Eidgenössische Technische Hochschule Zürich
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Measuring change in ecosystem service-providing vegetation on densified areas

Bachelor Thesis

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Abstract

Vegetation provides important ecosystem services. Especially in cities, where climate change and air pollution threaten human health among other things, green spaces and trees provide an improvement in the quality of life. However, due to the densification of urban areas, permeable surfaces and vegetation come into competition with potential building ground. In Switzerland, there is no standardized method to measure change in vegetation during construction projects.

The aim of this thesis was to test a method for assessing open space developments on overbuilt sites. For this purpose, the changes in tree stocks, vegetated grounds and unsealed grounds were measured at six study sites in the city of Zurich using orthophotos and LiDAR point clouds. The developments then were assessed with evaluation schemes. These assessments showed that densification does not necessarily come with more sealed area. Vegetated area, which provides more ecosystem services than unsealed but non-vegetated area, increased on four of the six sites. Furthermore, it was observed that the number of trees increased with the superstructures at all study sites, and for half of the examined areas the tree stocks are well adapted to climate change.

The software i-Tree Eco estimates the ecosystem services provision by trees. It calculates both positive and negative effects of trees based on parameters measured in the field. Since field measurements are time consuming, the question arose as to how well the input parameters can be determined based on airborne remote sensing data. For a sample of 18 trees, the input parameters were determined both in the field and with LiDAR point clouds. The outputs of i-Tree Eco on the basis of the two input parameter sets differed more than expected. Based on field data, a tree cover of 21.3% was calculated by i-Tree Eco. Moreover, a carbon storage of 950 kg, an avoided stormwater runoff of about 21 m^3 per year and an air pollution removal of 6.5 kg per year were calculated. The data collected with remote sensing resulted in calculated carbon storage more than 200% higher than calculated with field data. The other calculated effects were also higher based on remote sensing, but the difference was less than 50%. For this reason it was concluded that ecosystem services are likely to be overestimated when calculated based on remote sensing data. The main reason for the deviations is that the input parameters diameter at breast height, missing crown and crown dieback could not be determined accurately without field surveys.

Acknowledgments

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1 Introduction

The population in Zurich is growing. Nevertheless, building zones should not be expanded in order to reduce urban sprawl and protect the cultural landscape and nature. Therefore, existing settlements must be densified. (Stadt Zürich (2021)) Densification is seen as a threat to green infrastructure because densification in inner cities puts unsealed green spaces and old tree stocks in competition with potential building sites (Cimburova and Barton (2020)). At the same time, urban vegetation is becoming increasingly important because it is one of the most cost-effective approaches to mitigating environmental threats in cities, and there are several circumstances that threaten urban livability (Livesley et al. (2016)).

1.1 Environmental threats to cities

The temperature is rising because of climate change. Cities are particularly affected by this trend due to the emerging urban heat island effect (Gehrig et al. (2018)). The urban heat island effect describes the situation when urban or industrial areas experience higher temperatures than surrounding, often more rural areas. There are two forms: the surface urban heat island and the atmospheric urban heat island. Surfaces are heated by sunlight. There is usually less tree cover in cities and thus less shade than in rural areas. Lack of shading results in increased heating of surfaces. If not surfaces but the air in urban or industrial areas heats up more than the air in rural areas, it is called an atmospheric urban heat island. The warming of the air is influenced by the surface heat island effect. (A et al. (2017))

The absence of shading in city centers favors surface heating, but it is not the only factor leading to the urban heat island effect. Developed areas tend to be less open, consist of more concrete, and have less permeable surfaces and less vegetation (A et al. (2017)). Dark materials like asphalt but also dark gravel have a lower albedo than vegetation, which means they absorb more short-wave radiation (Davies et al. (2003)). Also, concrete and asphalt store heat better than vegetated grounds because they have a high heat capacity. This causes these materials to emit long-wave thermal radiation, keeping urban areas warm at night.

In cities there are significantly more tropical nights, i.e., nights when the temperature stays above 20 degrees, than in rural areas. For example, in summer 2018 there were 15-18 tropical nights in the city of Zurich while there were none in Zurich Affoltern, which is at the edge of the city (Gehrig et al. (2018)). The heat in cities leads to increased energy demand for cooling. Also, the heat can have adverse health effects and for example lead to heat strokes, heat cramps or respiratory difficulties. (A et al. (2017)) Tropical nights in particular can be life-threatening for children, the elderly and sick people (Gehrig et al. (2018)).
However, urban heat islands are not the only consequence of climate change. There is also an increase in extreme weather events such as dry episodes and heavy rains, which, in combination with urbanization, favor decreasing infiltration rates in soils. One problem of decreasing infiltration is that aquifers are not being recharged. Reduced infiltration rates additionally result in increased surface runoff. Surface runoff can lead to flooding and channel erosion. Also, the runoff can contain many pollutants. (Scharenbroch et al.

(2016)) Swiss wastewater treatment plants are not capable of treating all water of a heavy rain event, and most of the stormwater drain is discharged into open waters without any treatment (AWEL (2009)). Thus, polluted water enters downstream water bodies and drinking water.

Besides these two impacts favored by climate change, air pollution also threatens the quality of life in cities. Outdoor air pollution is associated with about 8 million deaths worldwide per year. (Sicard et al. (2018)) In Zurich, there are only a few pollutants whose concentrations still partially exceed the limit values of the Swiss Air Pollution Control Ordinance. The limit exceeding pollutants are nitrogen dioxide (NO_2), particulate matter smaller than 10 µm (PM_{10}), particulate matter smaller than 2.5 µm ($PM_{2.5}$) and ozone (O_3). There has been an improvement of air quality over the past 30 years. For example, at Stampfenbachstrasse, which is a measurement station in the center of Zurich, both PM_{10} and NO_2 complied with the limit values in 2019. The yearly average of $PM_{2.5}$ concentration was 10.2µg/m^3, which exceeds the limit value of 10µg/m^3 for the yearly average. The limit values for ozone are exceeded over large areas. Ozone concentrations vary during the day; therefore, the limit value is determined for one hour. The hourly mean value of 120 µg/m^3 may only be exceeded once a year. In the heat summer of 2018, 312 hourly mean values were above the limit at the measuring station at Stampfenbachstrasse. (Luftreinhalte-Verordnung (2020)), (Stadt Zürich), (Stadt Zürich (2016a))

Tropospheric ozone is one of the most common air pollutants in Europe and a component of the so-called summer smog (Fitzky et al. (2019)). Due to mixing processes in the air layers, ozone concentrations can already be high without anthropogenically emitted precursors (Stadt Zürich). Nevertheless, it is also formed under anthropogenic influence, i.e. because of the emission of volatile organic compounds (VOCs) and nitrogen oxides (NO_x). High VOCs/NO_x ratios lead to more ozone formation. Ozone can be degraded by NO, which occurs in higher concentrations where there is much traffic. (Sicard et al. (2018)) As a result, suburbs are often more affected by high ozone concentrations than city centers because the NO_x concentrations are lower there. In the periphery of Zurich, 674 hourly mean values of ozone exceeded the limit in 2018 (Stadt Zürich). It is expected that NO_x emissions will decrease in city centers because combustion-powered vehicles will be replaced (Fitzky et al. (2019)). Therefore, ozone concentrations might also increase in inner cities. According to the Zurich Air Quality Report , ozone precursors would need to be reduced by at least 50% to achieve compliance with ozone limits. Furthermore, only 10-20% of ozone formation is influenced by local pollutant emissions. This means that the formation of ozone is mainly due to regional or even international air pollution. (Stadt Zürich (2016a))

Human health would strongly benefit from keeping the ozone concentration below the limit because besides NO_2 and PM, ozone is one of the most health threatening pollutants occurring in cities (Sicard et al. (2018)). High ozone concentrations can lead to respiratory diseases and intensify the symptoms of people suffering asthma or allergies. Especially in combination with heat, urban air pollution by ozone and particulate matter can lead to death for some risk groups. In addition, tropospheric ozone is a powerful greenhouse gas and damages cultivated crops, which is leading to yield losses in agriculture. (Staehelin et al. (2016)), (Sicard et al. (2018))

1.2 Study objectives

It is known that green spaces and particularly trees can have positive impacts on microclimate, surface runoff, air quality, carbon storage and biodiversity (Gill et al. (2008)). Moreover, green spaces are attributed a recreational function and are considered to upgrade the cityscape (Arduser et al. (2020)).
However, there is no standardized tool to survey and quantify green spaces with remote sensing data in cities of Switzerland (Felber (2020)). In fact, no standardized tools to survey the development of green areas or tree stocks in Switzerland could be found at all.

The goal of this thesis is to help identifying appropriate methods with which vegetation-based climate adaptation strategies can be evaluated. This is especially of interest when new, densified residential areas are built.

The explorative evaluation consists of 3 parts:

- A compilation of the state of knowledge of the potential of unsealed surfaces, vegetated soils and trees to mitigate the above-mentioned threats.
- A survey of green space and tree stock development on six newly built residential areas in Zurich and their assessment based on findings in literature.
- A test whether the software i-Tree Eco can be run with less effort.

Based on the state of knowledge, a scheme for assessing the developments on the study sites should be created. The chosen approach to survey the development of green spaces on residential areas was inspired by the master thesis of Wild (2013), in which she analyzed the development of green spaces in Zurich with a focus on biodiversity.

The ecosystem service provision by trees cannot be assessed by a scheme alone. A common software for the analysis of environmental impacts of urban trees is i-Tree Eco. This American software is based on the Urban Forest Effects (UFORE) model. In a so-called complete inventory analysis, environmental effects of specific trees can be calculated based on input parameters and with respect to local meteorological and pollution data of a certain year. i-Tree Eco is made for qualitative data analysis which is the reason why the input parameters should be measured in field surveys. However, data collection in the field is time consuming and thus expensive (Cimburova and Barton (2020)). Therefore, it should be investigated whether data collection for the i-Tree software also works with airborne remote sensing data and image interpretation, which is a less costly method. Such an approach would facilitate the evaluation of impacts of urban trees in cities, especially because the city of Zurich provides open access to remote sensing data.

