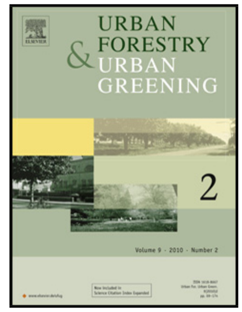
Richter, S., **Haase, D.**, Thestorf, K., Makki, M. (2020):
Carbon pools of Berlin, Germany: Organic carbon in soils and aboveground in trees
Urban For. Urban Green. **54** , art. 126777

http://dx.doi.org/10.1016/j.ufug.2020.126777

Journal Pre-proof



Carbon Pools of Berlin, Germany: Organic Carbon in Soils and Aboveground in Trees

Scarlet Richter, Dagmar Haase, Kolja Thestorf, Mohsen Makki

PII: S1618-8667(20)30594-X

DOI: https://doi.org/10.1016/j.ufug.2020.126777

Reference: UFUG 126777

To appear in: *Urban Forestry & Urban Greening*

Received Date: 23 September 2019

Revised Date: 13 June 2020

Accepted Date: 1 July 2020

Please cite this article as: Richter S, Haase D, Thestorf K, Makki M, Carbon Pools of Berlin, Germany: Organic Carbon in Soils and Aboveground in Trees, *Urban Forestry and amp; Urban Greening* (2020), doi: https://doi.org/10.1016/j.ufug.2020.126777

Carbon Pools of Berlin, Germany: Organic Carbon in Soils and Aboveground in Trees

Authors:

Scarlet Richter[1], Dagmar Haase[1,2,*], Kolja Thestorf[1], Mohsen Makki[1]

[1]Department of Geography, Humboldt Universität zu Berlin, Rudower Chaussee 16, 12489 Berlin, Germany

[2]Helmholtz Centre for Environmental Research, Department of Computational Landscape Ecology, Permsoser Street 15, 04318 Leipzig, Germany

*corresponding author: dagmar.haase@geo.hu-berlin.de

Highlights

- The aim of this study is to estimate the carbon pools of a city like Berlin by combining the organic soil carbon and the carbon found in aboveground biomass.
- This study is the first of its kind to combine the carbon pools of the soil and the vegetation in a city in order to estimate its carbon storage potential.
- We used 432 soil samples across 18 different land uses and we estimated the carbon stored in 596,975 street trees and park trees using biomass equations.
- The results show that more than two-thirds of the carbon present is accounted for by soils; park trees store the most carbon apart from urban forest trees.
- The total soils and tree carbon pool of Berlin was estimated to be 24,087,344 tons, approximately 270 t/ha.

Abstract

The emission of climate-relevant gases, especially carbon dioxide, is often associated with urban areas. However, cities have accumulated organic carbon in their soils and vegetation over centuries and offer important ecosystem services for the city through carbon storage. The aim of this study is to estimate the total carbon storage of the central European city of Berlin by combining the organic carbon (C_{org}) stored in soils and the carbon found in aboveground biomass. We used 432 soil samples that were taken across 18 different land uses in order to estimate the carbon content for each land use based on the laboratory findings of each sample. This large amount of data, which is excellent for such a study, provides an important basis for the evaluation and analysis of the carbon storage potential. Taking into account the degree of soil sealing, the carbon calculations for each individual land use were then transferred to the total area of Berlin in order to produce a spatially explicit carbon map. Soil carbon stocks are reported as units of carbon either as kg/m² or in t/ha for each block. The carbon storage was estimated for both topsoil and subsoil. In addition, we estimated the carbon stored in 596,975 street trees and park trees according to the biomass equations for each tree species. The results show that more than two-thirds of the carbon present is accounted for by soils, which makes them the largest carbon reservoir of the city. Park trees store the most carbon in urban trees apart from urban forest trees. The total carbon stock of Berlin was estimated to be 24,087,344 tons, which corresponds to an approximate quantity of 270 t/ha. The distribution of carbon storage across the city shows the highest values towards the city boundaries. This holds true for the soil as well as the vegetation. The greatest quantities of total carbon are stored in the subsoils of the city's suburbs. This study is the first of its kind to combine the carbon stocks of the soil and the vegetation in a city in order to estimate its carbon storage potential. It provides detailed soil carbon maps and biomass estimations, which can contribute to carbon storage investigations in other cities with similar climatic and ecological conditions.

Keywords

Urban carbon storage, Soil organic carbon, Urban vegetation, Carbon dynamics

1. Introduction

Urban areas have gained increasing attention in past decades as more land area is now transformed from non-urban to urban land uses globally, affecting socio-ecological patterns as well as soil physical characteristics and the spatial distribution of the aboveground biomass (Pouyat et al. 2002, Vogt et al. 2015). The expansion of urban areas exceeds the population growth in those areas by double, resulting in more than 10 % of European land surface being allocated to urban areas (Haase 2009, Scharenbroch 2012, Seto et al. 2012). Changing from natural, self-maintaining ecosystems to anthropogenic and artificially maintained ecosystems comes at the expense of environmental factors like natural soil functions, biodiversity, and habitat sustainability (Churkina 2008, Haase 2009, Vasenev et al. 2018).

These changes not only affect the soils and vegetation but also – and most importantly – the carbon pools and fluxes of urban landscapes, as most of the carbon emissions globally are attributed to urban areas (Pouyat et al. 2002, Strohbach and Haase 2012). The soils of these areas are of particular interest as they may differ greatly from natural soils that have not been influenced anthropogenically (Meuser 2010, Morel et al. 2015). Especially urban activities like construction, housing, traffic or industrial production alter the soil's physical characteristics that contribute to mitigating air and water pollutants (Lehmann and Stahr 2007, Vasenev and Kuzyakov 2018). By depositing organic carbon bearing anthropogenic material (e. g. compost, manure, sludges etc.) or technogenic material (e. g. ashes, rubble, road dust) which contributes to the amount of inorganic and black carbon (Makowsky and Meuser 2007, Meuser 2010) also the natural carbon cycle is disrupted.

This shows that urban soils are a pivotal foundation of the urban environment that provide essential ecosystem services (ESS) to cities from which the population benefits (Washbourne et al. 2012, Edmondson et al. 2014b, Zhu et al. 2018). This includes the storage and sequestration of organic carbon (C_{org}) in particular, because besides the oceans, soils are the largest terrestrial reservoir for C_{org} (Jobbágy and Jackson 2000, Edelmann 2013, Zhu et al. 2018). Soils in temperate regions currently store three times as much carbon as plants (Strohbach and Haase 2012). Through ongoing global change and increasing urbanization rates, urban soils are prone to changes that could alter their carbon content (Dinakaram and Rao 2012, Edelmann 2013). Based on those alterations, these soils are now considered as an important natural source of carbon dioxide (CO_2) in the atmosphere, illustrating the high interaction between soils and atmospheric composition (Jobbágy and Jackson 2000, Yigini and Panagos 2016).

In addition, aboveground biomass and especially trees also greatly interact with the atmosphere as they fix carbon during photosynthesis (Nowak and Crane 2002). Despite the fact that the urban environment differs from forests or parks, trees in such environments still store one third of the existing carbon and thus also represent an important element of the carbon cycle (Vogt et al. 2015, Hayat et al. 2017).

Until today, carbon storage in urban areas has mostly only been viewed from one perspective. Although numerous studies have been carried out on assessing urban soil C_{org} pools, most of the studies calculated the carbon stocks of different urban land use types, only.

Usually, they are based on limited datasets or use localized study areas. (e.g. Pouyat et al. 2002, Canedoli et al. 2020). Only a few investigations estimate soil carbon stocks for a whole city (Edmondson et al. 2012, Cambou et al. 2018) based on evenly distributed data and all occurring urban land use types. Studies that have concentrated on carbon storage in urban soils mostly neglected the carbon that is stored in vegetation and vice versa (Edmondson et al. 2012, Velasco et al. 2016). In a recent study (Lindén et al. 2020), the C_{org} stocks in park soils and vegetation of Helsinki have been estimated in dependency of management practices, vegetation type and age. We are convinced, that holistic approaches of assessing the overall carbon stocks for a whole urban area are needed for developing concepts for mitigating climate change and urban heat stress, for reducing greenhouse gas emissions (GHGs) by carbon sequestration as well as environmental planning. In terms of global and climate changes, it will be important to integrate both approaches into one study in order to estimate the total carbon that is stored within the urban boundaries, which will also help us to understand feedback loops between carbon storage in soils and vegetation (Hayat et al. 2017).

The city of Berlin is a particularly interesting study site for mapping the carbon storage in urban soils and aboveground biomass because its soils have constantly underwent dynamic land use and land cover changes. These land cover dynamics—depending on their sealing rate—either store or release carbon and because Berlin has one of the highest number of park-, street- and forest-trees in European cities these considerably influence the city's carbon cycle (Strohbach and Haase 2012). Besides urban soils and the aboveground biomass, Berlin exhibits another carbon stock, which can be seen as the result of the city's geological past and climate conditions: peatlands. These peatlands represent a third major carbon reservoir that contributes to the carbon cycle. However, no study is known to the authors, which include peatlands when assessing a city's carbon storage. It shows that the city is characterized by high small-scale variations and high heterogeneity of ecological conditions (Vogt et al. 2015, Vitt and Short 2016). Generally speaking, Berlin is influenced by unique anthropogenic changes, which can be accounted for by rapid urbanization rates (Davies et al. 2011, Trammell et al. 2018).

The objective of the research reported in this article is to calculate the total quantities of carbon present in Berlin, taking the C_{org} stored in soils, peatlands and vegetation into account since no study yet has combined both approaches for the city of Berlin due to a lack of reliable data (Velasco et al. 2015, Yigini and Panagos 2016). For this study however, data from different soil and vegetation investigations in Berlin were provided for this study, which is why both approaches could be combined for the first time. So far, no comprehensive study combining vegetation and soil carbon has been done for a large and complex urban system such as Berlin. Special emphasis has to be placed on different land use types and the degree of soil sealing, as both factors affect the potential to store carbon (Haase 2009). This is especially important for the city's future since more land is constantly being converted into residential areas as part of increasing urbanization rates. These changes are of high environmental relevance with the potential to alter the carbon storage in Berlin even more (Vasenev and Kuzyakov 2018).

The approach is to map the carbon storage for soils and aboveground biomass individually in order to analyze the distribution of carbon within the city boundaries. The analysis follows three research questions:

1. What above and belowground carbon pools can be found in a large and heterogeneous city like Berlin?
2. How does urbanization impact these patterns and the spatial variability of above- and belowground carbon pools in Berlin?
3. What are uncertainties and limitations in modeling urban carbon pools in large cities?

To address these questions, the carbon storage in soils and aboveground biomass was calculated using quantitative statistics and visualized in order to analyze the resulting patterns with respect to the different site characteristics.

2. Material and Methods

2.1 Study area

The city of Berlin (52° 31' N, 13° 24' E) is the most densely populated city in Germany with a population of just over 3.6 million inhabitants. It is the capital of Germany, covering an area of approximately 890km^2 of which around 40 % is comprised of vegetation such as urban parks, forests, agriculture, and street trees (Edelmann 2013). The city exhibits around 2,500 public green spaces on which deciduous broadleaf trees are the prevailing land cover. These green spaces are distributed consistently throughout the city with each of the twelve urban districts comprising of at least one urban park larger than 34 hectares (Senate Department for the Environment, Transport and Climate Protection 2019). Whereas forest-like parts of Berlins green are considered as a separate vegetation type with wood meadow-grass-plane maple park forests (70 %), shrubs (20 %), and greater celandine-robinia forests (10 %), trees in the parks and on the streets therefore characterize the appearance of the dense built city. On average, there are about 80 trees for every kilometer of the city, which results in a total stock of 359,248 street trees. Over 50 different tree species are located along the streets, with the five most common tree species being lime, maple, oak, plane tree, and horse chestnut as they account for over 75 % of the total street tree population (Figure 1).

Figure 1. The five most common tree species in Berlin. From top left to bottom right: Lime tree (*Tilia*), Maple (*Acer*), Oak (*Quercus*), Plane tree (*Platanus*), Horse chestnut (*Aesculus*). Pictures of Lime tree, Maple, Oak and Horse chestnut were taken on June 10th, 2019 at Landschaftspark Herzberge, Berlin – Lichtenberg. The picture of one of the oldest plane trees ("Treskow-Plane") in Berlin was taken on June 14, 2019 in the district of Berlin-Lichtenberg. Source: author's pictures

For many years, lime trees (*Tilia*) have been regarded as the most typical tree species on the streets of Berlin. With a share of one-third, they characterize the street tree population. Maple trees (*Acer*) comprise about 20 % of the total population, whereas oak trees (*Quercus*) make up for about 9 %. Plane trees (*Platanus*) and horse chestnut trees (*Aesculus*) account for about 6 and 5 %, respectively of the total stock (Senate Department for Urban Development and Housing 2019). Most of these trees are located in the outlying districts of the city (e. g. Steglitz-Zehlendorf, Marzahn-Hellersdorf and Treptow-Köpenick) as they are less populated than the districts in the city center and thus provide more space for larger avenues with high tree populations (Roman et al. 2014, Nyelele et al. 2019).

