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Green in the City: Estimating the Ecosystem Services Provided by Urban and Peri-Urban Forests of Tbilisi Municipality, Georgia

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Abstract: Green spaces play a significant role in providing essential natural services to cities. This study aims to estimate Tbilisi's green cover and identify the surface cover classes, volumes, and values of ecosystem services. The study area embraces the territory of Tbilisi municipality in its legal/administrative boundaries, which is equal to 502 sq. km. We use the i-Tree Canopy program (v.7.1) to identify the surface cover classes and quantify and price the ecosystem services provided by Tbilisi's urban and peri-urban forests. The analysis includes the identification and distribution of the surface classes of the territory of Tbilisi, which is presented as follows: grass/herbaceous (38.71% +/− 1.36%), various impervious surfaces (approx. 21.18%), soil/bare ground (8.61% +/− 0.78%), trees/shrubs (28.55% +/− 1.26%), and water (2.95% +/− 0.47) surfaces. Analysis revealed the volumes of the removal of atmospheric pollutants, the annual removal of atmospheric carbon, and the total carbon stock fixed in the trees and shrub vegetation and provided the monetary values, expressed in US Dollars rounded per sq. km, of stored and sequestered carbon and pollution removal on the studies territory. The results showed that the annual removal of air pollutants (CO, NO_2, O_3, SO_2, PM2.5 and PM10) totals 1227 tons or 2.444 t/sq.km. The average annual carbon sequestration by trees and other vegetation is 43.72 thousand tons (87.09 t/sq.km), with an approximate value of 8.22 million USD. The trees are storing 1097.9 kilotons of carbon (2187.95 t/sq.km) with its CO_2 equivalent of 4025 kilotons. The estimated value of this service equals 206.4 million USD. This type of analysis of surface covers and ecosystem services has been performed in Tbilisi for the first time. The study revealed the significant magnitude and the great potential of "green benefits" provided by the urban vegetation to the city. It gives additional arguments for better utilization of this knowledge for advanced planning of the urban green infrastructure of Tbilisi for strengthening its sustainable and resilient development.

Keywords: urban ecosystem services; urban and peri-urban forests; Tbilisi municipality; ecosystems valuation; carbon sequestration; carbon storage

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1. Introduction

Currently, urbanized spaces with large built-up areas and high population density occupy only a small segment of the global surface, ranging up to 3% [1]. In the meantime, they are responsible for a large share of anthropogenic impacts on the biosphere [2]. Cities produce only a small fraction of total goods and ecosystem services, compared to the ever-increasing demand from urbanized areas [3], where more than half of the global population currently lives and about 60% of humanity will live in 2030 [4].

Besides, according to the 2020 UN-HABITAT report, the areas under cities and urban settlements are currently growing faster than the population of those cities, contributing to accelerated urban sprawl [5].

The benefits of green spaces, urban parks and generally, of urban green infrastructure, which consists of vegetated green surfaces, such as parks, urban trees and forests, grasslands, private gardens or green cover of cemeteries in big cities, are well acknowledged [6].

Trees play essential roles in maintaining the optimal conditions of the urban environment (air humidity, temperature mitigation, preservation of soil cover on erosion-prone sites, etc.), its soils and natural or semi-natural habitats, situated on various urban surfaces [7]. Trees and shrubs vegetation absorb pollutants from the air, affect temperature regulation, support biodiversity and maintain the ecological equilibrium in urban areas [8].

Trees in urban settlements also have multiple benefits and use that include but are not limited to the following:

1. Social benefits, which encompass recreation, development of better living and working conditions, positive influence on the mental and psychological health of citizens, cultural aspects, etc.
2. Architectural and aesthetic benefits, which include the tree and vegetation areas, incorporated in grey urban infrastructure, shaping and beautifying urban environment with various natural forms, colors and textures, providing cities with unique landscapes and views.
3. Benefits for the local climate and urban climatic conditions, which assume temperature regulation and cooling, humidity control, a decrease of air pollution, masking urban noise, reduction of "urban heat island" temperatures, controlling the soil erosion and the flood water volumes.
4. Ecological benefits that assume preserving local habitats and flora and fauna of the cities.
5. Economic benefits include increased property values (near the urban parks and tree-canopied settlements), tourism, and overall appreciation and beauty of the urban locations with natural and green infrastructure [9].

Urbanization caused the detachment of humans from nature and drastically reduced natural areas in cities so that in major cities, the green spaces such as urban parks and gardens, tree-lined streets, the vegetation of cemeteries and remnant plots of natural and semi-natural forests or herbaceous vegetation, urban and peri-urban forests are typically the only chance for citizens to get in touch with nature [10].

The focus on urban and peri-urban forests is made due to the overall benefits provided by forest systems to urbanized areas, which encompass an array of benefits (ecosystem services, recreational opportunities, economic prospects, other), directly funneled to cities and urban dwellers [11]. One of the most appropriate measures of mitigating urbanization and its effects on local biology, hydrology, climate and overall urban ecological, social and economic conditions are well described by the concepts of low-impact development (LID) [12], biophilic urban design [13] and by the advancement of more permeable and vegetated areas in cities [14].