Against the backdrop of the explanations above, the questions of this thesis are as follows:

- What is the current state of knowledge of the effects of vegetated areas, unsealed areas and urban trees on heat island mitigation, surface runoff and air pollution?
  - How do vegetation, including trees, and unsealed grounds mitigate these problems? What needs to be considered when using vegetation?
- Did densification at six specific study sites result in housing developments that are better adapted to climate change and air pollution than the site was before the new superstructure?
  - Did vegetated and unsealed grounds increase or decrease?
  - Did the number of trees increase or decrease?
  - What are the consequences of the changes? What could be improved?
- Is it possible to reduce the effort of data acquisition for the i-Tree Eco software to be able to assess ecosystem services of trees on residential areas in a city?
  - What is the difference of the outputs of i-Tree Eco when data is either collected in the field or extracted from remote sensing data?

2 Material and Methods

2.1 Material

2.1.1 Literature review

The literature research was started with *Schlussbericht Urban Green & Climate Bern - Die Rolle und Bewirtschaftung von Bäumen in einer klimaangepassten Stadtentwicklung* (Blaser et al. (2016)) and *Stadtbäume der Zukunft* (Casanelles et al. (2020)). These two publications show the relevance of trees and vegetation in urban areas of Switzerland. By reading cited authors and looking for similar literature in *Web of Science* and *Google Scholar*, other sources were found, which are listed in the chapter *References*.

2.1.2 Study areas

In order to investigate the development of ground coverage and tree stocks, six study areas were selected. The sites have in common that residential areas have been developed there recently, i.e., they were completed after 2010. Three of the sites were already residential, and the other three are former industrial sites. The settlements at the sites should be representative of modern housing estates in Zurich. The sites were found using orthophotos and Google maps. Two of the selected sites, Kalkbreite and Hunzikerareal, are famous for their architecture and listed as exceptional buildings in a report by the city of Zurich (Stadt Zürich (2016)).

The following six areas were examined:

Rautistrasse

At the location in Zurich Altstetten shown in fig. 1, an older housing estate from 1948 was replaced with a new one. In 2014, the settlement was completed. The buildings were certified with the label Minergie-Eco. (Stadt Zürich Amt für Hochbauten (2016))

Fig. 1 Rautistrasse, 2010 and 2018

Escherpark

A housing estate of the 1950s was replaced at this site in Zurich Wollishofen. The residential area, which was certified with the *greenproperty label* and complied with the requirement of Minergie-Eco, was completed in 2015. (Wincasaweb) Before and after are shown in 2.

Fig. 2 Escherpark, 2010 and 2018

Triemli
The development with multi-floor houses on the site in Zurich Albisrieden was completed in 2016 (Papazoglou (2017)). The view of the place changed, which is shown in 3.

Fig. 3 Triemli, 2007 and 2018

Hunziker Areal

This site in Zurich Seebach, shown in fig. 4, was the location of the concrete factory Hunziker. In 2010, the building cooperative *mehr als wohnen* took over the building rights and planned an affordable, environment-friendly residential area with some commercial space. In 2014/2015, the superstructure was completed. (mehr als wohnen (2017))

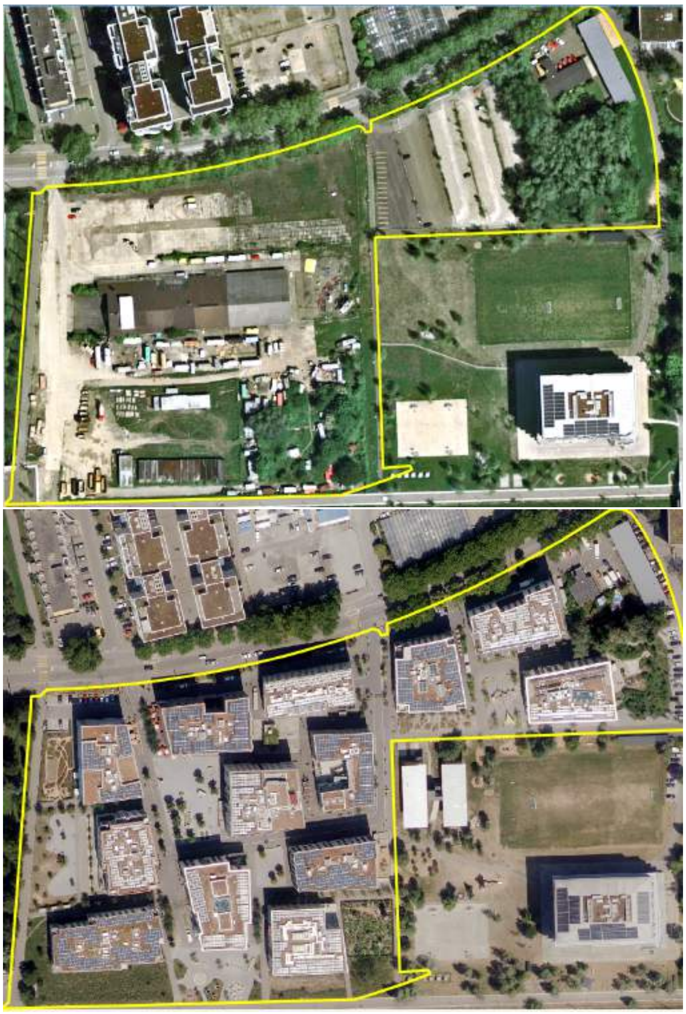

Fig. 4 Hunziker Areal, 2010 and 2018

Kalkbreite
The Kalkbreite area in Zurich Wiedikon was an urban wasteland between roads and railroads. In 2014, the construction of the housing cooperative was completed Kalkbreite (2021). The change from industrial area to housing estate is evident in fig. 5.

Fig. 5 Kalkbreite, 2010 and 2018

Freilager
In the past, the area shown in fig. 6 located in Zurich Albisireden was a duty-free zone where cars and other import goods were stored. From 2013 to 2016 the area was overbuilt, and residential buildings were constructed. Freilager Zürich was certified as a 2000-Watt area. Zürcher Freilager AG

Fig. 6 Freilager Areal, 2010 and 2018

2.1.3 Data sources and preprocessing

Unless otherwise indicated, the data analysis was conducted with the software ArcGIS Pro 2.6. The data sets shown in table 1 were used to analyze the development of green and unsealed areas and tree cover, as well as for data collection for the experiment with i-Tree Eco.

Table 1 Datasets used in this thesis

Dataset	Origin	Link
Orthophoto 2010 Bund – Sommer - quasi true – CIR Spatial Resolution: 0.25m	© Stadt Zürich (Geoportal)	https://www.stadt-zuerich.ch/geodaten/download/Orthofoto_2010_Bund___Sommer___quasi_true___CIR, 02.02.2021, 02.02.2021
Orthophoto 2007 Stadt Zürich – Frühling Spatial Resolution: 0.1m	© Stadt Zürich (Geoportal)	https://www.stadt-zuerich.ch/geodaten/download/Orthofoto_2007_Stadt_Zuerich___Fruehling, 02.02.2021
Orthophoto 2018 Kanton Zürich – Sommer – inkl. Infrarot – 1m Spatial Resolution: 1m	© Stadt Zürich (Geoportal)	https://www.stadt-zuerich.ch/geodaten/download/Orthofoto_2018_Kanton_Zuerich___Sommer___inkl._Infrarot___1m,02.02.2021, 02.02.2021
Amtliche Vermessungsdaten Stadt Zürich, Jahresstand 2018	© Stadt Zürich (Geoportal)	https://www.stadt-zuerich.ch/geodaten/download/Amtliche_Vermessungsdaten_Stadt_Zuerich_Jahresendstand_2018, 02.02.2021
Baumkataster (of February 2021)	© Stadt Zürich (Geoportal)	https://data.stadt-zuerich.ch/dataset/geo_baumkataster, 02.02.2021
Normalisiertes digitales Oberflächenmodell Vegetation (nDOM Veg)-2017/2018 (kantonaler Datensatz)	© Stadt Zürich (Geoportal)	https://www.stadt-zuerich.ch/geodaten/download/521, 27.02.2021
LIDAR Laserscanning Punktwolke – 2017/2018 (kantonaler Datensatz) Vertiacl accuracy of 0.1m	© Stadt Zürich (Geoportal)	https://www.stadt-zuerich.ch/geodaten/download/24, 27.02.2021
Amtliche Vermessungsdaten Stadt Zürich, Jahresstand 2018	© Stadt Zürich (Geoportal)	https://www.stadt-zuerich.ch/geodaten/download/Amtliche_Vermessungsdaten_Stadt_Zuerich_Jahresendstand_2018, 02.02.2021
Vegetation Height Models (VHM) 1990 (1993-1998)	©WSL	

- Orthophotos are rectified photographs obtained from aerial photographs (Zürich (2007)). In this thesis, orthophotos of 2007, 2010 and 2018 were used to address the question concerning the green space development on the six study areas, i.e. to determine changes in green spaces and the number of trees. The orthophoto of 2018 has the reference system CH1903+LV95 but because of an error, ArcGIS could not identify the reference system of this raster data set. Therefore, it was georeferenced manually based on the orthophoto of 2010.

- The data set of official survey data was used to investigate the six study areas. The feature class *AV_BO_BOFLAECHE_A* was chosen to define the study areas precisely, as this polygon feature class contains boundary lines framing the official property sizes. Also, the feature class *AV_BO_BOFLAECHE_A* was used to help identifying green spaces because it contains building contours and pathways. The feature class *AV_EI_FLAECHENELEMENT_A_R_V* contains information about underground building structures, which was used to determine the percentage of green area that has underground structures.

- The tree record (Baumkataster) of 2021 was used because no version of 2018 was available. On one hand, information from the tree record was used to study the changes in tree numbers at the six study sites. On the other hand, it was needed to clearly identify the tree species for the i-Tree analysis. The following trees were removed from the data set prior the analysis:
  - Trees planted after 2018
  - Trees which seemed to be wrongly recorded, for example if they were shown on a building
  - Trees that were not confirmed by LiDAR data, that means no point classified as vegetation existed for these locations

- LiDAR (Light Detection And Ranging) systems measure distances using laser beams that are reflected when they hit objects. The height of the objects is calculated based on the time it takes the system to receive the reflected signal (Bundesamt für Landestopografie (2019)). In this study, LiDAR data clouds were used to determine the canopy height and the crown base height for the i-Tree analysis. Moreover, the LiDAR data was used to vectorize trees at the six study sites and to determine the heights of buildings in terms to analyze the developments of the six study sites. The data had to be normalized with LAS tools to compute the height of each point above the ground, and only the points representing vegetation were kept for further analysis (rapidlasso GmbH). The used data set has a point density of at least 5 points per m^2 (Kanton Zürich (a)). The LiDAR data provided by the city of Zurich come from the Swiss surface3D data, which is planned to be collected between 2017 and 2023. The airborne measurements were conducted when there was no snow and little vegetation. (Bundesamt für Landestopografie (2019))

- The normalized digital surface model (nDOM) of 2017/2018 was used to measure tree parameters for the i-Tree analysis. The raster model of 0.5 m pixel size was derived from the LiDAR data described above (Kanton Zürich (b)). This dataset was used for two purposes: First to identify trees and determine their crown diameter, and second to verify whether the heights were correctly determined by LiDAR data with the chosen method of profile viewing, which is further explained below.