By contrast, the large continuous forest areas are mainly composed of conifers and birches. Their occurrence however, is mainly limited to the undeveloped areas outside the city center in the western and southeastern parts of the city (Tigges et al. 2017). Because urban parks and forests cover almost 350 km^2 of the administrative area, Berlin itself claims to be one of the greenest cities in Germany (Senate Administration 2019).

The climate of the city is moderate and lies in the transition area between temperate and continental zones with a mean annual temperature of 9.2°C and approximately 580mm of precipitation annually (Tigges et al. 2017). The climate and the city's location in the periglacial influenced landscape with low inclination shape the prevailing soil types of Berlin. Both, natural- and anthropogenic-influenced soil types show large percentages of sand and till, leading to high water permeability. The different soil types in Berlin have been strongly modified by humans for almost a century because of rural-urban migration. Due to the city's adaption to this movement, soil conditions have been altered, resulting in high small-scale variability of soil types (Hollis 1991).

In addition, the distribution of peatlands in Berlin also contributes to the high heterogeneity of soil types. With approximately 7.40km^2, peatlands cover only a small fraction of the city's surface but are of high importance as they store about 6 % of the total carbon stored in the city of Berlin (Klingenfuß et al. 2015). Most of the peatlands are located in the glacial valley and its lowlands in the districts of Treptow-Köpenick in the southeast as well as Reinickendorf and Pankow in the north.

At present, the city of Berlin faces recent land-use and land-cover changes because of rapid population growth and associated urbanization. The city structure is likely to be altered through ongoing processes, which could in the long-term result either in the storage or in the emission of carbon through soils and vegetation (Vasenev et al. 2014).

2.2 Terms and definitions

To analyze the carbon storage in urban areas, different units and approaches are used. This is especially important in order to represent these areas in all their complexity. In this study, the entire city of Berlin is seen as an urban area, which is why the term *urban area* is used synonymic to the term *city*. Therefore, everything located within the city's boundaries is also considered as part of the urban area, especially urban soils and urban trees.

The C_{org} storage of urban soils is expressed as the quantities of carbon per surface area [t C/ha] (Vasenev and Kuzyakov 2018). This applies to both natural and semi-natural soils that are present in the city of Berlin. The C_{org} storage is calculated at two different depths (Topsoil: 0-20cm, Subsoil: 20-100cm) − which is consistent with the latest published studies on carbon storage in urban soils (Yigini and Panagos 2016, Vasenev and Kuzyakov 2018). The different soil depths are referred to as *horizons* and not *layers* because the term *layers* is often used in geology to describe stratification or to express the presence of artificial compounds in soils, which is then usually described as *cultural layers*. In a city like Berlin, artificial compounds are also expected to be present in soils but because attention is only paid to the C_{org}contentin this study, the different depths are addressed as *horizons* (Dinakaram and Rao 2012, Vasenev et al. 2018). Except for elemental and inorganic carbon, the consideration of $C_{org}$is of great interest as more than half of the soil functions are directly or indirectly linked to the storage of C_{org} (Dinakaram and Rao 2012).

Additionally, more than 95 % of aboveground organic carbon is found in trees and plants, which is why this particular form of carbon is of great interest − especially when trying to link the carbon stored in soils to the carbon present in trees (Davies et al. 2011, Edmondson et al. 2014a). In order to measure the carbon content of trees, the diameter at breast height (DBH) was chosen as it is the most common method for measuring trees and their relevant influencing variables (Ugle et al. 2010, Vollrodt et al. 2012). This method also helps to detect the differences in carbon content between various tree species and simultaneously reveals the specific and often fragmented patterns of carbon storage within the city (Seto et al. 2012, Strohbach and Haase 2012, Edmondson et al. 2014a).

2.3 Data aggregation for calculating soil carbon storage

The collection of soil data and its corresponding C_{org} content depends on different factors, especially on the prevailing land use. In cities, the specific land uses are divided into sealed surfaces and open areas. This differentiation is important as more data were collected in open areas due to better accessibility. Thus, almost twice as much data were collected in open areas (Table 1 and for the spatial pattern/distribution of Berlin's land use see Figure 2).

Table 1. Representation of the soil samples taken per land use class.

Land Use (Sealed Surfaces)	Number of Soil Samples	Land Use (Green Spaces and Open Areas)	Number of Soil Samples
Residential Use	44	Forest Areas	65
Mixed Use	10	Grasslands	9
Business Zones	-	Farmlands	18
Industrial Use	32	Parks / Public Green Spaces	95
Public Purpose Land	15	Cemeteries	6
Disposal Facilities	-	Allotment Gardens	7
Traffic Areas	39	Brownfields (no vegetation)	2
Weekend Homes and Allotment Garden-like Usage	2	Brownfield Meadows	26
Construction Sites	-	Brownfields with Mixed Stands	42
		Civic Centers / Boardwalks	8
		Sports Areas	2
		Arboretum parks	10
		Waterbodies	-
Total	**142**	**Total**	**290**

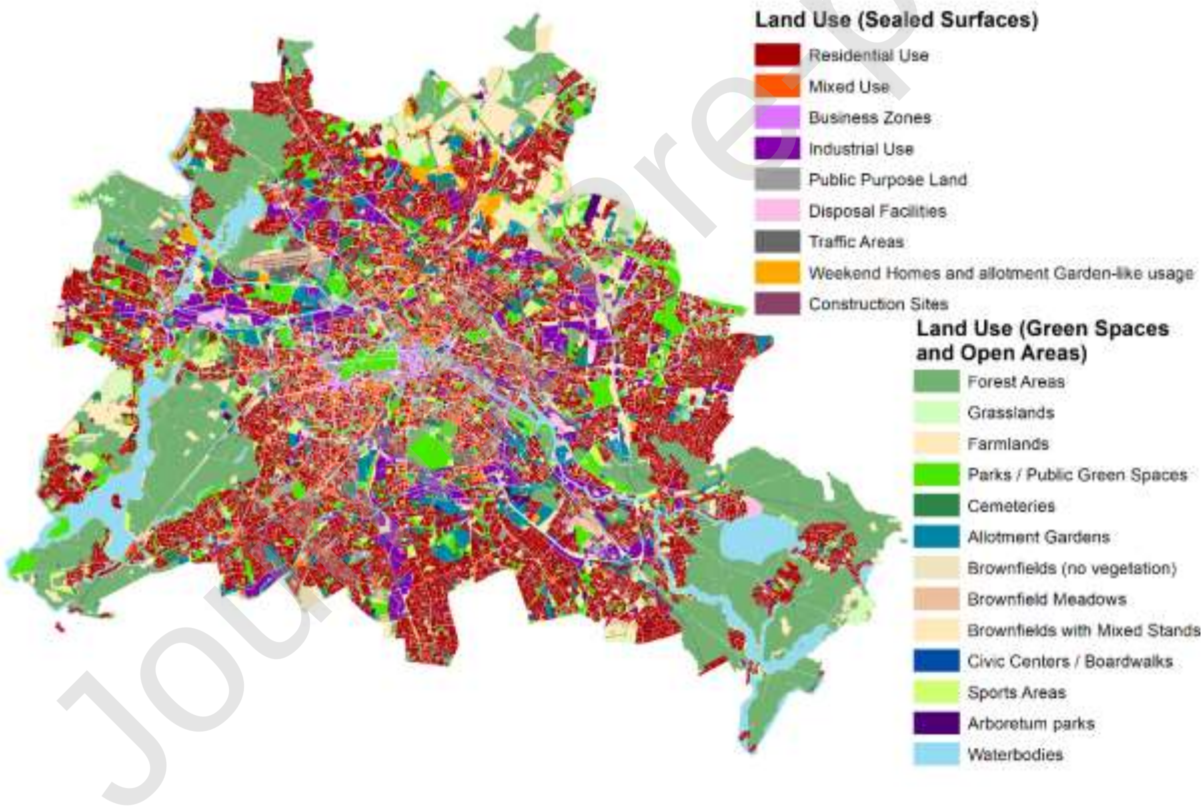


Figure 2: Land use classes' distribution for Berlin (based on Copernicus Urban Atlas data, retrieved March 3, 2020, from https://land.copernicus.eu/local/urban-atlas, and the Berlin Environmental Atlas by the Senate Department for Urban Development and Housing (2016)). The classes displayed in the map exactly correspond to the land use classes used in Table 1 and mentioned in the text.

In this case study, in total 432 soil samples were collected in 22 different studies between 2005 and 2012, an excellent and rich sample for a city of the size of Berlin. The samples taken are distributed equally throughout the city. Each soil sample contains information about the site itself, the laboratory findings as well as geospatial information derived from a geoportal. The most important variables from each category are shown in the following diagram (Figure 3) as they are crucial for calculating the C_{org} content.

The terrain data and geospatial information are mainly used to describe the area where the soil sample was taken and any influencing factors. The laboratory findings however, provide information about soil organic matter (= humus) content (SOM) and therefore also indirectly about C_{org} content. The latter cannot be derived directly from the sampled data but can be calculated through the loss on ignition (LOI), which is the proportion (in %) of SOM in a soil sample (Ad-hoc AG Boden 2005).

Soil samples were all analyzed according to DIN 19684-3:2000-08. To determine SOM, the soil sample was put in the furnace at temperatures of either 420°C (high carbonate content in the sample or anthropogenic/technogenic soil) or 550°C until no further loss of weight was observed. By using reduced temperature, the effect of inorganic carbon and technogenic carbon (“black carbon”) on the C_{org} content was reduced.

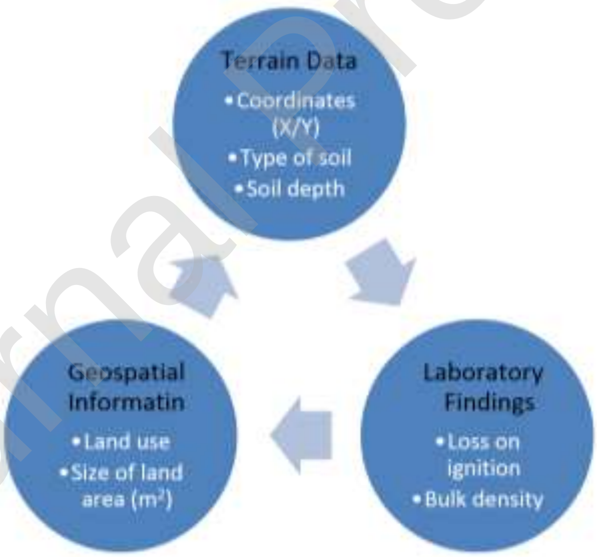


Figure 3: The most important values for calculating the soil carbon storage, which influence each other. Source: author’s depiction

The conversion of SOM into C_{org} is carried out under the assumption of a mean C_{org} content of 58 % in the SOM of. Because 1mg of carbon corresponds to 1.724 mg of organic matter, the following equation was used to calculate the C_{org} content (%) for each soil sample and soil horizon (Ad-hoc AG Boden 2005, eq. 1):

$$Corg\ (\%) = \frac{LOI(\%)}{1.724} \qquad (1)$$

One of the main goals of this study is to calculate C_{org} in (kg/m^2) for the city of Berlin. Therefore, two additional variables have to be considered – the soil depth (cm) and bulk density (g/cm^3). The soil depth for each sample was recorded on collection, whereas the bulk density could only be calculated separately after 100cm³ of sample taken with core cutters had been dried at 105 °C in the laboratory (acc. to DIN EN ISO 11272:2017-07). Because more than 20 different researchers were involved in taking the soil samples mostly for their own purposes, not all of them additionally calculated the bulk density. For these cases, the bulk density was estimated after Renger et al. (2008) by considering the soil texture. The C_{org} content (kg/m^2) could then be calculated using equation 2:

$$Corg\ \left(\frac{kg}{m^2}\right) = \frac{(Corg\ (\%) * Bulk\ density * \left(\frac{Soil\ depth}{100}\right) * 10000))}{1000} \qquad (2)$$

With this equation, the carbon content (kg/m^2) for each of the areas (m^2) where the soil samples were taken could be determined. C_{org}content was calculated for both, topsoil and subsoil as the quantities of carbon stored in the soil varies greatly between the different depths. Since the land use was also mapped for each soil sample, the average quantities of C_{org} per soil depth and land use could be calculated.