A proper understanding of the dynamics of urban expansion and its effects on urban and peri-urban environments, greenhouse gas emissions, and air, soil and water pollution processes, is needed. As a relief to counter the negative consequences of urban expansion and as a cost-effective apparatus for mitigation of the urbanization effects, the installation of green urban infrastructure and the likely nature-based solutions are proposed and tried [15]. This might become a good mitigation tool, especially in developing countries with less developed and ineffective urban planning, and as suggested, should become a part of the global urban planning agenda [16].

The current urbanization process, in its variations and particularities, in several parts of the world, stresses the need to study and understanding the developments in the vector of human-nature relations, especially in an urban setting, where the intensity of human impact on nature is maximal [17].

A conflict between city and nature, development and preservation, safeguarding and growth, the necessity of urban densification and valuing nature and its beneficial influence on the urban environment is evident [18]. This dichotomy affects modern urban planning and sustains the confrontation between development needs and nature preservation efforts [19]. Thus, the research on urban territories' ecological and economic potential may add extra arguments for resolving this fundamental confrontation of rivalling interests represented by urban administrations, businesses, developers, local dwellers and the plethora of civic activist associations.

The fast-track urbanization process signifies the need to have comprehensive information on the distribution of various urban surfaces (densely built urban areas, pervious and impervious land plots, various urban and peri-urban areas with a green cover, unmaintained and maintained natural habitats, open ground/bare soil plots, water areas, remnant natural areas, etc.) and understanding the character of impacts of ecosystem services [20]. This is especially crucial in urban setting for assuring the well-being and maintaining the optimal environmental conditions for the city, as a whole system, for its inhabitants.

This research aims to study the surface cover of Tbilisi and the ecosystems services, associated with urban green infrastructure. The goal of this study is twofold: (i) estimating surface cover classes of Tbilisi municipality, and (ii) defining the volumes and the values of the ecosystem services provided by the trees and other green infrastructure to the city. This research employed the i-Tree Canopy platform to serve these goals and check its efficiency for our particular case. The testing of this software for parametrization of Tbilisi ecosystem services also was an important objective of the study.

2. Materials and Methods

2.1. Study Area

Tbilisi, the capital city of Georgia, is located between mountains, along the river Mtkvari (Kura) ravine. It occupies 502 sq.km in the administrative boundaries and gives home to almost 1.2 million inhabitants [21].

The city was founded in the 5th century AD and according to historical sources [22] was surrounded by suburban gardens and thick forests. However, in the Middle Ages, frequent foreign invasions destroyed great part of them [23]. Destruction of indigene forest cover of Tbilisi (mostly dominated by oak-wood, beech, hornbeam and ash-tree forests) has continued during industrialization in the late 19th and early 20th centuries, when Tbilisi was a regional center of the Russian Empire. The capitalism development in Georgia increased demand in wood for heating, manufacturing goods and constructing Transcaucasian railroad. These activities resulted in massive cuts of urban and peri-urban forests and the change of landscapes in Tbilisi metropolitan area [24]. This process partially continued in the 20th century during industrial development under the Soviet rule.

The re-establishment of independence and national statehood in 1991 was followed by economic downfall and dramatic changes in the city's social fabric and economic system, characteristic of many post-Soviet transitional countries. Today, Tbilisi is a modern metropolis with well-developed urban and economic infrastructure. It enjoyed dramatic territorial expansion both during the Soviet Era (1921–1991) and in the times of independence so that the municipal area increased more than tenfold and the population—sixfold, over the last century [25]. Such a growth, in most cases, had occurred at the expense of agricultural lands and green cover of the Tbilisi municipal territory [26].

Since the natural forests of Tbilisi had been systematically destroyed and cut, artificial afforestation was introduced during the post-WWII decades. The stands of various pines (*Pinus nigra*, *P. eldarica*, *P. sosnowskyi*) dominate among artificial tree forests. These forests are essential in maintaining the optimal ecological parameters (humidity, temperature and flood water regulation, soil protection at rocky slopes, etc.) at the edges of Tbilisi municipality.

For example, the forested lands of former suburban villages Kojori, Kiketi and Betania in the west and south-west, and forests of Saguramo Nature Reserve in the north and north-east, are the closest richly wooded areas; those territories compose the 'green protective belts' of Tbilisi. They are organically connected with densely built city neighborhoods, such as Vake, Saburtalo, Digomi, and Gldani (Figure 1).

In general, the inner urban green spaces of Tbilisi municipality are mainly represented by man-made and natural green zones, such as parks, public gardens, and tree-lined streets, whilst urban and peri-urban forests encircle the municipal territory. In total, green areas cover about 145 km^2, which is 28% of the total area of Tbilisi municipality, and is less than built urbanized space (158 km^2 or 32% of the total) [27]. Other land use areas of Tbilisi municipality include water bodies (3% of total), agricultural lands (4% of total) and the category of other areas (33%), comprising bare soil, rocks, grassland, etc. [28].