- The VHM of 1993-1998 should have been used to determine the number of trees in 2010 and 2007 for the analysis of changes on the study sites. It was the newest available VHM created before 2010. In the end it was not used because the spatial resolution was too low.

2.2 Methods

2.2.1 Analysis of green and unsealed spaces

The green area, unsealed area and the number of trees of the current and the previous development were compared based on orthophotos. Aerial photograph sampling is, according to Gill et al. (2008), an established method, which was for example used by Nowak et al. (2006) to determine the tree canopy cover. For all sites except for Triemli, the orthophotos of 2010 and 2018 were used. The settlement Triemli has already been under construction in 2010, therefore the orthophotos of 2007 were examined. The orthophotos of 2010 and 2018 are available in infrared. All orthophotos were taken in spring or summer, so the trees were leafy.
To determine the development of green and unsealed spaces, polygonal green areas were vectorized for each study area and year and subsequently classified into into vegetated areas, unsealed areas and green roofs, see fig. 7.

- Vegetated areas are recognizable as overgrown grounds, without distinction between grass and bushes. Unlike the unsealed areas, areas counted in this category are capable of photosynthesis and transpiration because they contain vegetation.
- Unsealed areas are pervious pavements such as gravel or cobblestone pavements.
- Green roofs are flat roofs that are vegetated.

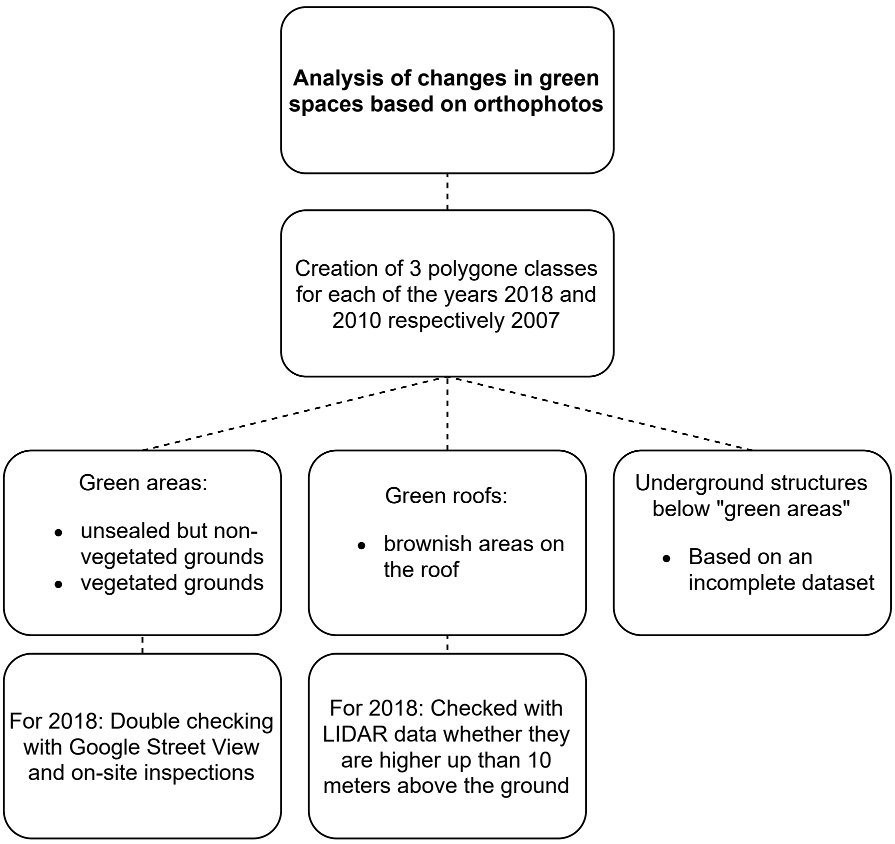

Fig. 7 Approach to the determination of green and unsealed spaces

Buildings were excluded from green spaces by analyzing the polygons in *AV_BO_BOFLAECHE_A*. Green roofs were visible as brownish areas on the roofs. Green, vegetated soils were clearly identifiable due to the infrared coloration on the orthophotos. If the grounds seemed to be unsealed on the orthophotos of 2018, it was verified with Google Street view. In most cases, Google Street view provided incidence whether there was gravel lawn, paving stone or concrete. If it was still unclear, the ground structures were checked live at the site, which was done for Freilager Areal.
If it was not clear whether grounds of the orthophoto of 2010 were sealed or unsealed, they were considered to be sealed and thus not recorded. This was the case for some small areas at Hunziker Areal.

Porous asphalt, which could also be counted as unsealed because stormwater can percolate, is hardly identifiable even with field surveys. On the websites of the examined residential areas, no information could be found whether paths and parking lots are sealed with normal, impervious asphalt or paved with porous asphalt. The distinction was not possible with the data available and therefore not performed. However, according to Scholz and Grabowiecki (2007), porous asphalt and porous concrete usually clog within three years after implementation.
The trees at the sites were often planted in gravel covered surfaces. Therefore, it was decided that the area where trees are planted was counted as unsealed area, unless it was visible on the orthophotos or on site that a tree was planted on vegetated ground. If the second was true, the area was counted as green area.

In addition to the determination of green areas, an estimation of green area with underground structures was made. The dataset *AV_EI_FLAECHENELEMENT_A_R_V* was used. According to the metadata, this data set is incomplete, which most probably means that it was not checked whether the information is up to date. Therefore, the found percentages of underbuilt green areas could deviate from the real ones.

2.2.2 Analysis of changes in the number of trees

The determination of changes in the number of trees at the sites was kept simple and is shown in fig. 8. A point feature class was created. For the year of 2007 for Triemli and for 2010 for the other sites, the number of trees was determined on the basis of orthophotos. Each identified tree was manually vectorized. The vegetation height model (VHM) of 1990 should have been used to verify the number of the trees. However, due to insufficient spatial resolution and the fact that the VHM only included buildings, it could not be used to clearly determine the number of trees. Thus, trees could only be recorded whenever a tree was clearly identifiable on the photo or when tree-shaped shades were visible. It was assumed that most of the trees present on the sites in 2007/2010 were old and thus rather high because the developments at the sites were old. Therefore, counting only clearly identifiable trees was considered a legitimate approach.

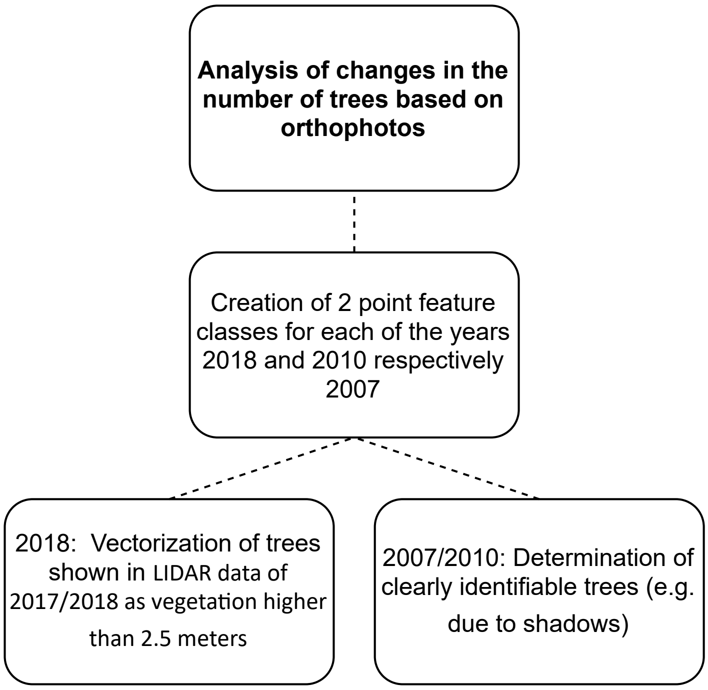

Fig. 8 Approach in determination of the number of trees

For the trees that were at the sites in 2018, the LiDAR point clouds of 2017/2018 were used to verify trees identified on the orthophotos. The data set was filtered for high vegetation, thus the points lower than 2.5 meters were dropped. For this reason, only trees with a height above 2.5 m were identified as trees and recorded to be compared to the number of trees in 2010/2007. This was done to differentiate between trees and shrubs. Finally, for each site, the number of the vectorized trees of the two investiagted years were compared.

2.2.3 Analysis with i-Tree Eco

To answer the question whether i-Tree Eco generates usable results with remote sensing data, input parameters for i-Tree Eco were collected both in the field in 2021 and with remote sensing data from 2018. The western half of the settlement Rautistrasse was selected as study area, shown in fig. 9. The reason is that the settlement Rautistrasse features a considerable number of old tree stocks.

Fig. 9 The yellow line frames the study area for the i-Tree Eco analysis. The red dots show the 18 trees that were included in the study. The brown dots mark trees that could not be identified with the LIDAR data. The blue dots show trees that were removed because the DBH was too small. The purple dot represents the tree that was no longer on the site.

The area measures 0.62 hectares. In total, there were 49 trees listed in the tree record for this area. Nevertheless, only 18 trees of 11 different species were taken into account. Most of the remaining 31 trees were removed from the sample because the trees were too low to be visible in the LiDAR point clouds. Being recorded in the point cloud was a prerequisite to be able to determine parameters. One tree was removed because in 2021, it was not standing at the site anymore. Another reason to remove trees from the sample was that their diameter at breast height was too small. For iTree Eco projects, only woody plants taller than 30.5 cm and with a DBH greater than 2.54 cm are considered trees (Rogers and Rogers (2020)). The fourth reason to remove trees was that they were too low to apply equation 1 to find the DBH, which is explained later.
In i-Tree Eco, the following features and services of a tree inventory can be calculated:

- Species distribution and origin of the species
- Carbon storage and annual carbon sequestration of the trees
- Oxygen production
- Hydrology effects: Avoided runoff
- Air pollution removal by trees (CO, NO_2, O_3, $PM_{2.5}$, SO_2)
- VOCs emissions by trees
- Building energy savings and resulting avoided carbon
- Potential pest impact
- Forecasts concerning species distribution and ecosystem services

Two sets of input parameters for the same 18 trees were collected.
The sets of input parameters then were compared. Afterwards, both of them were inserted into i-Tree Eco. The deviations of the outputs calculated by i-Tree Eco based on the two measuring approaches were studied.