As stated, we used 432 soil samples that were taken across 18 different land uses in order to estimate the C_{org} content for each land use based on the laboratory findings of each sample. This large amount of data, which is excellent for such a study, provides an important basis for the evaluation and analysis of the carbon storage. Taking into account the degree of soil sealing, the carbon calculations for each individual land use were then transferred to the total area of Berlin in order to produce a spatially explicit carbon map. Soil carbon stocks are reported as units of carbon (C_{org}) either as kg/m² or in tons/ha for each block. The carbon storage was estimated for both topsoil and subsoil.

As shown in Table 1, almost one-third of the data were collected in built-up areas. Most of the soils are sealed, which is why soil samples could only be taken from non-sealed areas such as backyards of residential areas. Because sealed surfaces are an influencing and limiting factor for C_{org} storage, the degree of soil sealing (imperviousness) has to be taken into account.

Table 2 shows the average imperviousness for each land use, which in a next step was subtracted from the total area for each land use in order to map the carbon storage in soils more precisely and reliably (Haase 2009, Senatsverwaltung für Stadtentwicklung und Umwelt 2016).

Table 2. Classification of the degree of soil sealing (%) per land use class.

Land Use (Sealed Surfaces)	Mean Degree of Soil Sealing (%)	Land Use (Green Spaces and Open Areas)	Mean Degree of Soil Sealing (%)
Residential Use	39.3	Forest Areas	0.5
Mixed Use	62.2	Grasslands	1.3
Business Zones	83.2	Farmlands	0.2
Industrial Use	68.3	Parks / Public Green Spaces	9.6
Public Purpose Land	41.1	Cemeteries	8.1
Disposal Facilities	43.5	Allotment Gardens	22.3
Traffic Areas	42.0	Brownfields (no vegetation)	32.5
Weekend Homes and Allotment Garden-like Usage	26.7	Brownfield meadows	16.0
Construction Sites	34.4	Brownfields with Mixed Stands	16.5
		Civic Centers / Boardwalks	46.7
		Sports Areas	24.7
		Arboretum parks	24.6
		Waterbodies	0

In order to map the C_{org} content in soils throughout the city, the calculations for carbon content in both topsoil and subsoil, together with the prevailing land use class (after subtracting imperviousness) were then extrapolated to the total area of Berlin by associating the mean of all 432 soil samples (for two depths > and <20cm) per land use class to all polygons of this respective land use class.

2.3.1 Measuring carbon storage in peatlands

Near-natural peatlands with high water levels fulfill diverse and important ESS. They provide habitats for rare animal and plant species and store considerable quantities of CO_2 in the form of soil carbon in peat.

Numerous peatlands with different characteristics exist in the urban environment of Berlin. They are characterized by a variety of anthropogenic influences such as urban development, soil deposition and drainage as a result of drinking water extraction from bank filtrate. The ventilation and degradation of peat releases large quantities of CO_2 and nutrients into the atmosphere (Klingenfuß et al. 2014, 2015). The number of peatlands that exist in Berlin is rather small in contrast to the carbon stored in them. Therefore, the carbon storage of urban peatlands should not be overlooked in the carbon cycle of the city.

The data used to estimate the carbon storage of peatlands in Berlin were provided by Klingenfuß et al. (2015), who—for this purpose—investigated all peatlands in terms of soil science. In order to record the quantities of carbon stored in the peatlands of Berlin, it was important to obtain precise information on the soil structure of the individual peatlands. With regard to this, all of these wetlands were drilled and described systematically in terms of their soil and substrates. The data on bulk density and carbon content were determined on representative peatland horizons in Berlin. More than 500 peat and mud horizons were sampled and analyzed in the laboratory in the same way that the different soil samples were analyzed. In addition, data on dry bulk densities were partially supplemented with legacy data (Klingenfuß et al. 2015). As these data from 2015 are the most current ones for estimating the carbon content of peatlands in Berlin, they were used for the calculation of the total soil and aboveground carbon stored within the city's boundaries. Carbon storage has been calculated up to the peat base.

2.4 Biomass and carbon storage in urban trees

As trees provide vital ESS to urban dwellers, it is important to estimate the carbon content in the aboveground biomass, especially in the context of the carbon storage potential in Berlin.

In order to do so, the senate administration of Berlin provides open source data on all existing park and street trees within the city boundaries. For this study, all 237,727 park trees and 359,248 street trees were taken into account (Senate Department for Urban Development and Housing 2019). The data on these different trees contain a large quantity of information. However, for this study only some of the individual tree characteristics such as the tree species, the location of the trees, and the year of planting are of particular interest as this information is needed to calculate the biomass and carbon content. This calculation is divided into two different parts because the DBH, one of the most important variables for estimating the biomass and carbon content, was not initially provided and thus had to be calculated. For this, equation 3 was used:

$$BHD\ (cm) = \left(1 - EXP\left(x * (y)\right)\right) * 171.28 \qquad (3)$$

where *x* is the age of the tree and *y* is the average tree growth rate.

The age of the tree was derived from the year of planting, whereas the average tree growth rate for each individual tree species was extracted from studies by Ter-Mikaelian and Korzukhin (1997), Jenkins et al. (2003), and Johnson and Gerhold (2003). The same holds true for the constant of integration (171.28), which is a fixed value for tree biomass calculations (Ter-Mikaelian and Korzukhin 1997).

After the DBH for each individual tree was calculated, the next equation was then used in order to estimate how much volume a given stock of tree holds (eq. 4):

$$Biomass\ (kg) = EXP(\alpha) * DBH^\wedge\beta \qquad (4)$$

Both, the scaling exponent (α) and the coefficient of proportionality (β) for every individual tree species were already established for landscape ecology by Ter-Mikaelian and Korzukhin in 1997 and were therefore derived directly from the literature.

In a final step, the calculated biomass was divided by two as half of the biomass is composed of carbon (Ter-Mikaelian and Korzukhin 1997). The summation of the carbon content of all individual trees then shows the total quantities of carbon stored in park and street trees of Berlin.

As mentioned in section 2.2, the city of Berlin can be categorized as one of the greenest cities in Germany due to its large number of unique urban green spaces and urban forests. The latter also contribute to the storage of great quantities of carbon from the atmosphere and therefore cannot be overlooked (Nowak and Crane 2002, Scharenbroch 2012, Velasco et al. 2015). However, access to open source data on the different forest stands in Berlin proves to be difficult as each one of the five main forestry commission offices in the city has its own way of processing and preserving the data. Biomass and carbon calculations like the ones done for park and street trees could not be applied to forest trees as there was hardly any access to information about the tree characteristics (age, species, and tree density in the respective forest stand). For that reason, the data on carbon storage in Berlin forest stands by Rock (2017) were used. Rock (2017) was the first researcher to recently gain access to the data of each forestry commission office and was therefore able to calculate the biomass and carbon storage of the different forest stands accordingly. These results were eventually added to the carbon contents that were calculated for park and street trees in order to display the total quantities of carbon stored in the aboveground biomass present in the urban area.

3. Results

3.1 Modeling C_{org} content

Land use patterns are changing at high rates, especially in cities with ongoing urbanization, meaning that carbon dynamics are also changing rapidly and making it hard to accurately predict and map them (Yigini and Panagos 2016).

Berlin is not only the most populated city in Germany, but also the largest in terms of surface area, therefore storing great quantities of C_{org} in its soils. Expressed in figures, 17,143,012 tons of carbon are stored in the city's soils of which 18 % account for C_{org} stored in the first 20cm of the soil and 82 % for the C_{org} stored in subsoils. The distribution of carbon for different types of land cover and at different soil depths can be seen in Table 3. More than 70 % of the urban area is covered by different types of buildings, construction sites and traffic areas and displays a wide range of the stored carbon.

In the category of sealed surfaces, mixed uses exhibit the most C_{org} in both topsoil (7.94kg/m^2) and subsoil (58.94kg/m^2), whereas the remaining land uses do not vary substantially in terms of C_{org} storage. They accumulate between 3.99kg of C_{org} per m^2 (residential use) and 5.94kg/m^2 (industrial use). Similar dynamics can be seen in green spaces and open areas. Carbon storage in topsoil does not vary widely between the different land uses (from 2.61kg/m^2 in brownfields without vegetation to 9.52kg/m^2 in sports areas). In the corresponding subsoils the range of C_{org} storage is even higher compared to sealed surfaces. Grasslands store the most C_{org} (119.62kg/m^2) and civic centers and boardwalks the least quantities with 19.21kg/m^2. These measurements confirm the results by Edmondson et al. (2014b) and show how soil C_{org} concentrations are substantially influenced by the different land uses as well as soil depths. To visualize these results, Figure 4a shows the distribution of C_{org} stored in the topsoil.

For a better depiction and comparability, the values were converted from kg/m^2 (Table 3) to t/ha in the soil carbon maps. A total of 3,047,364 tons of carbon is stored in the first 20cm of the soil. As mentioned above, most of these surfaces are sealed to a certain extent (Table 2) and therefore store the least quantities of C_{org} (maximum 500t/ha).

Table 3: Classification of the carbon stored in the topsoil (<20cm) and subsoil (>20cm) in each land use class

Land Use (Sealed Surfaces)	C_{org} Content Topsoil (kg/m^2)	C_{org} Content Subsoil (kg/m^2)	Land Use (Green Spaces and Open Areas)	C_{org} Content Topsoil (kg/m^2)	C_{org} Content Subsoil (kg/m^2)
Residential Use	3.99	24.66	Forest Areas	7.27	27.91
Mixed Use	7.94	58.94	Grasslands	7.33	119.62
Business Zones	4.00	11.70	Farmlands	5.31	45.48
Industrial Use	5.94	12.80	Parks / Public Green Spaces	7.02	26.55
Public Purpose Land	5.13	25.25	Cemeteries	5.37	20.92
Disposal Facilities	4.19	35.87	Allotment Gardens	5.26	37.88
Traffic Areas	4.70	10.40	Brownfields (no vegetation)	2.16	61.45
Weekend Homes and Allotment Garden-like Usage	5.26	37.22	Brownfield meadows	7.48	46.02
Construction Sites	-	-	Brownfields with Mixed Stands	5.18	25.12
			Civic Centers / Boardwalks	5.70	19.21
			Sports Areas	9.52	34.38
			Arboretum Parks	7.42	30.89
			Waterbodies	-	-

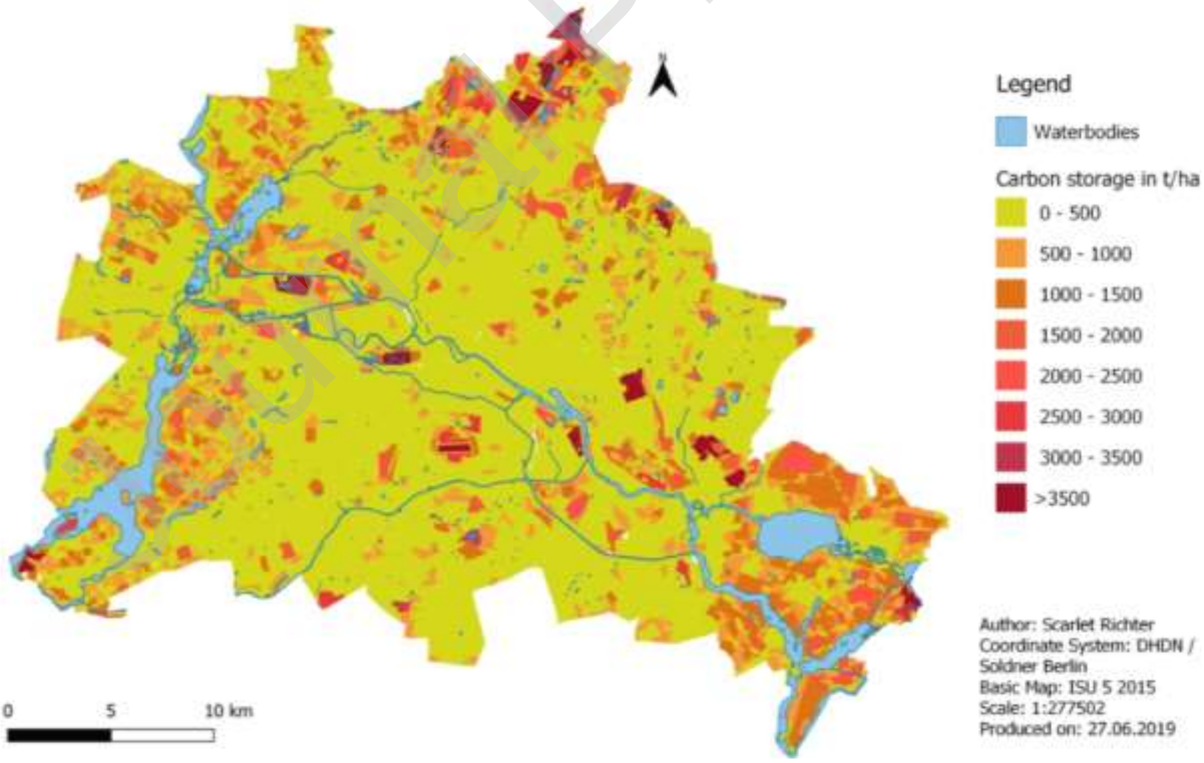


Figure 4. Average carbon storage (t/ha) in the topsoil (<20cm).