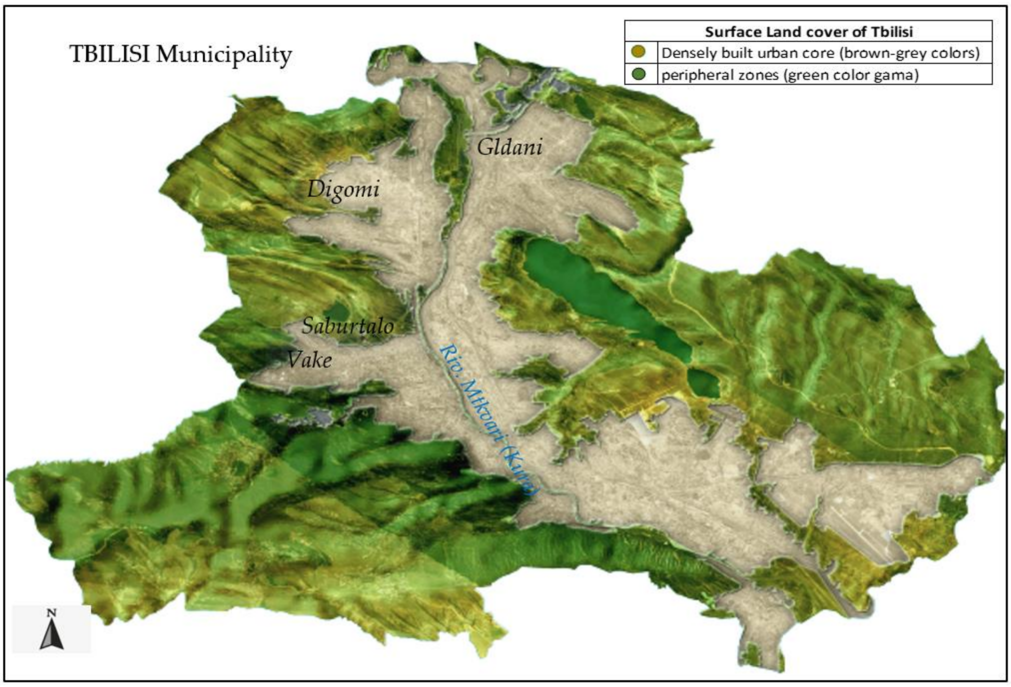

Figure 1. Distribution of densely built urban core and peripheral landscape zones in Tbilisi Municipality. Schematic image -The image is made by merging of isohypse and aerial photos (source: City Institute Georgia. 2017. Tbilisi Land-use Plan. Vol. 4. Tbilisi Land Use Concept [29] (Adapted with permission from ref. [29]).

The vicinity of forests to residential districts of Tbilisi is not even: in some cases, they are close to residential zones (10–15 km), and in other cases—further away. Peri-urban areas with natural vegetation stretch from the north to south-east axis along River Mtkvari canyon (Figure 1).

Overall, Tbilisi's green cover, including various natural, semi-natural or artificial green spaces (as parks, gardens, cemetery vegetation, remnant vegetation, other) is scarce. Data, partially available from 2001, state that the green space in Tbilisi's densely built urban core, calculated per capita, is less than 5.6 m^2 [30], whereas the European average is about 18 sq. meters per capita [31–33] and in some cities of Europe, green space's per capita indicator is much higher (Ljubljana—560; Leipzig—254, Vienna 120, Stockholm—70, Nantes—57, Lisbon—37, Prague—36 and Paris—12) [31–33].

The above comparisons explicitly prove that Tbilisi's green infrastructure is at its minimum and detailed study of Tbilisi's urban vegetation and surface cover is much needed for further plans of improving of the deficit of green spaces.

Additionally, given the great diversity of landscapes, nature and the territory's geographical features, the urban and suburban lands of Tbilisi have significant diversity. They greatly influence local microclimate and ecosystems. Congruently, there is a great diversity of vegetation in the suburban zones. Due to complex topography and different climatic and geographic conditions (elevation, precipitation, temperature and sunlight exposure), closer to the municipality's outer limits, mainly deciduous forests (oak-wood, beech, hornbeam, ash-tree, elm-tree, aspen, spruce and Caucasian oak—*Quercus macranthera*), shrubs and steppe vegetation cover large areas. Unfortunately, forests in flood meadows and river canyons are almost destroyed and represented by tiny fragments of black poplars and white willows on the River Mtkvari terraces.

There is an unequal distribution of natural services of urban ecosystems within the municipal territory. In peri-urban and suburban areas of Tbilisi artificial forests and natural stands play an essential ecological role (Figure 2). In northern, southern and south-eastern low-moistening edges of Tbilisi municipality, arid sparse forests are allocated, with Junipers as a dominant genus. The limited availability, the extent of forests and scarcity of urban green is observed in the city core. Its uneven and fragmented distribution within the built areas of Tbilisi makes the study of the actual green cover of the city more valuable for further urban planning.

