “priority” species, and others marked as “recommended” ones. Some of the suggested species are also among the dominant species in the Red and Expo parks (Tab. 3). Considering carbon sequestration, Cedrus deodara, Cupressus sempervirens, and Fraxinus americana are the species that accumulate more carbon per unit of canopy cover. Fraxinus americana, Picea pungens, Platanus orientalis, allow for a greater reduction in stormwater runoff, and Fraxinus americana, Picea pungens, Tilia cordata contribute to remove a higher amount of air pollutants. Fraxinus americana, Fraxinus excelsior, Tilia cordata, and Tilia platyphyllos are non-emitting species of VOCs.

In general, evergreen species in Tbilisi, despite a longer growing season, are not able to provide more ecosystem services than deciduous species. For example, rainfall is abundant in spring-summer season, which allows for greater fine particulate matter removal (Nowak et al 2013; Pace and Grote, 2020; Pace et al. 2021a), as well as greater rain interception and thus reduced runoff (Fig. 5-7). Furthermore, rainfall allows to increase the soil water content and ensures a higher stomatal conductance and therefore a cooling effect and uptake of gaseous pollutants (Morani et al. 2014; Pace et al. 2021b). Another important selection criterion is the choice of non-VOC emitting species (Churkina et al. 2015), such as species within the genus Acer, Fraxinus and Tilia, to ensure high ozone removal (Sicard et al. 2018) by preventing its formation (Calfapietra et al. 2013).
Table 3. Results per unit of canopy cover of dominant species in Red and Expo parks. [**Expo Park, *Red Park – R=Recommended, P=Priority**]

| Dominant species parks       | Suggestion | Carbon sequestration (g m⁻² yr⁻¹) | Avoided Runoff (l m⁻² yr⁻¹) | Pollution removal (g m⁻² yr⁻¹) | Total VOCs (g m⁻² yr⁻¹) |
|------------------------------|------------|-----------------------------------|-----------------------------|-------------------------------|-------------------------|
| Aesculus hippocastanum**     | R          | 259.1                             | 18.2                        | 8.1                           | 0.3                     |
| Cedrus deodara*              | P          | 473.4                             | 16.8                        | 7.6                           | 4.1                     |
| Cupressus sempervirens**     | R          | 403.1                             | 17.7                        | 7.8                           | 4.1                     |
| Fraxinus americana**         | P          | 397.9                             | 24.3                        | 10.8                          | 0                       |
| Fraxinus excelsior**         | P          | 242.8                             | 10.5                        | 4.7                           | 0                       |
| Ligustrum japonicum**        | P          | 10                                | 12.3                        | 5.4                           | 12.9                    |
| Morus alba*                  |            | 212.1                             | 16.2                        | 7.3                           | 1.8                     |
| Picea pungens**              | R          | 314.8                             | 21.9                        | 9.7                           | 14.5                    |
| Platanus orientalis**        | P          | 219.4                             | 20.4                        | 7.6                           | 4.5                     |
| Platycladus orientalis*      |            | 352.8                             | 9.7                         | 4.4                           | 1.7                     |
| Styphnolobium japonicum*     | P          | 181.9                             | 11.4                        | 5.1                           | 5.9                     |
| Tilia cordata**              |            | 349.4                             | 18.4                        | 8.2                           | 0                       |
| Tilia platyphyllos*          | P          | 248                               | 12                          | 5.4                           | 0                       |

The value and role of urban forests

The topics of urban green infrastructure, urban forestry, and ecosystem services, as a conceptual framework for the nature and society relations, is relatively new scientific discipline and it had started its development form early 70-ies of XX century (Gomez-Baggethun, 2009). Despite the popularity, inclusiveness, multifunctional principles, and political appeal of ecosystem services approaches in urban planning, the concept of natural benefits, flowing from nature to society, has very often difficult times of realization and practical applicability in the real-life situations, especially at the stages of spatial urban planning and managerial decisions (Turkelboom et al. 2018). Urban parks, as an important part of the city’s infrastructure are generally recognized as an important element of the citiescape. They provide city and its inhabitants with pleasant, livable beautiful environment and act as important biodiversity hotspots in the city space (Nielsen et al. 2014). Urban parks, gardens, other green areas often give the cities their major identity and a recognizable “look” due to the uniqueness and the beauty of the natural, or man-made environment, interwoven in urban fabric (as Englischer Garten in Munich, Germany, or the Central Park in New York City, USA). Nevertheless, also very often, the green spaces, urban parks, or other green elements of the city, are not considered as “drivers” and “determinants” of the city’s land-use policies, general urban development, or sustainable urban practices.