The distribution of these surfaces is equal throughout the city and aligns with the densely built-up areas (Figure 4). However, small patches of open areas also store less than 500t of C_{org} per hectare and are mostly located in close proximity to the corresponding areas of sealed surfaces. Towards the outskirts of the city, more carbon is stored in the topsoil, following the urban-rural gradient even within the city (Pouyat et al. 2002). Forest areas in the north, southeast, and south-west accumulate large quantities of C_{org} (up to 3,500t/ha) as they influence and supply the soils through decomposition (Scharenbroch et al. 2018). The most topsoil carbon per hectare is stored in peatland areas, especially in the north and southeast of the city.

Similar patterns emerge when looking at the C_{org} stored in the subsoil (Figure 5). 14,095,647t are currently present at depths exceeding 20cm. The least quantities of C_{org} is stored in the city center and densely built-up areas, whereas the highest C_{org} content can be found with increasing proximity to the city boundary. Especially the forest areas in the southeast and north accumulate great quantities of C_{org} due to the presence of peatlands and soil types typical of that region, which can also store substantial quantities of C_{org} because of their composition.

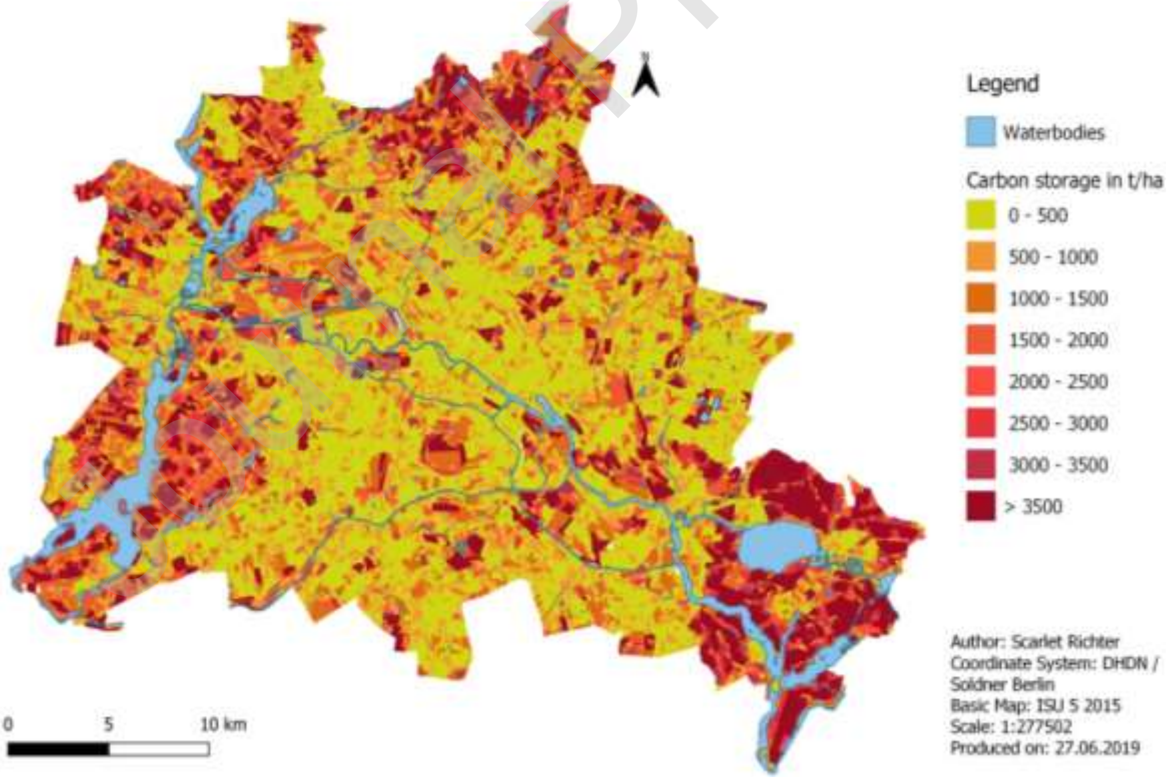


Figure 5: Average carbon storage (t/ha) in the subsoil (>20cm).

Apart from the city center and built-up areas, the majority of the remaining areas have moved up by at least one category, which means that they store at least twice as much C_{org} in the subsoil. In fact, it is only in a few areas around Tempelhof Field (south of the city center) that less C_{org} is present in the subsoil compared to the topsoil.

When combining topsoil and subsoil carbon storage, it becomes obvious that even more areas now store more than 3,500 tons of C_{org} per hectare (Figure 6). As much as 9,884t/ha in sealed surfaces and 16,370t/ha of C_{org} in non-sealed surfaces are stored in certain areas. However, the city center and highly built-up areas are an exception because the combined C_{org} content only increases to the extent that it still remains below 500t/ha. Soil carbon content varies greatly between different land uses and soil types. The highest C_{org} content per area was found in recreational areas as well as in areas for public use.

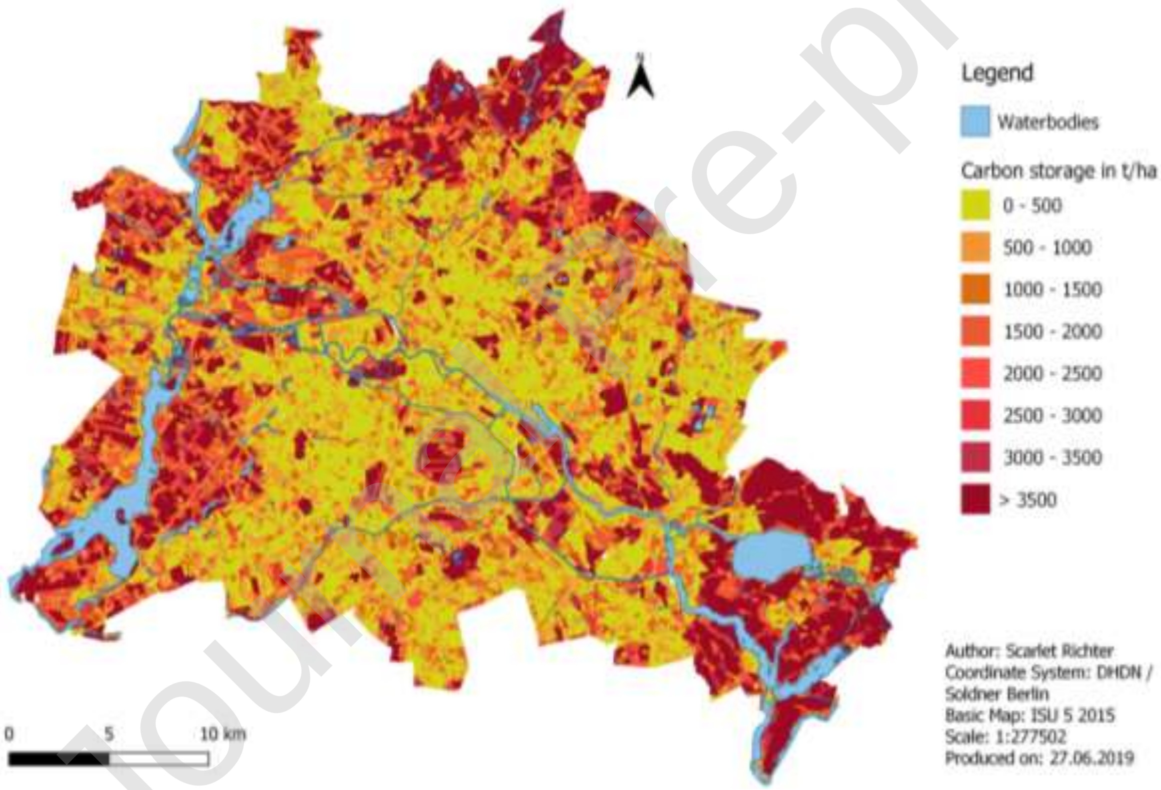


Figure 6. Total soil carbon storage (t/ha) in the city of Berlin.

Apart from the different urban land uses, peatlands are the most effective carbon reservoirs of all terrestrial habitats (Vitt and Short 2016). The global carbon storage capacity of all peatlands is estimated to be over 500 billion tons, which is more than half the quantities of carbon currently in the atmosphere in the form of CO_2 (Houghton 2007, Klingenfuß et al.

2015). Great differences in carbon storage between individual peatland areas were found. The total quantity of carbon in peatlands quantities to 1,092,656t. The size of the carbon pools varies greatly and depends on the size and thickness of these ecosystems as well as on the chemical-physical soil properties. The most area-effective carbon storage is found in the thick peatlands to the south-east of Berlin. Here, a maximum carbon storage capacity of more than 6,000t/ha was calculated in the middle of this area. The average carbon storage capacity for this smaller peatland was calculated at around 3,700t/ha (Klingenfuß et al. 2015).

3.2 Current distribution of urban trees per species and their carbon storage

Average carbon storage per tree species varies depending on the age of the tree, its location and the prevailing soil type. This holds true for both street and park trees. A total of 596,975 street trees and park trees are currently present in Berlin, consisting of more than 60 different tree species. As mentioned by the city (Senate Department for Urban Development and Housing 2019), over 75 % of the total tree population account for lime trees (*Tilia*), maple (*Acer*), oak (*Quercus*), plane trees (*Platanus*) and horse chestnut (*Aesculus*). This distribution can also be seen in Table 4, which shows the total number of street trees per tree genus. In total, 359,248 street trees line the traffic areas in the city.

Table 4: Total number of street trees and %age per tree species.

Tree species (bot.)	Distribution of street trees per species (%)	Tree species (bot.)	Distribution of street trees per species (%)
Total number of street trees: 359,248			
Tilia	37.9534	*Ostrya*	0.0448
Acer	18.6075	*Ameanchier*	0.0354
Quercus	9.2051	*Pseudotsuga*	0.0289
Platanus	6.2951	*Taxus*	0.0281
Aesculus	5.0169	*Abies*	0.0264
Betula	3.0491	*Rhus*	0.0242
Fraxinus	2.3321	*Morus*	0.0187
Robinia	2.2077	*Other*	0.0159
Corylus	1.9268	*Celtis*	0.0150
Sorbus	1.7011	*Mespilus*	0.0145
Prunus	1.6415	*Parrotia*	0.0131
Crataegus	1.6128	*Cercidiphyllum*	0.0125
Carpinus	1.6014	*Zelkova*	0.0109
Populus	1.5789	*Cupressus*	0.0097
Ulmus	1.0781	*Elaeagnus*	0.0092
Pinus	0.6341	*Liriodendron*	0.0072
Gleditsia	0.5615	*Cercis*	0.0067
Pyrus	0.5528	*Phellodendron*	0.0064
Styphnolobium	0.4195	*Sequoioideae*	0.0064
Gingko	0.2942	*Rhamnus*	0.0056
Liquidamber	0.2004	*Thuja*	0.0053
Fagus	0.1826	*Paulownia*	0.0031
Salix	0.1601	*Cornus*	0.0025
Malus	0.1595	*Sambucus*	0.0025
Ailanthus altissima	0.1461	*Gymnocladus*	0.0022
Alnus	0.1339	*Juniperus*	0.0014
Juglans	0.1074	*Laburnum*	0.0014
Picea	0.1044	*Euodia*	0.0011
Magnolia	0.0774	*Hippophae*	0.0011
Larix	0.0509	*Ilex*	0.0008
Catalpa	0.0457	*Buxus*	0.0006
		Cedrus	0.0006

Almost 40 % of the total street trees are accounted for by lime trees, making lime the most prevalent street tree species in Berlin. The total number of trees per species varies widely and distinctly decreases in the lower third of Table 4 as these species are less typical for street trees (e. g. *Cupressus*). The reason that almost half of the street trees are lime trees is that this species is the most resistant to urban pressures and changes and is therefore the most frequently planted (Senate Department for the Environment, Transport and Climate Protection 2019).