Table 2 shows the parameters that were collected in a field survey and via remote sensing. Most parameters are not mandatory for the i-Tree analysis, they just lead to more accuracy. These optional input parameters are shown in italics.

Table 2 Approaches to collect input parameters for i-Tree Eco

Input parameter for i-Tree	**Variables/properties measured from Ortophotos/LIDAR data or calculated**	**Variables/properties measured in the field**
Diameter at breast height (DBH)	calculated with equation 1	calculated based on the measured circumference
Species of the tree	tree record (Baumkataster)	tree record (Baumkataster)
Height of the tree	measured (LiDAR, nDOM)	measured to the nearest 0.5 m with "Suunto" or estimated
Crown width N-S and E-W	measured (nDOM)	measured with a measuring tape to the nearest 0.05 m
Crown base height	measured (LiDAR)	measured with *Suunto* or with a measuring tape to the nearest 0.05 m
Crown top height	measured (LiDAR, nDOM)	measured to the nearest 0.5 m with *Suunto* or estimated
Crown light exposure	estimated based on surrounding, shade-providing objects and their heights in ArcGIS	estimated based on surrounding, shade-providing objects and their heights
Missing crown in %	could not be determined because the resolution of the orthophotos was too low, was set on 0%	estimated based on the possible crown volume
Dieback crown in %	could not be determined because the resolution of the orthophotos was too low, was too low, was set on 0%	estimated based on dead shoots
Distance to buildings	Measured (measurement tool from ArcGIS)	not measured

The absolute error for the height parameters determined with the LiDAR data set is assumed to be 0.1 m, since this is the vertical accuracy of the LiDAR point cloud. The resolution of the nDOM dataset was 0.5 m, thus the absolute error of crown diameters, which were directly measured with nDOM, is assumed to be 0.5 m.

For the measurement of crown width in the field, an error of around ±10cm is expected. The height measurement device *Suunto* provides an accuracy of ±0.5 m for a tree of 20 meter height (The Australian National University). Most crown base heights were measured with a measurement tape, for which an inaccuracy of ±2 cm is expected.

Data collection: Field survey

Height of the tree: The heights of trees were determined with *Suunto Clinometer* which is a device for determining heights based on optical laws. The height was determined to the next 0.5 m. For small trees of around 3 meters height, the height was estimated, which, as expected, has an error no greater than ±0.5 m.

Crown width N-S and E-W: The crown widths were measured with a measuring tape to the next 0.05 m.

Crown base height: Depending on the height of the tree, crown base height was either measured with the measurement tape to the next 0.05 m or with *Suunto Clinometer*. The crown base height is the distance between the lowest leaf of the tree and the ground.

Crown top height: Since all trees had healthy crown tops, this parameter was set identical to the total tree height.

Crown light exposure: This input parameter is a number between 0 and 5. The crown is divided in 4 quadrants around the stem, additionally the crown top is considered. (Rogers and Rogers (2020)) According to the i-Tree Eco template for field surveys of ZHAW, the 5 sides are counted as receiving sunlight, if no object higher than the tree itself is closer than the average crown diameter (ZHAW et al. (2021)). Potential light barriers around the tree were identified and accordingly, a number of light receiving sides was determined.

Missing crown in %: i-Tree Eco calculates the shape of the crown of a tree based on crown base height, crown top height and crown widths. If parts of the volume described by this calculation are missing, for example due to shading, heavy snowfall or pruning, they have to be recorded in the software to be considered. Otherwise, the ecosystem services or also adverse effects could be overestimated. Thus, the percentage of missing crown was estimated and expressed in a range such as 0%-5%, 5%-10% etc. Missing crowns due to self-shading were not counted. An example of a missing crown is shown in fig. 10.

Fig. 10 On the left, there is a pinus sylvestris with full crown. The pinus sylvestris on the right has a missing crown of 35%-40%. The pictures were taken at Rautistrasse.

Crown dieback in %: This parameter describes the percentage of dead shoots in relation to all shoots.

Diameter at breast height (DBH): The circumference of each stem was measured with a measuring tape to the nearest 0.01 m at a height of 1.3 m. Subsequently, the diameter was calculated by assuming that the circumference was a perfect circle.

Data collection: Remote sensing data

Most parameters were measured manually in ArcGIS.

Height of the tree: In order to determine the height of trees, point clouds were displayed in the profile view, as shown in fig.11. By zooming in, the highest point was identified and its value was compared the highest value of the normalized digital surface model nDOM. Finding the tree height with vegetation height models was the approach chosen by Cimburova and Barton (2020). The values were always similar and thus the more precise value delivered by LiDAR was selected as tree height.

Crown width N-S and E-W: Crown width distances can be measured manually with the tool *measure* in ArcGIS. The crowns were measured on the base of nDOM. This raster data set has a resolution of 0.5 meters, so the measurement can only be accurate to within half a meter.

Crown base height: To determine the crown base height, also LiDAR point clouds in the profile view were used. For some trees the lowest branches could be determined. But especially for smaller trees the crown base height had to be estimated from an unclear structure of data points, as shown in fig. 11. In this case, the lowest point was determined as the crown base height.

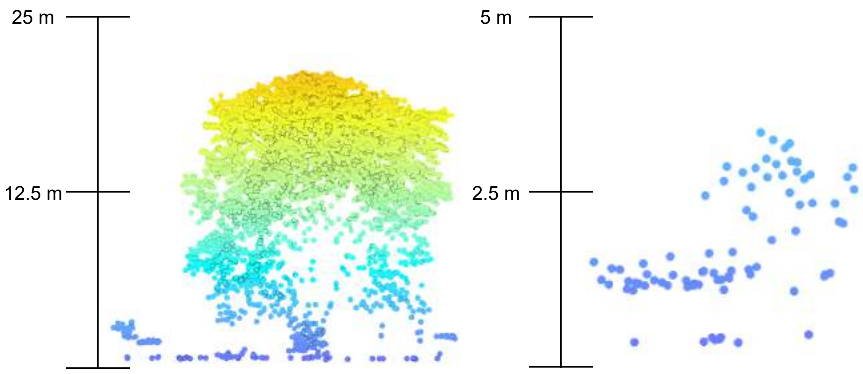

Fig. 11 On the left, tree AL-5680 is shown, which has a total height of 21.5 meters. The crown size is quite well identifiable, it is even visible that there are 3-4 stems if the profile is looked at from different directions. On the right, a profile view of AL-5756 is shown, which has a total height of 3.4 meters. It is unclear where the crown starts.

Crown height: The crown top height was set identical to the total height of the tree, given in meters.

Crown light exposure: This parameter was estimated by measuring distances between buildings and trees in ArcGis. Thanks to the data point clouds, the heights of adjacent buildings or trees were known and the light receiving sides could be determined.

Distance to buildings: Distances to nearby buildings could be measured using the *measure* tool in ArcGIS Pro. Measurements were made to the west (270 degrees), east (90 degrees), north (0 degrees) and south (180 degrees) of the tree. In i-Tree, only values between 1 m and 18.29 m can be inserted for the building distance. If there was no building in a certain direction, the maximal value of 18.29 m had to be used, because it was not possible not to specify a value.

Missing crown in %: If any information about the canopy should be processed, also information about the missing crown in % are required. As this parameter could not be estimated based on remote sensing data, it was set to 0% for all trees. This means that the software assumes that the inserted trees are not damaged or shaded by any objects.

Crown dieback in %: The same as for the missing crown also applies to the crown dieback: it is mandatory to specify a value, but the parameter could not be determined. Therefore, 0% was inserted for all trees, so the software assumes that all trees are completely healthy.

Diameter at breast height (DBH): The diameter at breast height cannot be measured with remote sensing data. Literature research was conducted to find a method to estimate the diameter at breast height based on other parameters. Three papers were found which provide models for determining DBH values. The first one was the paper of Lee et al. (2016), who recommended an equation based on crown diameters. The second one was a paper by Peper et al. (2001), which provided an equation based on the age of the tree.

The parameters in both equations were calibrated for California. Both models only were applicable on certain tree species, for this reason the DBH could not be calculated for all trees occurring at the site.
Moreover, the estimation of DBH for a given tree with both equations yielded values of different magnitudes, which argued against the suitability of these models. For these reasons, it was decided to use the model of the third paper:

Jucker et al. (2017) found a model for the calculation of the stem diameter. In their publication it is not clear whether the stem diameter at breast height is meant. However, this allometric model had already been used to determine DBHs in a study of Cimburova and Barton (2020), who also used it for an i-Tree analysis. The equation is the same for all tree species. It is based on tree height and crown diameter and was found by analyzing a global database containing 108'753 trees all over the globe which have a wide range in tree height and species.
The trees considered in the model had a height >= 1.3 m and a diameter >= 1cm. For this reason, trees with smaller parameters than required were removed from the sample and not considered in this thesis. The allometric model is as follows:

$$D_{pred} = 0.557 \times (H \times CD)^{0.809} \times e^{\frac{variance}{2}} \quad (1)$$

Where $\mathrm{D_{pred}}$ is the predicted stem diameter in cm, H is the total tree height in m, CD is the crown diameter in m and $\mathrm{e}^{\mathrm{variance}/2}$ is the error term with a variance of 0.0562.

No information could be found on how to deal with trees which have several stems. Because the stem diameter is calculated with height and crown width, a total diameter is defined. Therefore, a simplified approach was chosen: If it was found that a tree has several stems by looking at point clouds, the total calculated DBH was divided by the number of stems.

Sensitivity analysis

The DBHs were calculated based on an equation that was not calibrated for the study area. Therefore, it was assumed that calculated DBHs deviate significantly from measured DBHs. To find whether the accuracy of the diameter at breast height is crucial for the results of i-Tree or not, a sensitivity analysis was conducted. While all other parameters determined with earth observation data were fixed, the diameter at breast height was changed.