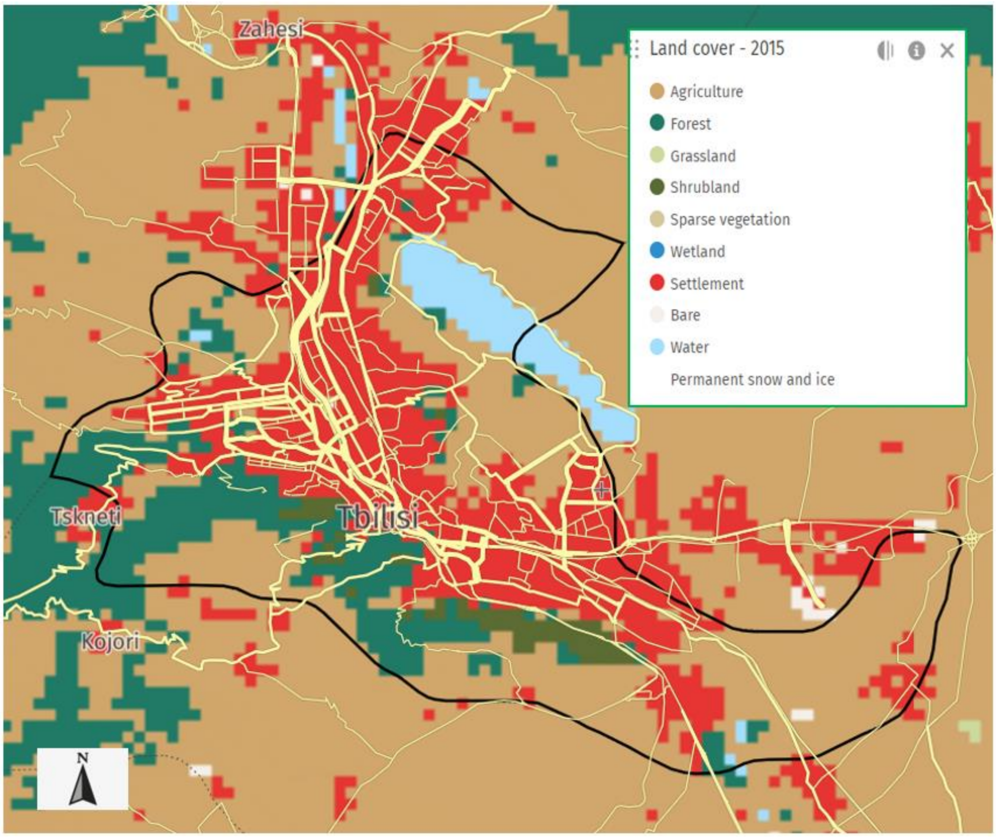

Figure 2. Schematic Map of Tbilisi Municipality, displaying land-use and land cover types (source: https://www.globalforestwatch.org, accessed on 22 November 2022) [34].

Tbilisi's surface cover classes has not been studied since the 1980s. Given the absence of detailed and updated green inventory of Tbilisi [30], the emphasis of our research has been given to identifying the various types of surfaces, within Tbilisi municipal territory.

2.2. Data Acquisition/Collection and Method

The distribution of tree canopy cover of Tbilisi is not well documented and since 1988, Tbilisi municipality did not conduct a new study of tree inventory so far [30]. However, some data and cartographic depictions may be found on the globalforestwatch.org website (accessed on 23 November 2022) [34], where the global information on tree canopy cover and the cover changes are collected for selected locations during the years of monitoring (Figures 2 and 3). As the website explains, the algorithm of globalforestwatch.org approximates the results by sampling the selected area. Results are more accurate at closer zoom levels.

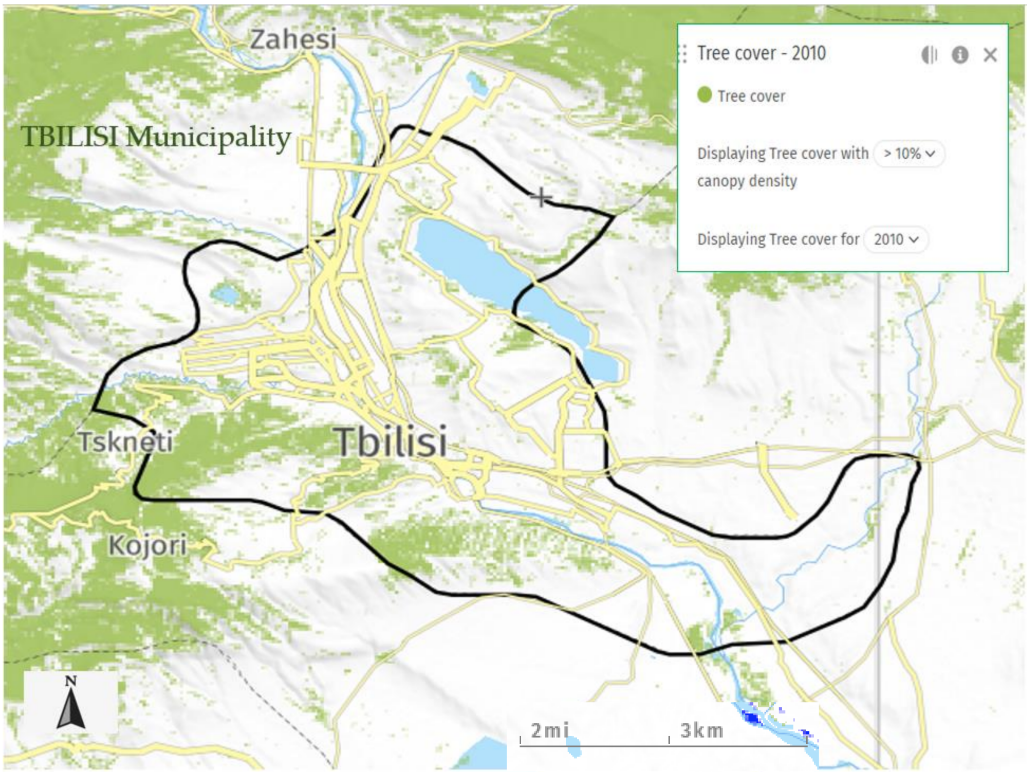

Figure 3. Map of Tbilisi Municipality, displaying tree cover with 10% and higher canopy density (Lat. Lon.: 41.70493, 44.76485, zoom: 10.48) (source: https://www.globalforestwatch.org/, accessed on 23 November 2022) [34].