The lack of knowledge is still present in ecology and ecosystem services of urban parks, when small urban green spaces and parks were often regarded as being an attribute, or a decorative element of municipal and urban open space systems due to assumptions that their small size and isolation restricts their
capacity of delivering ecosystem services, i.e., making them ecologically less valuable than large city and county parks (Forsyth and Musacchio, 2005). Besides, the studies of ecological benefits and functions of urban green spaces are necessary for putting more focus on the type and quality of park vegetation (Nordh and Olafsson, 2021), its ecosystem functions and benefits than on the share and measure of green space per capita, as it is often presented in general urban literature (Badiu et al. 2016). A small urban forest like Expo park can offset CO$_2$ emitted by more than 80 Georgian citizens (2.14 t per capita, www.worldometers.info) and fine particles of about 40 diesel cars EURO IV with an annual mileage of 2000 km (assuming the concentration of PM$_{2.5}$ is half of the total mass of particles 0.025 g/km).

This kind of scientific studies may significantly contribute to the gaps in general knowledge of cities, as ecological systems with its multiple elements and complex interactions between ecosystems, the climate, biotic and abiotic parts of the nature, urban ambient air, soil, human activities and in general, between the social and ecological functions of green spaces in the urban context. It must be emphasized that the topics related to urban parks’ contribution to human health and the well-being of the city dwellers is a less studied area though sufficient scientific evidence exists that urban parks directly benefit the physical and mental health of city population (Jasmani, 2013), and number of health and well-being benefits could be well grouped, as increased physical activity, increased life expectancy and reduced health problems and the promotion of psychological health and mental well-being (Lafortezza et al. 2013). Besides, the presence of nature supplements the human life and fills it with emotions and various senses (Chiesura and de Groot, 2003). All those positive impacts could be named as social and psychological services, which directly or indirectly contribute to the livability, comfort, positive image and attractiveness of the city, or the town (Chiesura and de Groot, 2003; Yessoufou et al. 2020).

Additionally, the provision and the availability of urban green spaces as a common, shared natural asset for all urban residents, poses ethical questions of environmental justice, equitable distribution of urban green infrastructure and their accessibility to various groups of urban population (Selmi et al. 2020). Unfortunately, the social-environmental services, provided by the urban parks is poorly studied in Georgia and in future, the research questions related to the equality, equity and just distribution of urban green infrastructure, as a social aspect of sustainable development of Tbilisi, could be of major priority for urban studies in Georgian research institutions.

CONCLUSION

Urban green infrastructure and park trees contribute to improving air quality and mitigating climate change and its effects in cities. These features of the urban vegetation are well recognized though less implemented in managerial, or other climate-conscious and health safety decisions of the local administrations. In this study, we showed the impact and the environmental importance of trees in Tbilisi’s two urban parks using for the first time the i-Tree Eco model in a Southern Caucasus city. The evaluation of ecosystem services provided by urban forests and the selection of suitable and effective tree species for future reforestation programs, are essential for a proper planning and management of urban greening and the sustainable development of rapidly sprawling and growing cities such as Tbilisi.
DECLARATIONS

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Authors’ contributions
LA designed the research, carried out the field measurements, and wrote the main text. RP contributed significantly to the design, analysis and discussion of results, and writing of the text.

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Figure 1

Vaso Godziashvili and Expo Georgia parks, Tbilisi aerial photograph (designed by Giorgi Kirkitadze and Levan Alpaidze, 2020) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 2

Weather data used for model simulation of Tbilisi in 2018. From top to bottom: daily average photosynthetically active radiation (PAR), daily average air temperature, and total monthly precipitation.
Figure 3

Daily average pollution concentration of CO, SO2, PM2.5, PM10, O3, and NO2 in Tbilisi (year: 2018).
Figure 4

Species that store (carbon storage) and sequester (carbon sequestration) the most carbon in Expo and Red park.
Figure 5

Monthly pollution removal of CO, NO2, O3, PM2.5, and SO2 from Expo and Red Park of Tbilisi in 2018.
Figure 6

Monthly isoprene and monoterpenes emitted by Expo and Red park of Tbilisi in 2018.
Figure 7

Monthly transpiration and avoided runoff by trees in Expo and Red Park of Tbilisi in 2018.