Through error propagation calculation it was found that the calculated DBH resulted in relative errors between 3% and 42%, where it has to be mentioned that they were greatest for very small DBHs. According to the manual for field surveys of i-Tree Eco, the error of DBH measurements should be within 0.254 cm for DBHs smaller than 25,4 cm and within 3% of the size for DBHs bigger than 25,4 cm (Rogers and Rogers (2020)). The errors resulting from error propagation were higher, which demonstrates the need for a sensitivity analysis. In addition, Nielsen et al. (2014) states that DBHs measured with remote sensing data have low accuracy with a deviation of 22% from field measurements.

Based on these insights, five i-Tree projects were created. For all five projects, the parameters were set identical, except for the values of DBH, which were:

- the calculated DBH
- the calculated DBH + the individual propagation error of each tree
- the calculated DBH - the individual propagation error of each tree
- the calculated DBH + the 22% error found by Nielsen et al. (2014)
- the calculated DBH - the 22% error found by Nielsen et al. (2014)

Both when the propagation error and when the 22% error was deducted from the sample, two trees had to be removed from the sample because their DBH was too small to comply for the definition of a tree by i-Tree Eco. Therefore, the projects with the calculated DBH minus the individual propagation error of each tree and with the calculated DBH minus the 22% error contained 17 trees, the other three projects contained 19 trees.

Definition of i-Tree Eco projects

For the main analysis, two identical projects were set up in i-Tree Eco. One was run with the data set of input parameters generated with remote sensing, the other one with the data set based on the field survey.

Since the parameters crown missing and crown dieback were not determined with remote sensing, they were set to 0%. Thus, i-Tree Eco assumed the canopies of the trees of the remote sensing data set to be full and completely healthy. In the project based on field data the parameters were inserted as they were determined in the field.

The distance to buildings is rapidly measured in ArcGIS but takes its time in the field. Moreover, the distance to buildings is used to calculate energy savings which is a benefit that was not addressed in this thesis. For these reasons, the distance to buildings was not considered for the comparison between the two measuring methods. However, it was considered for the sensitivity analysis of DBHs.
During the project definition, a weather station had to be selected. The closest one to the study site was the station Zurich Fluntern. The latest precipitation and air pollution data available in i-Tree was from 2015. To insert new weather data in i-Tree would have gone beyond the scope of this thesis.

In i-Tree, adjustments for costs can be made. For example, it can be adjusted how much it costs to plant trees, how much one ton of carbon dioxide is worth or how much has to be paid for the maintenance of trees. Except for the current exchange rate between USD and CHF, which is a mandatory specification, no such adjustments were made, as the focus of this work is on the ecosystem services and not on economic benefits. The calculated outputs concerning monetary benefits were not analyzed.

The forecast function in i-Tree Eco predicts the ecosystem services of the studied trees in the future. A forecast was run for both the field data-based project and the remote sensing-based project. The settings were set to default values, except for the number of days without frost. These were set to 321 as MeteoZurich recorded 44 days with frost in 2014, which is less than usual (MeteoZurich (2015)). However, it is expected that due to climate change the days with frost will become fewer. The forecasts were run for the next 30 years.

3 Results

3.1 State of knowledge

This section is a compilation of current knowledge on the positive as well as negative effects of vegetation on heat effects, stormwater runoff and air pollution.

3.1.1 Mitigation of the urban heat island effect

To mitigate urban heat island effects, urban forest would be the most efficient method because cooling effects through vegetation are highest for forests (Jaganmohan et al. (2016)). However, this is not the focus of this thesis because only residential areas are examined.
Different types of vegetation can contribute to the cooling of residential areas. At night, open green areas allow cold air flows. Cold air emerges above meadow and grassy areas and flows into the surrounding areas. During the day, large tree canopies are important to provide shade and evapotranspiration contributes to cooling. (BAFU (2018)) Evapotranspiration consists of transpiration and evaporation, therefore it describes the whole water release of vegetation (Stadt Zürich (2020)). If water evaporates, the solar energy is not turned into sensible but into latent heat, which does not cause the temperature to rise (Davies et al. (2003)). Vegetated soils are capable to store water which promotes the transpiration of plants as they can take up and consequently release water. Additionally, water directly evaporates from the soil, but soils-covering planting can prevent dehydration of the ground (BAFU (2018)). According to Bhargava et al. (2017), each 10% of vegetative cover can reduce the temperature of an area by 0.6 Kelvin.
Also sparsely vegetated but unsealed or partially unsealed grounds contribute to cooling. These pavements have little retention capacity, so stormwater either evaporates directly or infiltrates and for example recharges aquifers. (Amt für Umwelt und Energie Basel Stadt (2007)) But even if little water evaporates, these grounds absorb less heat and are therefore not trapping heat like completely sealed soils. Examples for such grounds are turfstones, joint pavers or macadam pavements. On the contrary, impermeable surfaces lead to less available water, which reduces the cooling effect of evapotranspiration in urban areas. If there are sealed grounds, infiltration trough could be installed and collect the water from streets and roofs. Consequently, the water runoff from sealed areas can still evaporate and thus contribute to cooling. (BAFU (2018))
Not only grounds but also flat roofs can contribute to the mitigation of heat islands. If they are greened, they also provide cooling through evapotranspiration. Green roofs only have a cooling effect on the ground level if they are not higher than around 10 meters above ground level and cover several 100m^2. Nevertheless, lush vegetation can serve as isolation for buildings, which lowers energy consumption for heating and cooling. Extensive green roofs, in contrast, contribute less to cooling or isolation due to the lack of greening, but they can have a retention function for water because they are permeable. Isolation can also be provided by vertical greening, which is an alternative for densely built residential areas where there is no space for green areas. In addition, vertical greening has a bigger potential to influence the microclimate on ground level because it is lower than roofs. But vertical greening does only provide cooling by transpiration and not by evaporation.(BAFU (2018)) Since the albedo is also crucial for the energy consumption of buildings, it should be considered that also white roofs can lower heat fluxes between buildings and the environment. However, green roofs also provide other advantages such as better stormwater management, improvement of air quality and higher biodiversity. (Susca et al. (2011))
Cooling effect at a distance only occurs when the green space is about one hectare in size

(BAFU (2018)). Hamada and Ohta (2010) found that the cooling effect of green space was detectable no more than 500 meters from the edge of the green space. They had investigated a park of the size of 147 hectares in Nagoya, Japan. Although the climate is different in Zurich, the finding that the cooling effect only influences short distances supports the assumption that it is important to have many green spaces in cities instead of few large ones. Also the report about heat adaption from BAFU states that each unsealing, also in private grounds, contributes to more comfortable urban climate (BAFU (2018)). It remains unclear whether the sum of smaller green spaces has the same cooling effect like fewer but larger green areas (Jaganmohan et al. (2016)). But it is obvious that green spaces are obligatory on residential areas in cities to create a pleasant microclimate.

Just like green spaces and shrubs, trees also contribute to heat mitigation via transpiration. Through transpiration, trees can release up to 500 liters of water per day (Blaser et al. (2016)). Additionally, the shading effect of trees provides an area which receives less heat and solar radiation during the daytime. As already mentioned in the introduction, shading also reduces the heating of the ground, which results in less long-wave radiation at night and thus less heat at night (BAFU (2018)). According to a factsheet of the university of applied sciences for agricultural, forest and food science (HAFL), a single tree can provide the cooling capacity of ten medium air conditioners, which is 20 to 30 kW. Still, at a location underlying seasonal changes like Switzerland, trees should not prevent the sunlight from entering buildings in winter, because that could increase the need for heating. (HAFL (a))

3.1.2 Mitigation of stormwater runoff

Surface runoff is caused by heavy rainfall, but is also a result of sealed, impervious soils. Such runoff occurs when rain cannot infiltrate into the soil and therefore collects on the soil surface. (Scharenbroch et al. (2016)) Urbanization and soil sealing favor this occurrence. The lack of water infiltration possibility is usually addressed with constructed detention basins that collect water runoff from impervious pavements. However, according to Booth and Leavitt (1999), most detention ponds have little or no effect on the volume of stormwater entering stream channels because the retention volume is reduced by around 90% compared to natural soil. Additionally, such man-made systems are expensive. The widespread use of unsealed soils such as permeable paving, vegetated spaces and green roofs can reduce the need to build costly stormwater drainage systems.

Green roofs, for example, reduce peak runoff because water is captured by vegetation or temporarily stored in the substrate medium. The stored water can either evaporate or infiltrate towards the top of the building. Unless the substrate layer reaches saturation, infiltration results in delayed runoff so that no peak runoff occurs.

Runoff peaks can also be reduced by permeable pavements. These pavements usually consist of a permeable pavement surface, a storage layer, and optionally an underdrain system. (Li et al. (2019)) They are suitable for parking lots or pathways and thus for residential areas (Amt für Umwelt und Energie Basel Stadt (2007)). A report by *Entsorgung und Recycling Zürich* states that on properties where new infrastructure is being built, all unpolluted rainwater should be infiltrated as far as possible. Gravel lawns, grass pavers or paving stones with open joints are suggested as permeable surfaces. (ERZ Entsorgung und Recycling Zürich (2010)). Booth and Leavitt (1999) studied four types of permeable pavements for their ability to reduce runoff. It was shown that turf pavers, gravel pavers, grass pavers, and eco-stone pavers are capable of managing runoff from small and medium sized storms. All four types of permeable pavements can achieve the hydrologic goal of