Table 5: Total number of park trees in Berlin and in % per tree species.

Tree species (bot.)	Distribution of park trees per species (%)	Tree species (bot.)	Distribution of park trees per species (%)
Total number of park trees: 237,727			
Acer	22.9478	*Thuja*	0.1540
Quercus	10.7640	*Styphnolobium*	0.1489
Tilia	9.0103	*Morus*	0.1447
Betula	6.2126	*Catalpa*	0.1190
Robinia	5.2834	*Gingko*	0.1039
Pinus	4.9536	*Liquidamber*	0.0917
Populus	4.6961	*Syringa*	0.0526
Carpinus	4.3205	*Tsuga*	0.0526
Fagus	3.9104	*Elaeagnus*	0.0505
Prunus	3.7059	*Cornus*	0.0437
Aesculus	2.9218	*Sambucus*	0.0379
Fraxinus	2.5029	*Ilex*	0.0349
Ulmus	2.0831	*Celtis*	0.0324
Salix	1.8277	*Sequoioideae*	0.0324
Alnus	1.3919	*Magnolia*	0.0265
Platanus	1.3229	*Liriodendron*	0.0244
Crataegus	1.1980	*Cedrus*	0.0236
Picea	1.1576	*Euonymus*	0.0164
Taxus	1.1286	*Laburnum*	0.0151
Malus	1.0853	*Amelanchier*	0.0135
Pseudotsuga	1.0769	*Rhamnus*	0.0135
Sorbus	0.9229	*Cercidiphyllum*	0.0114
Other	0.8846	*Rhus*	0.0105
Ailanthus altissima	0.5561	*Gymnocladus*	0.0084
Larix	0.4354	*Hippophae*	0.0084
Carya	0.4219	*Buxus*	0.0080
Corylus	0.4034	*Cydonia*	0.0063
Juglans	0.3798	*Paulownia*	0.0059
Pyrus	0.3424	*Euodia*	0.0050
Mespilus	0.2759	*Phellodendron*	0.0046
Gleditsia	0.2002	*Ostrya*	0.0038
Cupressus	0.1897	*Cercis*	0.0029
Abies	0.1775	*Parrotia*	0.0013

These dynamics change when we look at park trees. Even though these trees are also located within the city's boundaries, their species composition is different from that of street trees (Table 5).

Maple, oak and lime trees are still by far the most common tree species and account for 43 % of the total park tree population. However, lime trees (unlike with street trees) are no longer the predominant species in parks as this is maple for park trees. As the total number of park trees (237,727) is less than the number of street trees, it is obvious that fewer trees per species exist. However, the distribution of trees per species is more balanced among park trees.

For both, street and park trees, some tree species could not be clearly identified when mapping the trees based on aerial images. Therefore, the category "*other*" exists, which includes all of those unidentifiable tree species. As most of the street trees are planted by the city, there is a record of which species have been planted. Thus, only 57 trees were assigned to the category "*other*", whereas 2,103 of the total park trees, that sometimes also reseed themselves, were not identified.

Another difference between street and park trees is the species composition. About 10 % of the park trees are conifers, whereas just over 1 % of the street trees belong to coniferous species. The remaining trees are deciduous tree species, which effectively provide shade and cool their surroundings, especially during the summer months (Nowak et al. 2013). These regulating ESS are particularly important as they benefit urban dwellers experiencing the urban heat island (UHI) effect in cities. Trees regulate the city's climate and purify the air by absorbing air pollutants (Davies et al. 2011).

Another, yet most important ecosystem service of trees is the storage of carbon. In addition to soils, urban trees are considered a substantial sink for atmospheric CO_2 in built-up areas (Vollrodt et al. 2012). As of today, a total of 84,366.70t of carbon is stored in street trees in Berlin (Table 6).

Table 6: Total quantities of carbon (t) stored per street tree species.

Tree Species (bot.)	Total Carbon Storage per Tree Species	Tree Species (bot.)	Total Carbon Storage per Tree Species
Tilia	11078.10	*Ostrya*	0.06
Acer	6320.48	*Amelanchier*	0.69
Quercus	8361.63	*Pseudotsuga*	310.65
Platanus	6905.10	*Taxus*	8.11
Aesculus	6400.39	*Abies*	4.91
Betula	1395.82	*Rhus*	2.37
Fraxinus	69.95	*Morus*	2.21
Robinia	37371.65	*Other*	5.84
Corylus	232.81	*Celtis*	1.42
Sorbus	164.53	*Mespilus*	1.63
Prunus	233.35	*Parrotia*	0.05
Crataegus	87.16	*Cercidiphyllum*	0.49
Carpinus	20.11	*Zelkova*	0.45
Populus	2020.23	*Cupressus*	1.85
Ulmus	687.24	*Elaeagnus*	2.64
Pinus	129.13	*Liriodendron*	20.40
Gleditsia	52.90	*Cercis*	16.97
Pyrus	31.60	*Phellodendron*	3.02
Styphnolobium	161.44	*Sequoioideae*	0.25
Gingko	760.04	*Rhamnus*	0.55
Liquidamber	9.83	*Thuja*	3.68
Fagus	1145.68	*Paulownia*	0.01
Salix	110.02	*Cornus*	0.39
Malus	3.24	*Sambucus*	0.27
Ailanthus altissima	71.47	*Gymnocladus*	19.09
Alnus	28.60	*Juniperus*	0.03
Juglans	46.89	*Laburnum*	0.10
Picea	14.49	*Euodia*	0.02
Magnolia	1.17	*Hippophae*	4.83
Larix	27.31	*Ilex*	0.09
Catalpa	11.01	*Buxus*	0.09
		Cedrus	0.11
Total	**83,953.38t**	**Total**	**413.32t**
Total carbon pool of street trees: 84,366.70t			

Since lime trees are the most dominant tree species on the streets of Berlin, it was expected that these trees also store large quantities of carbon. However, measurements show that lime trees store the second largest quantities with 11,078.10t, which is 13 % of the total carbon stored in street trees. Locust trees (*Robinia*) store most carbon with 37,371.65 tons. Despite the fact that locust trees only make up for 2 % of the total street tree population, they store 44 % of the carbon present in street trees. Poplars (*Populus*) and beeches (*Fagus*) store the third and fourth largest quantities of carbon with 2,020.23 tons and 1,145.68 tons, respectively. This means that dominant tree species do not necessarily store the most carbon and vice versa. On the contrary, tree species that are not as common can also accumulate significant quantities such as the 104 Douglas firs (*Pseudotsuga*) and eight Kentucky coffee trees (*Gymnocladus*) mapped. They can store up to 50 times as much carbon as trees that occur just as often (e. g. *Sambucus*). With around 2,500 urban green spaces in the city of Berlin, many different tree species were established over recent decades and centuries (Vollrodt et al. 2012). In total, park trees store 153,810.54 tons of carbon and therefore contribute considerably to the overall carbon stock of the city (Table 7).

Table 7: Total quantities of carbon (t) stored per park tree species.

Tree species (bot.)	Total Carbon Storage per Tree Species	Tree species (bot.)	Total Carbon Storage per Tree Species
Acer	6033.41	*Thuja*	209.24
Quercus	15053.54	*Styphnolobium*	46.47
Tilia	2255.75	*Morus*	13.79
Betula	1863.61	*Catalpa*	26.19
Robinia	69827.93	*Gingko*	244.86
Pinus	737.97	*Liquidamber*	4.16
Populus	5595.92	*Syringa*	7.21
Carpinus	17.91	*Tsuga*	159.15
Fagus	35504.35	*Elaeagnus*	9.49
Prunus	405.28	*Cornus*	6.37
Aesculus	3015.29	*Sambucus*	2.11
Fraxinus	811.95	*Ilex*	3.96
Ulmus	1581.61	*Celtis*	7.12
Salix	924.98	*Sequoioideae*	4.03
Alnus	514.76	*Magnolia*	1.59
Platanus	1353.83	*Liriodendron*	95.37
Crataegus	55.15	*Cedrus*	2.35
Picea	150.30	*Euonymus*	0.17
Taxus	382.51	*Laburnum*	0.01
Malus	14.66	*Amelanchier*	0.51
Pseudotsuga	5322.38	*Rhamnus*	2.19
Sorbus	37.60	*Cercidiphyllum*	2.16
Other	263.60	*Rhus*	0.47
Ailanthus altissima	264.29	*Gymnocladus*	19.57
Larix	252.31	*Hippophae*	7.55
Carya	329.03	*Buxus*	2.81
Corylus	39.25	*Cydonia*	0.32
Juglans	105.92	*Paulownia*	0.31
Pyrus	16.78	*Euodia*	0.04
Mespilus	75.92	*Phellodendron*	2.31
Gleditsia	13.54	*Ostrya*	0.10
Cupressus	48.59	*Cercis*	3.30
Abies	50.56	*Parrotia*	0.04
Total	**152,920.47t**	**Total**	**890.07t**
Total carbon pool of park trees: 153,810.54t			

Even though there are 121,521 more street trees than park trees present in Berlin, the latter almost store twice as much carbon. As with the street trees, locust trees also store by far the largest quantities of carbon among the park trees with 69,827.93 tons, closely followed by beeches (35,504.35 tons) and oak trees (15,053.54 tons).

The carbon stored per species varies widely, which becomes clear when comparing poplars (*Populus*), hornbeams (*Carpinus*), and beeches *(Fagus*). Although all three species are represented equally with around 10,000 trees (± 1,000), the stored carbon varies from 5,595.92 tons (*Populus*), to only 17.91 tons (*Carpinus*), to one of the highest numbers with 35,504.35 tons (*Fagus*). The same pattern can also be observed in species that occur less frequently. Kentucky coffeetrees (*Gymnocladus*), seabuckethorns (*Hippophae*) and boxtrees (*Buxus*) each account for 0.08 % of the total park tree population but their carbon storage fluctuates between 19.75 tons, 7.55 tons, and 2.81 tons, respectively. This example clearly demonstrates how trees that do not occur as often can still store large quantities of carbon by their standards. Kentucky coffeetrees stand out in both, park and street tree populations as they are less frequent but accumulate significantly more carbon than those species that exist just as often.

Urban street trees and park trees combined store 283,177.24 tons of carbon. Figure 7 shows the carbon distribution in each of the 12 districts in the city of Berlin. According to this figure, the district of Steglitz-Zehlendorf in the south-west stores the most carbon from park and street trees combined, with a total of 64,764 tons. The second highest quantities can be found in the two northern-most districts of Reinickendorf and Pankow. Despite being one of the largest districts in size, Treptow-Köpenick stores the second lowest quantities of carbon in street trees and park trees. Considering that this district has one of the highest shares of forest areas in the city (Senate Department for Urban Development and Housing 2016), the small number of park and street trees can be explained The least amount of carbon is stored in the district of Marzahn-Hellersdorf with a total of only 2338 tons.