This research employed the i-Tree Canopy v. 7.1 software [35,36], to categorize and identify the various urban surfaces of Tbilisi and its relevant use. Research analyzed the overall urban fabric of the city and its surroundings, and the ecosystem services, provided by the urban and peri-urban forests, and other natural green spaces.

I-Tree Canopy uses Google's aerial images of the study area to produce the statistical estimates of tree and other land cover types, such as grass, built structures, urban grey infrastructure and other impervious surfaces. Random dots are placed in the defined area of interest, and the user identifies the land cover class at the dot centre (a yellow cross pointer). Cover classes are defined by the user. With 1289 random points, the cover estimate's standard error (SE) appeared to be less than 1.3 percent. Details on calculating sampling error from photo-interpretation are given in Nowak [35].

Identification of the study area: for delimitating the Tbilisi municipality legal boundaries, the shape files were uploaded to i-Tree Canop y software. It links the uploaded boundary coordinates with Google Earth and depicts a geographical configuration of the selected territory. The following steps were undertaken for starting the study:

1. Defining the research territory using the shape files integrated into the Google Earth map (Map data 2022 Google).
2. Selecting the land-cover categories/classes (from the program menu) as follows: (1) Grass/Herbaceous (H); (2) Impervious buildings (IB); (3) Impervious roads (IR); (4) Impervious other (IO); (5) Soil/bare ground (S); (6) Tree/shrub (T); and (7) Water (W).
3. Creating a canopy database: the i-Tree Canopy program automatically randomly produces geographical points in the selected area, pinpointing those generated points on the Google Earth map. The user gives the corresponding surface category to each generated point until a sufficient geographical sample volume is reached. Fixing at least 1000 points is recommended; therefore, 1289 study points for research has been selected for this research (Figure 4).

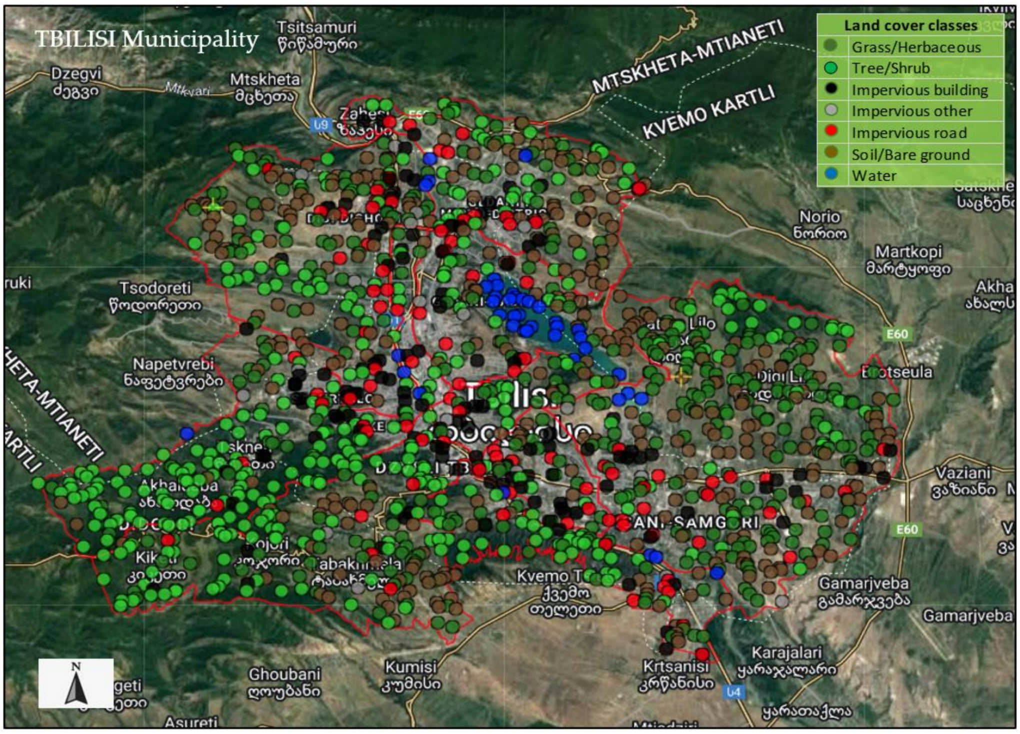

Figure 4. Distribution of land cover classes in Tbilisi municipality in current boundaries (prepared with i-Tree Canopy tool v.7 [35,36], indicating 1289 randomly selected study points).