infiltration, they just differ in capacity in respect to weight, which is especially important if they cover streets or parking lots. During their study, the most runoff was observed on turf pavers, and this was only 3% of the total rainfall volume. The runoff from the control group of impermeable soils was dramatically greater than that from the permeable soils.
The highest rainfall during the study was 7.4 mm per hour. On the northern side of the Alps in Switzerland, rain volumes above 120mm per 24hours, which equals 5mm/hour, are already considered a very big danger (Bundesamt für Meteorologie und Klimatologie (2020)). Therefore, it is assumed that most rain volumes in Zurich are below 7.4mm per h and the findings of the study are also valid for Zurich.
The office for environment and energy of the city of Basel provides an equation to calculate the water volume that infiltrates through a percolation system (Amt für Umwelt und Energie Basel Stadt (2007)). However, permeable pavements are not counted as infiltration systems and therefore this model cannot be used in this thesis. No models to estimate the quantity of infiltrating water in vegetated area or unsealed, vegetation-free area could be found.
The fraction of precipitation which infiltrates into natural soil is influenced by the number and distribution of macropores. Humus covered soils are often vegetated. On vegetated soils, shrinking or decaying roots create macropores. Additionally, vegetation covered soil is protected from the impact of energetic raindrops that could lead to the destruction of soil aggregates and therefore to soil compaction, which would decrease the infiltration rate. Therefore, vegetation helps to increase stormwater infiltration. (Zuidema (1985)) However, the effective pore volume, which leads to higher permeability, is greater with gravel than with soil (Hölting et al. (2013)), but the insertion of soil is cheaper than the insertion of permeable pavements (AWEL (2009)). Moreover, it is not clear how useful permeable pavement is when the soil beneath it naturally allows little infiltration. Another critical point is that permeable pavements possibly clog after a period of time (Booth and Leavitt (1999)).
Soils are not only characterized by their infiltration rate but also by their retention and filter capacity. Humus-covered soils of 20 cm thickness are expected to have a slight retention capacity, whereas permeable pavements are expected not to store any water unless they are coupled to infiltration systems. (Amt für Umwelt und Energie Basel Stadt (2007))The thicker the humus layer, the greater the retention capacity, a fraction of water is retained in rather impervious vegetated soils providing macropores (Zuidema (1985)). But still, to capture and use water, an infiltration swale is required. Vegetated soils have a greater ability to filter pollutants contained in the stormwater than unsealed but vegetation-less soils (AWEL (2009)) (Amt für Umwelt und Energie Basel Stadt (2007)). Booth and Leavitt (1999) state that most common pollutants, such as heavy metals, are rapidly filtered out during infiltration. Brattebo and Booth (2003) found that water that infiltrated permeable pavements contained lower concentrations of copper and zinc than asphalt runoff. However, the contaminants then remain in the soil, which is another problem.

Besides permeable areas, trees also contribute to the reduction of stormwater runoff; a large leaf area provides a surface where water gathers (Hand et al. (2019)). Also, trees channel water around the stem, where the soil is more pervious, and water can infiltrate along root channels. (Davies et al. (2003))

3.1.3 Mitigation of air pollution

Plants can take up air pollutants either through stomata or surface deposition, with dry deposition providing only temporary retention of pollutants. The best vegetation type to remove air pollutants is a tree because trees have greater surface roughness than other vegetation types (Davies et al. (2003)). According to a model, grass only absorbs a fraction of the amount absorbed by trees (Jeanjean et al. (2016)) and green roofs are only seen as a supplement to pollution control by trees. Vertical greening especially has a barrier function between pollutant sources and buildings. Pollution removal depends on the leaves, on one hand because of the surface area, on the other hand because that is where stomata are located. Stomata are closed at night. Therefore, the improvement of air quality is highest during the day and in spring, summer and early autumn except for coniferous, evergreen species. The longer the leaf season and the larger the percentage of tree canopy cover, the greater the removal of air pollutants. (Sicard et al. (2018)) The removal of pollutants by trees has a local effect rather than a large-scale effect (Jeanjean et al. (2016)).
The highest percentage of air quality improvement driven by trees was found for sulfur dioxide (SO_2), particulate matter and tropospheric ozone. The gaseous pollutants SO_2 and O_3 are particularly absorbed during transpiration, PM is mainly retained by dry deposition and also by aerodynamic dispersive effects. (Nowak et al. (2006)) The uptake ability of pollutants is influenced by meteorologically dependent plant features, for example by stomatal conductance or transpiration rates (Sicard et al. (2018)). In addition, the deposition and dispersion of pollutants is influenced by wind speed and Jeanjean et al. (2016) claim "the more trees the better" for cities with average wind speed above 2 meters per second. In case of lower wind speeds, trees can increase $PM_{2.5}$ concentrations locally because they trap pollution and therefore prevent dispersion. This interception effect is also the reason why it is not recommended to plant trees in street canyons, even though they would be most effective for $PM_{2.5}$ deposition. (Jeanjean et al. (2016))

There are different statements about the quantity of pollution removal by vegetation. For example, studies based on passive samplers conclude that local O_3 concentrations could be reduced by up to 40% in urban parks (Sicard et al. (2018)) or that the overall reduction of PM in 8 months due to urban deciduous trees was 27% (Dochinger et al. (1980)). Nowak et al. (2006) developed a model based on deposition velocity and pollutant concentration. With this model, the average air quality improvements during in-leaf season is only 2% even for areas with 100% tree cover. Moreover, a model of the city of Leicester which considered dispersion and deposition calculated a 9% reduction of $PM_{2.5}$ concentration by aerodynamic dispersive effects in summer (Jeanjean et al. (2016)).
According to this model considering dispersion and deposition, the particle deposition on buildings is negligible (Jeanjean et al. (2016)). Also, an atmospheric model led to the conclusion that O_3 deposition over lush vegetation is 40 times more efficient than O_3 deposition over urban land (Fitzky et al. (2019).

Several papers mention the importance of the choice of the tree species when planting in urban areas (Chaparro and Terrasdas (2009)),(Sicard et al. (2018)),(Calfapietra et al. (2013)). The reason is that trees cannot only reduce air pollution, but also contribute to it. To reach higher heat tolerance, due to wind stress or to protect themselves from ozone-induced plant issue damage, plants emit BVOCs (biogenic volatile organic compounds). BVOCs are VOCs and thus contribute to the formation of tropospheric ozone. Isoprene is one type of BVOCs and a very reactive precursor of ozone. (Fitzky et al. (2019)) Especially in combination with the heat island effect BVOCs emission is stimulated because isoprene emission depends on the leaf temperature (Calfapietra et al. (2009)). So, if there are highly emitting tree species, they should be located in places where they are shaded by other trees to lower the leaf temperature. It is assumed that BVOCs become more important precursors of O_3 when NO_x concentrations decrease (Sicard et al. (2018)). To maintain low O_3 concentrations, the VOCs/NOx ratio and thus the BVOC concentration should be kept low (Sicard et al. (2018)). Hence, on one hand, trees can remove ozone by dry deposition or uptake. On the other hand, trees have the potential to increase ozone concentrations by emitting BVOC. (Nowak et al. (2006)) In addition, some tree species release pollen which trigger allergic reactions (Sicard et al. (2018)).

3.1.4 Carbon storage and sequestration

This thesis focuses on climate adaption and not on the mitigation of climate change. For this reason, the effect of trees on carbon sequestration and storage is not strongly addressed. However, it should be mentioned that through photosynthesis, trees fix carbon dioxide and store it as biomass. The faster they grow, the more biomass they sequester. This is beneficial because CO_2, which is a driver of climate change, then is removed from the atmosphere. (Davies et al. (2003)) Therefore, trees can help cities to implement carbon neutrality policies (Livesley et al. (2016)). The ability to sequester carbon decreases when trees are severely pruned, exposed to heat or have poor rooting conditions (Davies et al. (2003)).

3.1.5 Assessment schemes

Based on the findings above, two schemes were drawn up to qualitatively assess the ground coverage and tree stock development of new housing estates in terms of climate adaption. These schemes were used to evaluate the development of the study areas in the discussion part.
The combination of certain criteria of the schemes leads to a specific scenario and recommended improvements. Criteria in hatched boxes do not have to be fulfilled, they are optional. If the scenario is colored in green, the site provides many ecosystem services. A yellow coloring means that there are many ecosystem services provided but the situation could be upgraded. The orange coloring means that there is much potential for improvements. If the scenario is colored in red, the ecosystem services provision clearly decreased and it might be that there are adverse effects triggered from vegetation.

The schemes can be downloaded in A3 format from the website of the WSL Landscape Centre.

Assessment of ground coverage developments

The assessment scheme of ground coverage development contains seven criteria concerning the changes in vegetated and unsealed soil, green roof area and vertical greening.
If the change in vegetated spaces should be evaluated, it must be considered how much green space there is in total. A decrease in vegetated area is never beneficial in terms of ecosystem services provision, but it is less problematic if there is still a high percentage of vegetated space. Therefore, a comparative size had to be incorporated. No reference values for the aimed percentage of green spaces in Swiss cities could be found. For this reason, the vegetated ground cover at the site is compared to 22.2 %, which corresponds to

the average percentage of green spaces such as parks, sports fields, farmland or meadows in Zurich in 2016 (Stadt Zürich (2016b)). This value is for orientation purposes only and should be treated with caution as this statistic also includes roads and open waters.

There are restrictions in the beneficial effects of green roofs. As mentioned above, green roofs only affect ground levels if they are lower than 10 meters and cover several m^2. Several m^2 is defined as more than 200 m^2. The scheme is shown in fig. 12.

Underground structures were not considered in the scheme. The reasons are that it is not possible to obtain information about the depth of the soil layers above the underground structures with the chosen methods. Additionally, no clear information could be found about how underground structures affect vegetation and infiltration rate.

Assessment of tree stock developments

Climate change is not only one of the drivers of urban heat island effects, but it also threatens the vitality of urban trees. High temperatures and sealed grounds result in trees showing symptoms of drought stress which can reduce their life expectancy. The uptake of ozone can damage plant issue (Fitzky et al. (2019)) and pollution emissions as well as urine or salt contamination reduce the vitality of trees. Not all tree species are suitable for urban locations. In addition, it was shown that small-scale life conditions have a greater impact on the vitality of a tree than the tree species does. (HAFL (b)) For example, underbuilding open spaces reduces root space and thus available locations for trees (Stadt Zürich (2013)). However, the underbuilt area was not considered in the scheme as there was too little knowledge about suitable layer depths and specific effects on vegetation. Also, as mentioned above, information about the soil depth was not determined for the study sites.

Urban trees should be drought and pest resistant to increase their lifetime, also a certain tolerance of compacted soil is beneficial. (HAFL (b))
In the scheme shown in fig. 13., climate adaption features such as resistances, but also the potential to trigger allergies or being invasive as well as the release of BVOCs are considered. Criteria such as the popularity of a species or danger through branch breakage are neglected.

Since the adaption to future life conditions was on focus, there was no emphasis on having only native species in the scheme. According to Andrea Saluz, who researches urban forestry and urban ecosystems at the ZHAW, the mix of different tree species is important and increases resilience. For example, heat-tolerant neophytes can shade heat-sensitive native species. The scheme is thought to roughly estimate the climate adaption of a site through trees. If the ecosystem services should be estimated more accurately, an i-Tree Eco analysis should be conducted.