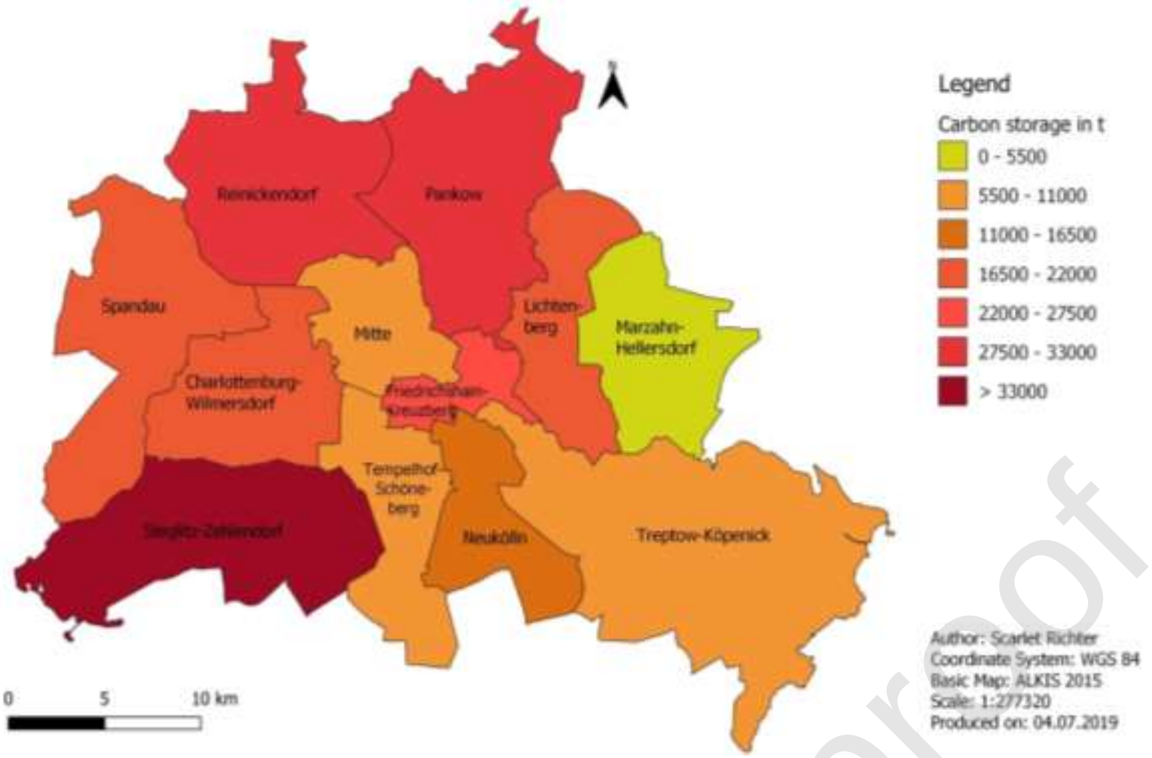


Figure 7: Total carbon storage of park trees and street trees combined per urban district in Berlin.

In general, the accumulation of carbon is highest in parks, despite the fact that there are less trees in parks. Due to their advanced age, they have longer life spans and therefore also the most substantial beneficial effect on CO_2 (Nowak and Crane 2002). The five most important tree species in Berlin also contribute to that as they account for 28 % of the total carbon stored in the urban aboveground biomass. As presented in Tables 5 and 6, great differences among the various tree species can be observed in terms of carbon storage, which is a common phenomenon in the urban biomass (Scharenbroch 2012). Nevertheless, vegetation is a CO_2 sink, and its contribution to the reduction of atmospheric CO_2 concentrations can be optimized. Healthy tree growth and high biodiversity ensure the stability of an ecosystem, especially in urban areas (Vollrodt et al. 2012).

Besides urban street and park trees, Berlin also has large urban forest areas, which considerably contribute to the city's carbon stock. In contrast to trees on the streets and in parks, trees in forest stands are mostly coniferous species. Pine trees (*Pinus*) account for around 60 % of Berlin's forest tree population, followed by oaks (*Quercus*) with 21 %. Other species (*Betula*, *Ulmus*, and *Fraxinus*) follow somewhat behind (Rock 2017). Since the total number of forest trees is not exactly known, the carbon storage of these trees was estimated as precisely as possible by Rock (2017) based on information from the different forest commission offices in Berlin. His research shows that a total of 5,613,500t of carbon are stored in Berlin forests, to which the biomass aboveground and below-ground was counted (Rock 2017). Together with street and park trees, a total of 5,851,676t of carbon are stored in urban trees, equating to 24 % of the total carbon storage including soils and peatlands. Together with urban soils, 24,087,344t of carbon are present in the city of Berlin.

4. Discussion

4.1 Carbon pools in a large and heterogeneous city

Referring to the first objective of this study, what above- and belowground carbon pools could be found in an urban region as large and heterogeneous in terms of land use like Berlin, soils were found to have accumulated substantial quantities of C_{org} over the last centuries. This is why soils now store significantly more carbon than urban vegetation and especially due to the hidden carbon stocks in the subsoils, cultural layers and sealed soils that were also found in other studies (Edmondson et al. 2014b, Vasenev and Kuzyakov 2018). As shown in the results (Section 3.1), almost all subsoils in Berlin store considerably more C_{org} than the corresponding topsoils. The reason for this distribution is not only because subsoils have greater depths but also because former topsoil (‘A’) horizons may have been buried in subsoils over the course of recent land use changes (Zhu et al. 2018). In addition, it was shown by Churkina (2012) that sealed surfaces are lacking in oxygen, which is why organic carbon does not decompose under impervious surfaces. Buried horizons and sealed surfaces are only two examples of anthropogenic influences in cities. Consequently, land cover and land uses are constantly changing within the city and thus can be regarded as the most important determinant of soil carbon storage (Marland et al. 2004). Therefore, high and low carbon densities can be detected within the city’s boundaries, whereas the latter is usually found in the city center and densely built-up areas.

In contrast, high carbon densities cannot only be found in forest areas or peatlands but also on the outskirts of the city. These areas are characterized by residential areas where detached family homes are the most common type of housing, meaning that they differ greatly from the housing development in the city center. As detached family home owners usually have their own private back gardens with lawns and trees planted for aesthetics and recreational purposes, soil carbon dynamics are influenced by the owners’ decisions and management (Zhu et al. 2018). Decision making on every scale can thus greatly alter carbon stocks within types or patches of soil, which then results in high spatial and temporal variability as well as high heterogeneity (Pouyat et al. 2006, Vasenev et al. 2018). Therefore, the spatial variability of carbon storage can be explained by the origin of the soil types, which initially influenced how much carbon can be stored according to different soil properties. In addition, continuing urbanization also affects spatial variability, depending on the new established land use. To a small extent it is also influenced by the personal choices of private land owners. If correlations between carbon storage and different land uses or municipal districts were calculated, the spatial variability could also be explained by corresponding variables. This could then be used as a solid basis for further studies.

And how does urbanization impact these patterns and the spatial variability of above and belowground carbon pools in Berlin? Recent and projected urbanization also contributes to the fragmentation of urban soils and therefore carbon stocks, which is associated with the sealing of soils in order to build more residential areas and roads. Carbon stocks and fluxes in urban areas are consequently limited by a higher imperviousness of soils (Vasenev and Kuzyakov 2018). These land use changes may alter the soil and deplete carbon stocks due to anthropogenic modifications, unless new urban green infrastructure is established, which could contribute to carbon storage in return (Vasenev et al. 2018). Therefore, land cover and land use changes might release carbon into the atmosphere but may also contribute to urban sustainability, which in the long term could then ensure carbon storage (Trammell et al. 2018). The continuing process of urbanization shows the increasing role that urban ecosystems have to play. In the city center, higher temperatures (2-4 °C) are being measured, which increases the UHI effect and increases temperatures. Hence, higher microbiological activity is expected that accelerates the mineralization of organic carbon and depletes carbon stocks. However, higher temperatures in the city center also mean a longer growing season for vegetation and higher photosynthesis rates, which could turn back the process and contribute to carbon storage in the biomass and soils (Trammell et al. 2018, Vasenev and Kuzyakov 2018). These processes show the high link between urban soils and vegetation and thus overall carbon storage. This also verifies the hypothesis that aboveground biomass depends on belowground carbon, even in a city.

In the aboveground vegetation, the total carbon storage depends on the tree cover as well as the number of healthy trees (Nowak and Crane 2002). Tree growth and the proportion of large, healthy trees are not only influenced by water stress and the competition for space, but also by the prevailing soil conditions (Vogt et al. 2015). Sealed surfaces in particular can affect the rooting volume, which limits root growth and aboveground growth. This shows that land use also significantly influences tree growth, survival rate and ultimately carbon storage (Vogt et al. 2015).

Faced with climate change and increasing urbanization rates, species are expected to adapt even further to urban pressures, which could result in new niches from adapted rooting systems so that land use may no longer be a limiting factor for carbon storage (Bae and Ryu 2015). Despite potential adaptation strategies, the tree survival rate in cities however is still substandard. The average maximum age of urban trees in Berlin is 60 years, depending on growth and environmental conditions (Senate Department for the Environment, Transport and Climate Protection 2019). Tree survival rates are especially low in the first years after planting, as these trees are prone to extreme climate conditions like heat stress. Therefore, the maintenance of these 2,500 trees planted annually in Berlin is very high and thus counteracts the carbon storage of these trees (Scharenbroch 2012, Senate Department for the Environment, Transport and Climate Protection 2019). Since young trees do not store that much carbon due to a lower DBH, maintenance methods emit more carbon through the burning of fossil fuels than the trees are able to store (Nowak and Crane 2002).

As revealed by the results, urban trees in Berlin (excluding urban forests) store 238,176 tons of carbon and thus act as a carbon sink. Ultimately, trees can turn into a carbon source when they die by releasing the captured carbon back into the atmosphere through decay and decomposition. In fact, only a small fraction of the carbon might be returned back to the soil. Hence, it is imperative to replace dead or destroyed trees to maintain the carbon balance (Davies et al. 2011, Scharenbroch 2012).

If trees cannot be replaced in the same place due to poor site conditions, they are usually planted on the outskirts where there are more open and less sealed surfaces (cf. Section 2.2). This management ignores the fact that those areas with a high degree of soil sealing are usually in greatest need of the benefits provided by trees (Vogt et al. 2015, Nyelele et al. 2019). This can result in self-reinforcing processes and an amplification of the UHI effect due to less shade and cooling supplied by trees. A reduction in ESS evidently decreases human well-being (Davies et al. 2011, Nowak et al. 2013, Nyelele et al. 2019).

We show that urban areas are complex systems, which constantly change over time and show strong interactions between anthropogenic and natural processes (Effland and Pouyat 1997). This holds especially true for the carbon pools in soils and vegetation.

Interactions between both ecosystems make it difficult to accurately map different pools of carbon storage. In line with other international studies, we found that the spatial variability of carbon in aboveground biomass and the soil change along the urban-rural gradient (Effland and Pouyat 1997, Pouyat et al. 2002, Strohbach and Haase 2012; Table 8).

Table 8: Soil carbon (SC) densities for urban land use types for different cities in Europe, Asia and the US. calculated values up to a depth of 1m belowground

<table>
<tr><th>Location</th><th>Land use</th><th>SC in topsoil (0-20 cm) in kg/m²</th><th>SC in subsoil (20-100 cm) in kg/m²</th><th>Source</th></tr>
<tr><td>Berlin</td><td>residential</td><td>4.0</td><td>24.66</td><td rowspan="3">Richter et al. (this study)</td></tr>
<tr><td>Berlin</td><td>park use</td><td>7.0</td><td>26.55</td></tr>
<tr><td>Berlin</td><td>brownfield (no vegetation)</td><td>2.2</td><td>61.45</td></tr>
<tr><td>Leicester</td><td>residential</td><td colspan="2">20.2</td><td>Edmondson et al. (2012)</td></tr>
<tr><td>Milan</td><td>park use</td><td>7.9***</td><td></td><td rowspan="2">Canedoli et al. (2020)</td></tr>
<tr><td>Milan</td><td>urban non-parks</td><td>5.3***</td><td></td></tr>
<tr><td>Paris</td><td>park use</td><td>9.8**</td><td></td><td>Cambou et al. (2018)</td></tr>
<tr><td>Atlanta</td><td>park use</td><td>7.1</td><td></td><td rowspan="2">Pouyat et al. (2006)</td></tr>
<tr><td>Boston</td><td>all types</td><td>5.9</td><td></td></tr>
<tr><td>Kings, NY</td><td>clean fill (material)</td><td colspan="2">3.8</td><td>New York City Soil Survey</td></tr>
<tr><td>Washington</td><td>clean fill (material)</td><td colspan="2">1.5</td><td>Short et al. (1986)</td></tr>
<tr><td>Richmond, NY</td><td>clean fill (material)</td><td colspan="2">4.6</td><td>New York City Soil Survey</td></tr>
<tr><td>New York City</td><td>park use</td><td>10.1**</td><td></td><td>Cambou et al. (2018)</td></tr>
<tr><td>New York</td><td>clean fill (material)</td><td></td><td>3.3</td><td>Pouyat et al. (2006)</td></tr>
<tr><td>Baltimore</td><td>residential</td><td>5.4*</td><td></td><td>Pouyat et al. (2002)</td></tr>
<tr><td>Baltimore</td><td>park use</td><td colspan="2">9.9</td><td rowspan="2">Pouyat et al. (2006)</td></tr>
<tr><td>Baltimore</td><td>residential</td><td colspan="2">12.2</td></tr>
<tr><td>Chicago</td><td>residential</td><td colspan="2">16.3</td><td>Jo and McPherson (1995)</td></tr>
<tr><td>Oakland</td><td>all types</td><td colspan="2">5.9</td><td rowspan="2">Pouyat et al. (2006)</td></tr>
<tr><td>Syracuse</td><td>all types</td><td colspan="2">7.1</td></tr>
<tr><td>Moscow</td><td>residential</td><td colspan="2">14.6</td><td>Stroganova et al. (1998)</td></tr>
<tr><td>Hongkong</td><td>park use</td><td colspan="2">4.2</td><td>Jim (1998)</td></tr>
</table>

* 0-15 cm, ** 0-30cm, *** 0-40cm

The higher the soil sealing, the lower the quantities of carbon that is stored in both (top and lower) soil and vegetation. Apart from peatlands and forest areas, the highest soil carbon can be found in parks and residential areas in the suburbs. The carbon storage in aboveground biomass follows the same pattern. Although urban trees can also be found in the city center and densely populated areas, they usually capture less carbon as their growth is limited by site conditions. Thus, the most carbon is stored in parks and cemeteries with their large, mature trees as well as in the less populated outskirts. Consequently, it can be said that soils and the aboveground biomass in Berlin act as a carbon sink (Rock 2017).