Figure 4 shows the final map/sketch layout after all three steps have been undertaken. Randomly selected land cover points correspond to the density of 38.9 points per hectare. Generated data was used to estimate the proportion of destined land surface cover and associated standard error (SE):

SE (Standard Error) = $\sqrt{(p*q/N)}$
N—the number of all randomly selected study points;
$N = 1289$
n = number of those study points that represent Tree/Shrubs category;
$n = 368$
$p = n/N$ *(i.e.,* $368/1289 = 0.285$*)*
$q = 1—p$ *(i.e.,* $1—0.285 = 0.715$*)*
SE (Standard Error) = $\sqrt{(p*q/N)}$ *(i.e.,* $\sqrt{(0.285*0.715/1289)}$*);*
$\sqrt{0.285*0.715/1289} = 0.01257$*, or SE of 1.257%.*

Thus, in this study, the canopy cover of Tbilisi municipality territory is approx. 28.55% (+/−1.26). More information about the data is available in Appendix A.

3. Results and Discussion

The study results show that "Grass/herbaceous" is the dominant land cover class in the city and occupies 38.71% of total territory; it is followed by the "Tree/shrub" (28.55%), "Impervious buildings" (11.33%), "Impervious roads" (9.23%), "Soil/bare ground" (8.61%), "water bodies" (2.95%) and "other impervious" surfaces (0.62%) (Table 1).

Table 1. Distribution of surface cover classes in Tbilisi, analyzed by i-Tree Canopy (v.7) software.

Surface Cover Class Description	Number of Points Surveyed	% of Land Cover (SE *)	Area (in km^2) (SE)
Grass/Herbaceous	499	38.71 (1.36)	193.73 (6.79)
Impervious buildings	146	11.33 0.88)	56.68 (4.42)
Impervious other	8	0.62 (0.22)	3.11 (1.10)
Impervious road	119	9.23 (0.81)	46.20 (4.03)
Soil/Bear Ground	111	8.61 (0.78)	43.09 (3.91)
Tree/Shrub	368	28.55 (1.26)	142.87 (6.30)
Water	38	2.95 (0.47)	14.75 (2.36)
Total	1289	100.0	500.44

*—SE—(+/−) Standard error in parentheses.

3.1. Pollution Removal

In addition to revealing the different surface cover classes of Tbilisi municipality, the research estimated the various ecosystem services, provided by trees (and shrubs). The ecosystem services provided by the trees and other green infrastructure to Tbilisi has never been researched so far.

The ecosystem services, estimated by i-Tree Canopy tool, included the following: (a) Carbon sequestered, annually by trees and Carbon stored in trees, in kilotons (this is the fixed Carbon in tree stems and branches) (Table 2); (b) Carbon monoxide, removed annually (in tons); (c) Nitrogen dioxide, removed annually, in tons; (d) Ozone, removed annually, in tons; (e) Sulphur dioxide, removed annually, in tons; (f) Particulate matter less than 2.5 microns (PM 2.5), in tons; (g) Particulate matter greater than 2.5 microns and less than 10 microns (PM 10), removed annually, in tons. The data of carbon sequestration and storage and the removal of various pollutants are provided in Tables 2 and 3 below.

Table 2. Tree Benefit Estimates: Carbon (Metric units), Tbilisi, Georgia, 2022 (estimates, using random sampling statistics of i-Tree Canopy on 15 August 2022).

Description	Carbon (1000 Metric Tons, i.e., Kilotons)	(+/−) SE	CO_2 Equiv. (1000 Metric Tons)	(+/−) SE	Value (USD)	(+/−) SE
Sequestered annually by trees	43.72	1.93	160.30	7.06	$8,219,181	362,166
Stored in trees (Note: this is not an annual rate)	1097.95	48.38	4024.81	177.39	$206,414,476	9,095,354

The data analysis revealed that the average total amount of the different pollutants' removal provided by the trees in Tbilisi in 2022 was 1227.74 metric tons (i.e., 0.02445 t/ha). The results of air pollutants' removal are well compared to those of Tbilisi 's two urban parks, studied by Alpaidze and Pace [37], where the average removal rate of the same air pollutants in the Expo Georgia urban park, was 0.0373 t/ha. For a comparison, very similarly, the annual rate of air pollutant removal by trees in New York City in 2018, was a bit lower—0.0131 t/ha [38].

The largest volume of the air pollutant removed was the Ozone (O_3 removed = 784.17 tons); the removal rate of Particulate Matter ($PM_{2.5}$)—the most dangerous pollutant for human respiratory system—was 38.10 tons. If we compare this service to other cities, we may see that the $PM_{2.5}$ removal rates, calculated per sq. km were the following (Table 4):

Table 3. Ecosystem Services, provided by the tree cover of Tbilisi municipality—Tree Benefit Estimates (metric units).

Description	Amount (t)	(+/−) SE	Value (USD)	(+/−) SE
Carbon Monoxide (CO) removed annually	14.44	0.64	$1354	60
Nitrogen Dioxide (NO_2) removed annually	78.74	3.47	$2331	103
Ozone (O_3) removed annually	784.17	34.55	$121,419	5350
Sulfur Dioxide (SO_2) removed annually	49.62	2.19	$407	18
Particulate Matter less than 2.5 microns, removed annually	38.10	1.68	$250,995	11,060
Particulate Matter greater than 2.5 and less than 10 microns, removed annually	262.67	11.57	$88,147	3884
TOTAL	1227.74	54.10	$464,654	20,474

Table 4. Removal rates of Particulate Matter, PM2.5 (tones per sq. km) in various cities.