To find tree species fulfilling the criteria, the German database citree was consulted. Information considering heat, drought and compacted soil tolerance, origin, crown size, ecosystem service provision and the potential to trigger allergies was taken from that database. Another source for the creation of the scheme was a publication of Calfapietra et al. (2009), where the main tree species found to be occurring in Italy and their potential to release BVOCs are listed. If a species also occurs in Switzerland according to the national data center of the Swiss flora, the species is recorded in the scheme (info flora). Furthermore, the scheme is based on a list provided by the German Garden Office Directors' Conference which defines the suitability of tree species in cities based on insights from tests (Deutsche Gartenamtsleiterkonferenz (2021)).

Fig. 12 This assessment scheme allows to qualitatively assess the development of green and unsealed spaces at an overbuilt site. The scenarios tell what changed at the site, under recommendations for improvement suitable strategies are suggested. The scenario is assigned where only the applicable fields are coloured. The hatched fields contain criteria that can be fulfilled optionally.

Criteria	Description	Criteria that apply					
1.1 Tree number	The number of trees decreased						
1.2 Tree number	The number of trees remained the same						
1.3 Tree number	The number of trees increased						
2.1 GALK list	Most trees are marked as suitable on the GALK street tree list and fulfill most recommendations listed in box 1.						
2.2 GALK list	Most trees are marked as unsuitable on the GALK street tree list and/or do meet few recommendations listed in box 1.						
3.1 BVOC	There are many trees known to emit high BVOCs, for example those listed in box 2, that are exposed to stressors.						
3.2 BVOC	There are many trees known to emit low BVOCs, for example those listed in box 3.						
Scenario		**1**	**2**	**3**	**4**	**5**	**6**
Descripition		This site benefits from more tree-based ecosystem services than before. It is likely that these services will be provided in the future because most trees are adapted to climate change. If 3.2 is met, most trees will not contribute to ozone formation even if there are many stressors at the site.	This site benefits from more tree-based ecosystem services than before. This might also be the case in the future because most trees are well adapted to climate change. However, some of the trees also have an adverse effect: They contribute to ozone formation.	This site benefits from more tree-based ecosystem services than before. However, most trees are not adapted to climate change and might not survive in the future.	This site benefits from more tree-based ecosystem services than before. However, most trees are not adapted to climate change and might not survive in the future. In addition, some of the trees have an adverse effect and contribute to ozone formation.	If old tree stocks were preserved this is beneficial because older trees are larger and thus provide more ecosystem services than young trees. However, the age of the existing trees should be taken into account. If they are very old and also not adapted to climate change, they could die in the next few years.	In terms of climate change and air pollution, it can be said that a decrease in the number of trees is a negative development. Not only did the mitigation of environmental threats decrease, but also the quality of life at the site, as there are most likely fewer shaded areas than before.
Recommended improvements		It is always beneficial to plant more trees, if not for ecosystem services then for biodiversity.	It is recommended to observe the local ozone concentration and to create the least possible stressed environments for trees listed in box 2.	It is recommended to plant new, more adapted trees or to replace damaged ones with some that are marked as suitable on the GALK list.	It is recommended to plant new, more adapted trees or to replace damaged ones with some that are marked as suitable on the GALK list. Moreover, it is recommended to observe the local ozone concentration and to create the least possible stressed environments for trees listed in box 2 or to replace them.	Rejuvenation of the tree population with site-appropriate species is recommended. If some trees were removed and new trees were planted, they should meet the criteria in box 1. The microclimate could be improved by increasing the number of trees at the site.	It is recommended to plant more trees. New trees should meet the criteria listed in box 1 and/or be recorded as suitable in the GALK list. If single trees are planted, they should emit few BVOCs like the species listed in box 3.

Box 1

Recommendations for newly planted urban trees

- Most of the newly planted trees should be heat and drought resistant.
- Trees with large canopies are recommended.
- Trees that trigger allergic reactions should not be planted next to balconies and windows.
- Evergreen species should not be planted on the south side of buildings.
- It is advantageous if trees tolerate compacted soil.
- In city centers, it is favorable if trees tolerate salt.
- The tree species should not be invasive.

Box 2

Examples of species not recommended to stand alone at hotspots of ozone formation (not exhaustive):

- **Quercus pubescens**
- **Quercus ilex**
- **Quercus petraea**
- **Quercus robur**
- **Salix sp.**
- **Populus sp.**
-

Box 3

Examples of species recommended at hotspots of ozone formation (not exhaustive):

- **Castanea sativa** emits moderatley monoterpenes and is drought and heat tolerant but does not tolerate compacted soil and also has medium allergy potential.
- **Acer platanoides** emits few monoterpenes, has a high drought and medium heat tolerance, does not tolerate compacted soils, strongly absorbs nitrogen oxides and ozone and has a medium allergy potential.
- **Robinia pseudoacacia** emits moderately isoprene, absorbs medium PM, tolerates heat and drought, but not compacted soil.

Fig. 13 This assessment scheme allows to qualitatively assess the development of tree stocks at an overbuilt site. The scenarios tell what changed at the site, under recommendations for improvement suitable strategies are suggested. The scenario is assigned where only the applicable fields are coloured. The hatched fields contain criteria that can be fulfilled optionally.

3.2 The development of densified residential areas in Zurich

3.2.1 Changes in vegetation and unsealed areas at the six study sites

This section presents the results of the examination of the six study areas, all changes of green spaces are given as shares in fig. 14. The area of underground structure was only measured below unsealed area such as gravel covered or vegetated ground.

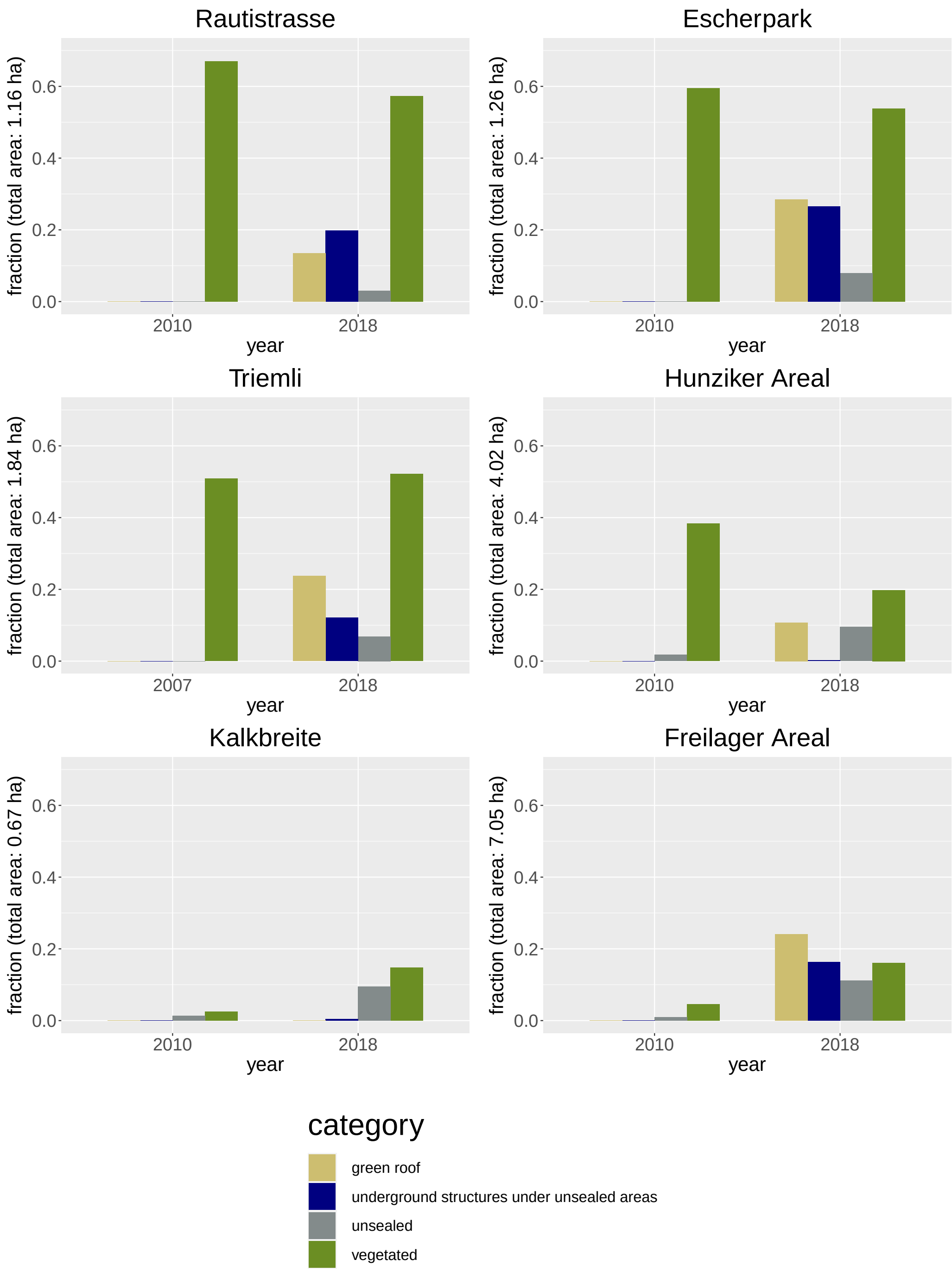

Fig. 14 The green space development at the 6 study sites shown as proportions of the total area. The x-axis shows the years for which the proportion of green space was compared.

All values given in percent are rounded to 1%, the number of trees per hectare is rounded to 1. The changes in the number of trees per hectare is shown in fig.15.

Rautistrasse

At this site, the vegetated ground decreased from 67% in 2010 to 57% of the total area in 2018. If green roofs and unsealed but vegetation-free areas are also counted, the total unsealed area covered 7% more of the site in 2018 than in 2010. In 2018, the flat roofs were located at a height of 20 meters and did not contain lush vegetation. During site inspections in 2021, no vertical greening was found.

Either way, the green area per flat decreased because the number of flats changed from 44 to 104. The apartments of the new housing estate provide between 3.5 and 5.5 rooms. If an average of 3 people live in a flat and vegetated ground and green roof area is counted as green space, there are 26 m^2 green space per person. (Stadt Zürich Amt für Hochbauten (2016))

There were underground structures below 33% of the unsealed or vegetated area in 2018, but it is not known if this area was already underbuilt in 2010.