4.2 Uncertainties and limitations in modeling urban carbon pools

Mapping carbon storage in selected ecosystems is accompanied by uncertainties and limitations as the storage is highly dynamic and can change rapidly within short time periods. Combining the carbon storage of soils and the aboveground biomass in a complex system like a city is no exception.

The data for soil carbon calculations was provided by 22 different studies, totaling some 432 soil samples between the years 2005 and 2012 throughout the city of Berlin. The combination of all collected data was used for total soil carbon estimates. However, some of the data provided were incomplete in terms of physical soil properties such as bulk density or LOI. This is because all study teams took the sample according to their own study interests and research. An attempt was made to fill in the missing data based on existing literature. For example, the bulk density was often neglected and had to be derived, although it is important for measuring C_{org} content (cf. section 2.3).

Furthermore, not all soil horizons could be sampled equally, as the soil properties and the sealing did not enable deeper drilling. From this, it follows that, for soil samples taken only in the topsoil, the C_{org} content of the subsoil was estimated based on similar samples with comparable soil properties. Therefore, the estimation of specific soil properties and their carbon storage proved to be one of the challenges encountered in this study.

Another uncertainty was the double usage of some land uses. The land use data was provided by the Berlin Senate Department for Urban Development and Housing (2016) based on the land use classes of Copernicus Urban Atlas and ATKIS. Most of them are characterized by double uses, which is why they cannot clearly be assigned to one specific land use. For this study, the land use with the highest share per given area was used for the carbon calculations.

For example, the carbon storage for residential use was measured when the area was mostly used for residential purposes. However, housing service companies and local green spaces may also be included as double uses, which could eventually alter the calculations because they were not taken into account for the specific area.

As mentioned previously, the data provided is based on land use from 2015. This means that for such a dynamic and changing city like Berlin, it is probable that since then some land uses and thus carbon content could have changed. This is even more likely in times of urbanization and its associated housing construction. In this context, the degree of soil sealing also changes with changing use and can therefore be a further source of errors in the calculation, in particular because the range of the degree of soil sealing is very high depending on the different land uses. For this study, the average degree of soil sealing was used (cf. section 2.3), which is more accurate the lower the soil sealing is.

When measuring the carbon storage in the aboveground biomass, uncertainties are lower compared to the calculations for soil carbon. This is mainly because tree species and their corresponding biomass and carbon formulas are well known because they have been established over decades (Ter-Mikaelian and Korzukhin 1997). However, some uncertainties remain and can be related to the age of some of the tree species. Street trees are planted and well-monitored by the city, which is why most of the information on street trees (tree species, year of planting, age of the tree, location) is complete in the dataset. Less than 1 % (57 trees) of the tree species have not been identified. Hence, the age of these trees was averaged based on the information of the remaining species. The same holds true for the DBH, biomass, and carbon calculations. Information and data about park trees on the other hand are less available as these trees are not observed as often. The missing information was averaged in the same way as for the street trees, but because more trees (2,103) lack valuable data, the uncertainties for park trees are higher. An overestimation or underestimation of the carbon stored might be a possible consequence.

This could also be the case with carbon storage in the urban forests of Berlin. Estimates by Rock (2017) are based on data from the different forestry commission offices, for which the accuracy is not known. According to the Leipziger Institut für Energie (2016), an overall uncertainty range between 10 % and 60 % can be expected for the total carbon storage in Berlin. The large range is due to the fact that aboveground carbon calculations are more accurate than soil carbon estimates because the soil samples taken represent a large part of the city but could be more expanded.

Due to the long data collections required to obtain meaningful results and rapidly changing urban land uses and built/non-built structures, as well as afforestation along streets, it is almost impossible to get a current picture of the total below- and aboveground carbon pool in Berlin. Furthermore, because it is the first study of its kind, many challenges arose that cannot be compared with previous studies such as Strohbach and Haase 2012 for the city of Leipzig or, including emissions, Bergeron and Strachan (2011) for Montréal.

5. Conclusions

This study is the first to combine organic carbon storage in urban soils and peatlands with the carbon stored in the urban aboveground biomass. It was conducted to estimate the total carbon stock for the city of Berlin and its potential for further carbon storage, especially in times of urbanization and climate change.

We conclude that more than two-thirds of the stored carbon can be found in soils, which makes them the largest carbon reservoir, not only in the city, but also globally. Peatlands in particular contribute to the stock as they store 6 % of the total carbon, despite their low occurrence. Nevertheless, Berlin is a city with one of the highest proportions of green spaces in Germany and therefore contributes to carbon storage as well as to human well-being. However, the accumulated carbon is not equally distributed throughout the city, but rather follows an urban-rural-gradient, which represents a high spatial variability. It shows that most of the carbon is stored at great depths in the subsoil and is expected to remain constant because land use and land cover changes predominantly influence the topsoil and the vegetation.

However, peatlands are extremely vulnerable to change and drying up, which is why these ecosystems need special protection. Because considerable quantities of carbon are currently stored in Berlin, the city's potential to store carbon is also very high. Therefore, the city can be seen as a carbon sink. This could change however, if peatlands – and other areas with high carbon content – are degraded due to climate change or disappear completely because of changes in land use.

The approach developed to map the total carbon storage in a city can enhance our understanding of local and regional carbon stocks and their spatial distribution, which is essential with continuing urbanization and associated land use and land cover changes. Therefore, further research is needed in order to provide a more detailed insight into carbon storage in a city with all its dynamics and links. This could either be done by mapping and analyzing a small fraction of a city first to capture all of the relevant carbon dynamics before projecting them to the entire area. Another way to improve estimations of carbon storage is to use consistent methods when taking soil samples and mapping the aboveground biomass. In this way, a bias between the sampling methods—and eventually carbon storage—could be avoided. This highly relevant topic could serve as a basis for further research in the field of urban geography and urban ecology and at the same time contribute to calculating the carbon storage potential of other cities.

Author statement

We, Scarlet Richter, Dagmar Haase, Kolja Thestorf and Mohsen Makki, are the authors of this manuscript.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We wish to thank our colleague Manuel Wolff for assisting in designing the graphics. Dagmar's research was supported as part of the project ENABLE, funded through the 2015-2016 BiodivERsA COFUND call for research proposals, with the national funders The Swedish Research Council for Environment, Agricultural Sciences, and Spatial Planning, Swedish Environmental Protection Agency, German aeronautics and space research centre, National Science Centre (Poland), The Research Council of Norway and the Spanish Ministry of Economy and Competitiveness. In addition, Dagmar benefited from the GreenCityLabHue Project (FKZ 01LE1910A) and the CLEARING HOUSE (Collaborative Learning in Research, Information-sharing and Governance on How Urban forest-based solutions support Sino-European urban futures) Horizon 2020 project (No 1290/2013). Dagmar further contributed to this paper as part of the EU Horizon 2020 project CONNECTING Nature – COproductioN with NaturE for City Transitioning, Innovation and Governance (Project Number: 730222).

References

Ad-hoc AG Boden, 2005, Bodenkundliche Kartieranleitung, 5th edition, Schweizerbart, Hannover.

Bae, J. and Ryu, Y., 2015. Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park. *Landscape and Urban Planning* 136, pp. 57-67. https://doi.org/10.1016/j.landurbplan.2014.11.015

Bergeron, O. and Strachan, I. B., 2011. CO_2 sources and sinks in urban and suburban areas of a northern mid-latitude city. *Atmospheric Environment* 45(8), pp. 1564-1573.http://dx.doi.org/10.1016/j.atmosenv.2010.12.043

Cambou, A., Shaw, R. K., Huot, H., Beaudet, L. V., Hunault, G., Cannavo, P., Nold, F. and Schwartz C., 2018. Estimation of soil carbon stocks of two cities, New York and Paris. *Science of The Total Environment* 644, pp. 452-464. https://doi.org/10.1016/j.scitotenv.2018.06.322

Canedoli, C., Ferrè, C, El Khair, D. A., Padoa-Schioppa, E. and Comolli, R., 2020. Soil organic carbon stock in different urban land uses: high stock evidence in urban parks. *Urban Ecosystems* 23(1), pp. 159-171. https://doi.org/10.1007/s11252-019-00901-6

Churkina, G., 2008. Modeling the carbon cycle of urban systems. *Ecological Modelling* 216(2), pp. 107-113. https://doi.org/10.1016/j.ecolmodel.2008.03.006

Churkina, G., 2012. Carbon Cycle of Urban Ecosystems. In: Lal R. and Augustin B. (Eds.), *Carbon Sequestration in Urban Ecosystems*, Springer, Dordrecht, pp. 315-330. https://doi.org/10.1007/978-94-007-2366-5_16

Davies, Z. G., Edmondson, J. L., Heinemeyer, A., Leake, J. R. and Gaston, K. J., 2011. Mapping an urban ecosystem service: quantifying aboveground carbon storage at a city-wide scale. *Journal of Applied Ecology* 48(5), pp. 1125-1134. https://doi.org/10.1111/j.1365-2664.2011.02021.x

Dinakaram, J. and Rao, K. S., 2012. Carbon Sequestration in Terrestrial Vegetation and Soils: A review. *Phytomorphology: An International Journal of Plant Morphology* 62(1&2), pp. 177-188.

DIN 19684-3:2000-08, 2000. Methods of soil investigations for agricultural water engineering - Chemical laboratory tests - Part 3: Determination of the loss on ignition and the residue of soil after ignition.

DIN EN ISO 11272:2017-07, 2017. Soil quality - Determination of dry bulk density (ISO 11272:2017). https://dx.doi.org/10.31030/2581910

Edelmann, S., 2013. Organischer Kohlenstoff in terrestrischen und semiterrestrischen Stadtböden – Eine Bilanzierung der organischen Kohlenstoffgehalte und –mengen in Abhängigkeit von der Flächennutzung im Berliner Stadtgebiet. *Diploma thesis*, Geography Department of Humboldt-Universität zu Berlin.