Removal Rates of PM by Urban Trees in Various Cities	PM2.5, (Tons per sq. km)
Tbilisi, Georgia	0.076
New York City, New York, USA [38]	0.050
Boston, Massachusetts, USA (Nowak et al., 2013) [39]	0.0547
Chicago, Illinois, USA [39]	0.0456
Syracuse, New York, USA [39]	0.070
Munich, Germany (Pace, 2020) [40]	0.050

As we may conclude from Table 4, the removal rates of $PM_{2.5}$ vary in different cities and the highest rates were indicated in Tbilisi, Georgia (0.076 t/per sq. km) and in Syracuse, New York, USA (0.07 t/per sq. km). The calculations, based on the multipliers for each pollutant, used in the i-Tree Canopy program, indicate that overall value of the ecosystem services provided by all trees of Tbilisi municipality amounts up to USD 464,657.

3.2. Carbon Removal (Carbon Sequestration and Carbon Storage) and the Valuation of Ecosystem Services Provided by the Trees in Tbilisi Municipality

Regarding the Carbon fixed in the trees, and removed from the air (i.e., Carbon sequestration) for the year 2022, we should underline that the Carbon Dioxide itself, is not an air pollutant. The presence of CO_2 in ambient air does not harm the humans directly (only at levels of CO_2 higher than 2000 ppm in confined spaces) [41]. Carbon dioxide is a byproduct of normal cell functioning and it is breathed out of a living organism. CO_2 is also emitted into the air, when hydrocarbon fuels (natural gas, petrol, diesel and coal) are burned, or the gas is emitted by the decaying vegetation [41]. In this study, the Carbon stocked in the trees totals 1097.95 kilotons, and the annual rate of Carbon removal (sequestration) from the air by trees was 43,000 tons (about 160,300 tons of CO_2 equivalent), with SE of +/− 1.93 tons (Table 2).

Table 5, below, provides the comparison of the Carbon sequestration data and the Carbon storage data (Carbon fixed in the trees, given the tree age, species/genus and the climatic conditions) in different cities, allocated in various climatic zones.

Table 5. Carbon removal by urban trees in different cities.

Carbon Removal by Urban Trees in Different Cities	**Carbon Sequestration per Annum, (t/per sq. km)**	**Carbon Stored (t/per sq.km)**
Tbilisi, Georgia	305.05	7660
New York City, USA [38]	300.00	7058
Sacramento, California, USA (McPhearson, 1998) [42]	606.97	33,272
Philadelphia, Pennsylvania, USA [43]	367.84	9564

Table 5 reveals that greatest Carbon sequestration and fixation (storage) rates are indicated in Sacramento, California, urban trees, which are way higher than in Tbilisi, New York City or Philadelphia, which are located in more or less similar latitudes (though with different climatic zones). As McPhearson [42] explains, regarding Sacramento urban trees, the Carbon sequestration and storage figures can be explained by high tree densities in the city (73/ha) and many large, old shade trees in the dense residential zones of the city, where the basal area densities are the greatest in residential land uses. Thus, the importance of high tree densities is a significant influencing factor for Carbon sequestration and storage in urban settings.

The overall benefits in terms of monetary estimation of such services as carbon sequestration and air pollutant removal, amount jointly to approximately USD 8.7 million per annum. Compared to several items of the Tbilisi municipality budget of 2022, it exceeds the annual costs on "Environmental expenses" (approx. USD 4.5 million), "Protection of biodiversity and landscapes" (USD 3 million), "Expenditures for outer urban lighting" (USD 5.6 million), "Revenues for sales of major assets" (USD 4.95 Million), "Development and promotion of local museums" (USD 6.47 million), etc. [44].

Furthermore, the value of the carbon stored (fixed carbon stock, stored in trees, reducing overall Green House Gas—GHG emissions) in Tbilisi trees surpasses USD 206 million (which is not an annual value), and far exceeds, for example, the whole annual budget of the all-transport and road infrastructure construction and repairs and green infrastructure development costs of Tbilisi municipality, combined (approx.88 million USD), for the year 2022 [44].

Besides, those significant benefits and the presence of urban forests and vegetation positively impact the life of city population, beautify its urban environment, and in general, support and contribute to overall well-being of the city, creating a positive living conditions and environment for its dwellers though all listed above, mostly could not be directly translated into the monetary values.

This study also aimed comparing the study data with that from official sources of Tbilisi Municipality [27], as well as the results of another recent research on Tbilisi land use/land cover (LULC) change [28], which applied for remote sensing (RS) and GIS techniques. Table 6 shows that the results received with i-Tree Canopy tool are well comparable to other research results and adequately describe the state and proportions of various land cover classes in Tbilisi municipality.

Table 6. Comparison of selected research and official data of distribution of green spaces (vegetated areas), water spaces and urbanized spaces (densely built, non-vegetated areas) in Tbilisi Municipality.