Edmondson J. L., Davies, Z. G., McHugh, N, Gaston, K. J. and Leake, J. R., 2012. Organic carbon hidden in urban ecosystems, *Scientific Reports* 2, 963. https://doi.org/10.1038/srep00963

Edmondson J. L., Davies, Z. G., McCormack, S. A., Gaston, K. J. and Leake, J. R., 2014a. Land-cover effects on soil organic carbon stocks in a European city. *Science of The Total Environment* 472, pp. 444-453. https://doi.org/10.1016/j.scitotenv.2013.11.025

Edmondson, J. L., O'Sullivan, O.S., Inger, R., Potter, J., McHugh, N., Gaston, K. J. and Leake, J.R., 2014b. Urban Tree Effects on Soil Organic Carbon. *PLoS ONE* 9(7): e10187. https://doi.org/10.1371/journal.pone.0101872

Effland, W. R. and Pouyat, R. V., 1997. The genesis, classification, and mapping of soils in urban areas. *Urban Ecosystems* 1(4), pp. 217-228. https://doi.org/10.1023/A:1018535813797

Haase, D., 2009. Effects of urbanisation on the water balance – A long-term trajectory. *Environmental Impact Assessment Review* 29(4), pp. 211-219. https://doi.org/10.1016/j.eiar.2009.01.002

Hayat, A., Hacket-Pain, A. J., Pretzsch, H., Rademacher, T. T. and Friend, A. D., 2017. Modeling Tree Growth Taking into Account Carbon Source and Sink Limitations. *Frontiers in Plant Science* 8(182), pp. 1-15. https://doi.org/10.3389/fpls.2017.00182

Hollis, J. M., 1991. The Classification of Soils in Urban Areas. In: Bullock, P. and Gregory, P. J. (Eds.), *Soils in the Urban Environment*, Blackwell Scientific Publications, Oxford, pp. 5-27. https://doi.org/10.1002/9781444310603.ch2

Jenkins, J. C., Chojnacky, D. C., Heath, L. S. and Birdsey, R. A., 2003. National-Scale Biomass Estimators for United States Tree Species. *Forest Science* 49(1), pp. 12-35. https://doi.org/10.1093/forestscience/49.1.12

Jim, C. Y., 1998. Soil characteristics and management in an urban park in Hong Kong. *Environmental Management*, 22(5), pp. 683-695. https://doi.org/10.1007/s002679900139

Jo, H. and McPherson, E., 1995. Carbon storage and flux in urban residential green space. *Journal of Environmental Management* 45, pp. 109-133. doi:10.1006/jema.1995.0062

Jobbágy, E. G. and Jackson, R. B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10(2), pp. 423-436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2

Johnson, A. D. and Gerhold, H. D., 2003. Carbon Storage by urban tree cultivars, in roots and aboveground. *Urban Forestry & Urban Greening* 2(2), pp. 65-72. https://doi.org/10.1078/1618-8667-00024

Klingenfuß, C., Roßkopf, N., Walter, J., Heller, C. and Zeitz, J., 2014. Soil organic matter to soil organic carbon ratios of peatland soil substrates. *Geoderma* 235–236, pp. 410-417. https://doi.org/10.1016/j.geoderma.2014.07.010

Lehmann, A. and Stahr, K., 2007. Nature and significance of anthropogenic urban soils. *Journal of Soils and Sediments* 7(4), pp. 247-260. https://doi.org/10.1065/jss2007.06.235

Lindén, L., Riikonen, A., Setälä, H. and Yli-Pelkonen, V., 2020. Quantifying carbon stocks in urban parks under cold climate conditions. Urban Forestry & Urban Greening 49, 126633. https://doi.org/10.1016/j.ufug.2020.126633

Marland, G., Garten Jr., C.T., Post, W. M. and West, T.O., 2004. Studies on enhancing carbon sequestration in soils. *Energy* 29(9-10), pp. 1643-1650. https://doi.org/10.1016/j.energy.2004.03.066

Makowsky, L. and Meuser, H., 2007. Quantification of carbon content in soils from abandoned contaminated land dominated by technogenic substrates. *altlasten spektrum* 2/2007, pp. 53-60

Meuser, H., 2010. Contaminated Urban Soils. *Environmental Pollution* 18, Alloway, B. A. and Trevors, K. T. (Eds.), Springer, Dordrecht

Morel, J. L., Chenu, C. and Lorenz, K., 2015. Ecosystem services provided by soils of urban, industrial, traffic, mining, and military areas (SUITMAs). *Journal of Soils Sediments* 15, pp. 1659–1666. https://doi.org/10.1007/s11368-014-0926-0

Nowak, D. J. and Crane, D. E., 2002. Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution* 116(3), pp. 381-389. https://doi.org/10.1016/S0269-7491(01)00214-7

Nowak, D. J., Greenfield, E. J., Hoehn, R. E. and Lapoint, E., 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution* 178, pp. 229-236. https://doi.org/10.1016/j.envpol.2013.03.019

Nyelele, C., Kroll, C. N, and Nowak, D. J., 2019. Present and future ecosystem services of trees in the Bronx, NY. *Urban Forestry & Urban Greening* 42, pp. 10-20. https://doi.org/10.1016/j.ufug.2019.04.018

Pouyat, R. V., Groffman, P., Yesilonis, I. D. and Hernandez, L., 2002. Soil carbon pools and fluxes in urban ecosystems. *Environmental Pollution* 116, Supplement 1, pp. S107-S118. https://doi.org/10.1016/S0269-7491(01)00263-9

Pouyat, R. V., Yesilonis, I. D. and Nowak, D. J., 2006. Carbon storage by urban soils in the United States. *Journal of Environmental Quality* 35(4), pp. 1566-1575. https://doi.org/10.2134/jeq2005.0215

Roman, L. A., Battles, J. J., and McBride, J. R., 2014. The balance of planting and mortality in a street tree population. *Urban Ecosystems* 17(2), pp. 387-404. https://doi.org/10.1007/s11252-013-0320-5

Scharenbroch, B. C., 2012. Urban Trees for Carbon Sequestration. In: Lal, R. and Augustin, B. (Eds.), *Carbon Sequestration in Urban Ecosystems*, Springer, Dordrecht, pp. 121-138. https://doi.org/10.1007/978-94-007-2366-5_6

Scharenbroch, B. C., Day, S., Trammell, T. L. E. and Pouyat, R. V., 2018. Urban Soil Carbon Storage. In: Lal, R. and Stewart, B. A. (Eds.), *Urban Soils*, CRC Press, Boca Raton, pp. 137-154.

Seto, K. C., Güneralp, B. and Hutyra, L. R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *PNAS* 109(40), pp. 16083-16088. https://doi.org/10.1073/pnas.1211658109

Short, J. R., Fanning, D. S., McIntosh, M. S., Foss, J. E. and Patterson, J. C. 1986. Soils of the Mall in Washington, DC: I, Statistical Summary of Properties. *Soil Science Society of America Journal* 50(3), pp. 699-705. https://doi.org/10.2136/sssaj1986.03615995005000030030x

Strohbach, M. W. and Haase, D., 2012. Aboveground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city. *Landscape and Urban Planning* 104(1), pp. 95-104. https://doi.org/10.1016/j.landurbplan.2011.10.001

Tigges, J., Churkina, G. and Lakes, T., 2017. Modeling aboveground carbon storage: a remote sensing approach to derive individual tree species information in urban settings. *Urban Ecosystems* 20(1), pp. 97-111. https://doi.org/10.1007/s11252-016-0585-6

Ter-Mikaelian, M and Korzukhin, M. D., 1997. Biomass equation for sixty-five North American tree species. *Forest Ecology and Management* 97(1), pp. 1-24. https://doi.org/10.1016/S0378-1127(97)00019-4

Trammell, T. L. E., Day, S., Pouyat, R. V., Rosier, C., Scharenbroch, B. C. and Yesilonis, I. D., 2018. Drivers of Urban Soil Carbon Dynamics. In: Lal, R. and Stewart, B. A. (Eds.), *Urban Soils*, CRC Press, Boca Raton, pp. 93-120.

Ugle, P., Rao, S. and Ramachandra, T. V., 2010. Carbon sequestration potential of urban trees. Conference Paper, Lake 2010: Wetlands, Biodiversity and Climate Change Conference at IISc, Bengaluru, 22nd-24th of December 2010

Vasenev, V. I., Stoorvogel, J. J., Vasenev, I. I. and Valentini, R., 2014. How to map soil organic carbon stocks in highly urbanized regions? *Geoderma* 226-227, pp. 103-115. https://doi.org/10.1016/j.geoderma.2014.03.007

Vasenev, V. I. and Kuzyakov, Y., 2018. Urban soils as hot spots of anthropogenic carbon accumulation: Review of stocks, mechanisms and driving factors. *Land Degradation & Development* 29(6), pp. 1607-1622, https://doi.org/10.1002/ldr.2944

Vasenev, V. I., Stoorvogel, J. J., Dolgikh, A. V., Ananyeva, N. D., Ivashchenko, K. V. and Valentini, R., 2018. Changes in Soil Organic Carbon Stocks by Urbanization. In: Lal, R. and Stewart, B. A. (Eds.), *Urban Soils*, CRC Press, Boca Raton, pp. 61-91.

Velasco, E., Roth, M., Norford, L. and Molina, L. T., 2016. Does urban vegetation enhance carbon sequestration? *Landscape and Urban Planning* 148, pp. 99-107. https://doi.org/10.1016/j.landurbplan.2015.12.003

Vitt, D. H. and Short, P., 2016. Peatlands. In: Lal, R. (Ed.), *Encyclopedia of Soil Science*, CRC Press, Boca Raton, pp. 1668-1673.

Vogt, J. M., Watkins, S. L., Mincey, S. K., Patterson, M. S. and Fischer, B. C., 2015. Explaining planted-tree survival and growth in urban neighborhoods: A socio-ecological approach to studying recently-planted trees in Indianapolis. *Landscape and Urban Planning* 136, pp. 130-143. https://doi.org/10.1016/j.landurbplan.2014.11.021

Vollrodt, S., Frühauf, M., Haase, D. and Strohbach, M., 2012. Das CO2-Senkenpotential urbaner Gehölze im Kontext postwendezeitlicher Schrumpfungsprozesse. *Hallesches Jahrbuch für Geowissenschaften* 34, pp. 67-92.

Washbourne, C.-L., Renforth, P. and Manning, D. A. C., 2012. Investigating carbonate formation in urban soils as a method for capture and storage of atmospheric carbon. *Science of the Total Environment* 431, pp. 166-175. https://doi.org/10.1016/j.scitotenv.2012.05.037

Yigini, Y. and Panagos, P., 2016. Assessment of soil organic carbon stocks under future climate and land cover changes in Europe. *Science of the Total Environment* 557-558, pp. 838-850. https://doi.org/10.1016/j.scitotenv.2016.03.085

Zhu, W., Egitto, B. A., Yesilonis, I. D. and Pouyat, R. V., 2018. Soil Carbon and Nitrogen Cycling and Ecosystem Service in Cities. In: Lal, R. and Stewart, B. A. (Eds.), *Urban Soils*, CRC Press, Boca Raton, pp. 121-135.

Internet Sources

Klingenfuß, C., Möller, D., Heller, C., Thrum, T., Köberich, K. and Zeitz, J., 2015, Berliner Moorböden im Klimawandel - Entwicklung einer Anpassungsstrategie zur Sicherung ihrer Ökosystemleistungen. UEPII-Forschungsprojekt, Abschlussbericht. Humboldt-Universität zu Berlin, unveröffentlicht. Retrieved June 26th, 2019 from http://www.berliner-moorboeden.hu-berlin.de/content/project.php

Leipziger Institut für Energie, 2016. Erstellung der Berliner Emissionskataster Industrie, Gebäudeheizung, sonstiger Verkehr, Kleingewerbe, sonstige Quellen, Baustellen. AVISO GmbH, Aachen. Retrieved June 26th, 2019 from https://www.berlin.de/senuvk/umwelt/luftqualitaet/de/emissionen/download/Endbericht_Emissionkataster_2015.pdf

Renger, M., Bohne, K., Facklam, M., Harrach, T., Riek, W., Schäfer, W., Wessolek, G. and Zacharias, S., 2008. Ergebnisse und Vorschläge der DGB-Arbeitsgruppe „Kennwerte des Bodengefüges“ zur Schätzung bodenphysikalischer Kennwerte, unveröffentlicht. Retrieved June 26th, 2019 from https://www.boden.tu-berlin.de/fileadmin/fg77/_pdf/publikationen/bodenphysikalischeKennwerte.pdf

Rock, J. (2017): Der Beitrag der Berliner Wälder zum Klimaschutz Berlins. Ökosystemdienstleistungen der Berliner Wälder mit den Schwerpunktthemen „Bilanzierung der Kohlenstoffspeicherung“ und „Klimaschutzfunktion“, Technical Report, Thünen-Institut für Waldökosysteme, Eberswalde. Retrieved June 9th, 2020 from https://www.berlin.de/forsten/_assets/waldschutz/walderhaltung/studie_beitrag_berliner_waelder_zum_klimaschutz.pdf

Senatsverwaltung für Stadtentwicklung und Umwelt, 2016. Flächennutzung und Stadtstruktur. Dokumentation der Karteneinheiten und Aktualisierung des Datenbestandes 2015. Retrieved June 26th, 2019 from http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/download/Nutzungen_Stadtstruktur_2015.pdf

Senate Department for the Environment, Transport and Climate Protection, 2019. Nature and Green / Urban Green Space. Retrieved June 26th, 2019 from https://www.berlin.de/senuvk/umwelt/stadtgruen/index_en.shtml

Senate Department for Urban Development and Housing, 2016. Berlin Environmental Atlas / 06.01/02 Actual Use of Built-up Areas / Inventory of Green and Open Spaces (Edition 2016). Retrieved March 3rd from https://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/edin_601.htm

Senate Department for Urban Development and Housing, 2019. Geoportal Berlin / Baumbestand Berlin, Retrieved June 26th, 2019 from https://fbinter.stadt-berlin.de/fb/index.jsp?loginkey=zoomStart&mapId=k_wfs_baumbestand@senstadt