Cover Class	**Data of Tbilisi City Hall [27]**	**Data by Gadrani et al. [28]**	**Data by Alpaidze & Salukvadze (2022)**
Green space (km^2)	145.5	117.86 ('Green area')	142.87 ('Tree/Shrub')
Urbanized area (km^2)	158.0	190.97 ('Built up area')	149.08 (46.2 + 3.11 + 56.68 + 43.09)
Water body (km^2)	n/a	14.22	14.75 (+/− 2.36)

4. Conclusions

The study revealed that the proportion of green spaces, especially those for recreation and provision of ecosystem services (i.e., parks, gardens, urban forests), is scarce in Tbilisi' s urban core. Comparison of its green cover and overall green space provision (approx. 5 m^2 of green space per capita) to the European average proves that Tbilisi's green infrastructure should be increased and developed yet before that, conducting a detailed inventory of the green urban infrastructure in the City proved necessary.

Besides, the findings of presented study also revealed several important management and environment-related aspects of the urban realm of Tbilisi, such as an uneven distribution of urban green cover, insufficient volumes of environmental services to city inhabitants, the need of further expansion of "green zones" supported and projected by urban planning, especially in the neighborhoods with limited availability and poor accessibility to large urban parks (over 10 ha), or other natural areas. It is especially crucial that the city administrations consider the urban "green" spaces not as "decorative elements" but as a vital urban asset of Tbilisi, important for its inhabitants.

As for urban ecosystem services, provided by the urban and peri-urban trees and other vegetation in Tbilisi municipality, the overall volumes of ecosystem services provided (i.e., 43,000 metric tons of carbon sequestered in 2021 and 1.09 million tons of carbon, stored in trees), and the pollutant removal efficiency (removal of various air pollutants—1244 Metric tons/year, or 0.02445 t/ha) prove to be comparable to those services in other cities of the world and their expansion will positively improve the provision of those important services to the city.

The values of ecosystem services, based on the benefit estimates of the i-Tree Canopy platform, provided by the urban and peri-urban forests of Tbilisi municipality, in monetary terms, are the following: USD 8.219 million for the sequestered carbon and USD 206,414 million for the carbon fixed in the tree bodies. Hence, the overall benefits of carbon sequestration and storage are significant.

The study results revealed an impressive scale of benefits provided by the ecosystem services performed by the trees and other vegetation in Tbilisi municipality.

The study has proved that using the i-Tree Canopy tool eases the data acquisition process and employs the random sampling method for researching various urban surfaces and the ecosystem services of the trees and vegetation housed on various urban green covers. It can partially fill up the information gap, existing due to the lack of systematic inventory, regarding the land cover structure of the city as well as some important parameters of the ecosystem services. This gives us the ground to conclude that the methodology and techniques provided by i-Tree Canopy tool are relevant and efficient for conducting studies on ecosystem services of large urban metropolises like Tbilisi.

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Appendix A

1. Urban heat island (UHI)—Urban Heat Islands are formed in the urbanized areas due to absorption and reflection of the sun's heat into urban environment, resulting in higher temperatures than in outer areas. Urban forms and structures such as buildings, concrete-built roads, trim stones and especially, the dark-colored asphalt cover, glass, plastic and other infrastructure, absorb and re-emit the sun's energy more than the natural bodies such as herbaceous vegetation, forests and water. In urban areas, with high concentration

of these structures, those "hot-spots" become "heat islands" and their day- and night-time temperatures are usually higher than in suburbs (https://www.epa.gov/heatislands, accessed on 24 December 2022).

2. Peri-urban forests and spaces—the transitional territories between urban and agricultural zones, which usually start after the urban borders and represent the natural or agricultural landscapes.

3. Currency is in US Dollars (data rounded). Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 0.306 kt (1000 metric tons) of Carbon, or 1.122 kt of CO_2, per km^2/yr. and rounded. Amount stored is based on 7.685 kt of Carbon, or 28.178 kt of CO_2, per km^2 and rounded. Value (USD) is based on $188,000/kt of Carbon, or $51,272.73 ky of CO_2 and rounded. (Metric units: kt = 1000 metric tons)

4. Currency used is US Dollars (data rounded). Standard errors of pollution removal are based on standard errors of sampled and classified points (1289 units). Air pollution estimates are based on these values in t/km^2/yr. @ $/t/yr. and rounded:

CO 0.101 @ $93.79; NO_2 0.551 @ $29.61; O_3 5.489 @ $154.84; SO_2 0.347 @ $ 8.21; $PM_{2.5}$ 0.267 @ $6587.05; PM_{10} 1838 @ $335.58. (Abbreviations for Metric units: t = tonnes, km^2 = square kilometers). NOTE: the multiplier data, used for various pollutants derived from extensive research of urban forests in the US cities, that has been employed in the i-Tree Canopy model for the year 2022 (Please, visit: https://canopy.itreetools.org/, accessed on 7 November 2022).

5. The concept and prototype of i-Tree Canopy program were developed by David J. Nowak, Jeffrey T. Walton and Eric J. Greenfield (USDA Forest Service); see https://canopy.itreetools.org/, accessed on 7 November 2022).

6. Note that Carbon storage data are not the annual rate!

7. Basal area is the common term used to describe the average amount of an area (usually an acre or hectare) occupied by tree stems.

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