The number of trees per hectare increased from 28 to 80 between 2010 and 2018. 16 tree species could be identified from the tree record, in which 101 single trees are recorded. From these 16 species, 9 are suitable or suitable with restrictions according to the GALK list and another species is meeting most criteria listed in box 1 of the assessment scheme. Overall, 5 out of 101 trees are classified as unsuitable, with one tree known to emit considerable levels of BVOCs. For 10 trees it is not known whether they are suitable or not.

In the analysis of changes in the number of trees, only 93 trees were determined with LiDAR point clouds, which is fewer than were recorded in the tree record.

Escherpark

At the housing estate Escherpark, the proportion of vegetated ground decreased from 60% in 2010 to 54% in 2018. If green roofs and unsealed space are counted, the share of unsealed area was 30% higher in 2018 than in 2010. The flat roofs were located at a height of 11.5 meters and did not have lush vegetation. No vertical greening was found to be there in 2021.

The current settlement offers 127 flats (Baunetz Wissen) instead of 72 before the superstructure (Gerling (2014)), thus the green area per flat decreased. Assuming that 3 people live in a flat, there are 27 m^2 of green space per person including green roof area.

43% of the unsealed or vegetated ground area had underground structures in 2018. The number of trees per hectare increased from 33 to 69. No trees are recorded in the tree record and no information on species could be found without field inspection.

The vegetated roofs are drained internally. Surface water from the loggias on site is drained via a channel. The rainwater is partly addressed with retention, but no further information on this strategy could be found. (Baunetz Wissen) (Gerber+Partner)

Triemli

At Triemli, there was more green space in 2018 than in 2007: The vegetated area increased from 51% to 52%. Moreover, if green roofs and unsealed areas are also counted, there were 83% unsealed area relative to the total property size in 2018. The flat roofs were located at a height of 17 meters in 2018. In 2021, no vertical greening was present at the site.

The new settlement offers 167 apartments, which is one third more than the old housing estate did. About 400 people live in the new residential area Triemli, which equals 35 m^2 green area including vegetated roofs per person. (Papazoglou (2017)) If green roof area is considered, the green area per flat increased at this site.

Basements or other underground structures were located under 21% of unsealed and vegetated ground area in 2018. The number of trees per hectare increased from 20 to 52. No tree is recorded in the tree record and thus no information about species could be found because no field survey was conducted.

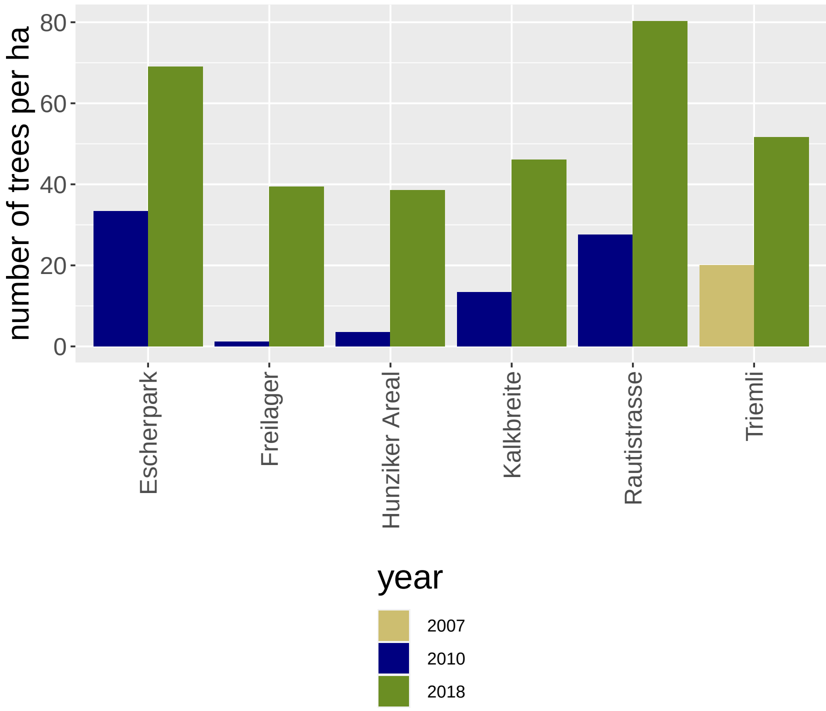

Fig. 15 Change in the absolute number of trees on the 6 study sites.

Hunziker Areal
When Hunziker Areal was still an industrial area, there was 38% vegetated ground and almost 2% of unsealed area, the orthophotos indicate that it was most likely grass pavers. In 2018, there was 20% of vegetated cover and 10% unsealed area, mostly gravel paving. If green roofs are also counted, the unsealed area remained 40% of the whole property size between 2010 and 2018. In 2018, flat roofs were located at a height of 20 meters. There is vertical greening on one building. About 1200 people live in the new estate and 150 work there. The vegetated ground and roof area per person corresponded to 10 m^2 in 2018 if only people living at the site are taken into account.

1% of the unsealed and vegetated ground area was underbuilt in 2018. The number of trees per hectare increased from 3 to 39. 155 single trees were recorded with LiDAR point clouds during the examination of the tree stock development. For 52 of them, the species could be determined either with the Baumkataster or with an overview of the area on the website (mehr als wohnen (2021)). Overall, 19 tree species were identified. 35 out of the total 52 trees are either not suitable according to the GALK list, not meeting the criteria listed in box 1 and/or emitting high BVOCs. 4 trees are known to emit very few BVOCs. Only 6 trees are clearly suitable and not emitting BVOCs, for 11 trees no information could be found.

At this site, rain water is captured and used to flush toilets or to water green spaces (mehr als wohnen (2017)). The Hunziker Areal is particularly affected by urban heat island effects. There are efforts to implement greening measures and to further unseal the soil to increase biodiversity and reduce heat in summer. In 2017, for example, parking lots were unsealed and greened. Some of these projects have only been in progress since 2020. By the end of 2020, 450 m^2 of asphalt were removed and covered with marl pavement. If these more recent developments are also taken into account, there is 1% more unsealed area at the site now than in 2010. Moreover, there are plans to implement green facades, plant another row of trees and optimize balcony greening. These projects are being carried out in collaboration with the ZHAW plant use research group. (mehr als wohnen (2021))

Kalkbreite
3% of the total area was vegetated and 1% unsealed in 2010. In 2018, 15% of the area was vegetated and 9% unsealed, so there was 20% more unsealed soil than in 2010. The unsealed area in 2018 was covered with gravel. There were neither green roofs nor vertical greening in 2018. But in the courtyard of the building, as well as on different floors, there were green areas dedicated to various purposes, for example to grow herbs, vegetables or to attract bees. (Kalkbreite (2021)) However, these areas could not be recorded because they were not well identifiable on the orthophotos. Additionally, these vegetation patches are located on different floors of the housing estate that are only accessible for inhabitants. The new housing estate offers flats for about 250 people, the vegetated ground area per person was 4 m^2 in 2018. There is also space for commercial, cultural and service activities.

Underground structures were under 2% of the unsealed and vegetated area in 2018. The number of trees per hectare increased from 13 to 46. The species could only be determined for 7 of the total of 31 trees surveyed with LiDAR: They are all of the same species and suitable with restrictions according to the GALK list.

Freilager Areal
The vegetated ground covered 5% of the area in 2010. 1% of the area was unsealed. In 2018, 16% of the area was vegetated and 11% unsealed. The unsealed areas of 2018 are covered with gravel. If green roofs are also counted, unsealed space took 51% of the whole area in 2018, while it was only 6% in 2010. The flat roofs were located at heights of 12, 25 or 40 meters in 2018, there was no vertical greening.
The new housing estate offers space for about 2'500 people living and working at the site. There are also WOKO-flats for students. Including green roofs, there were 11 m^2 vegetated space per person in 2018.

60% of the unsealed or vegetated area has underground buildings. Freilager Zürich was certified as a 2000-Watt area and 540 trees and 12'600 European hornbeams were planted during and after the construction of the housing estate. (Zürcher Freilager AG) Green spaces are watered with captured rainwater (Depner (2018)).
According to this analysis, the number of trees per hectare increased from 1 to 39 between 2010 and 2018. With LiDAR data, only 278 of the mentioned 540 trees were identified. On the website of a tree supplier of the area, the species of 401 single trees that were delivered

could be found (roth pflanzen (2015)). 4 different species were delivered, all of which are suitable or suitable with restrictions according to the GALK list or the criteria listed in box 1 of the tree development assessment scheme. None of the species is known to emit few or much BVOCs.

3.3 i-Tree Eco: Input parameters and outputs

3.3.1 Input parameters

A comparison of the parameters measured with the two measuring options is displayed in fig. 16. The difference between two measurements of a parameter is shown in relation to the mean value of the two measurements. There are deviations in both the positive and negative direction for all parameters. Due to the small sample size of 18 trees, no statements on significance can be made.

Tree height

For 14 out of 18 measured trees, the height determined with remote sensing is lower than the one determined with field measurements. Expressed in percentage, the height of trees measured with LiDAR deviated between -51% and +17% of the field measured heights, except for one outlier. Tree AL-5701 was determined to be 76% higher when measured with remote sense data than in the field. In the field it was found that this particular tree was bend below the tree right next to it.

Crown width

Except for one tree, the values for crown width determined with nDOM deviate between -49% and +82% from the widths measured in the field. The exception was tree AL-5677, for which the crown widths measured with nDOM were 1.5 and 2 meters while the crown widths measured in the field were 0.45 and 0.55. This results in deviations of +264% and +233% from field measured data.

DBH

The DBHs determined with equation 1 based on remote sensing data deviated between -84% and +245% from the sum of field measured DBHs. For most trees there were major deviations in the sum of DBHs, both in positive and negative direction.

Crown base height

The crown base height determined with point clouds deviated between -67% and +154% from the crown base heights measured in the field. The absolute deviation tends to increase with increasing mean of the crown base height measurements.

Sun exposure

The values for sun exposure determined in the field and in ArcGIS are very similar. For 12 out of 18 trees, the same number of sunlight receiving sides was determined. For four trees, there was a deviation of one side, and for two trees a difference of two sides.

Crown dieback and missing crown

The two parameters crown dieback and missing crown were only measured in the field survey. For 12 of the 18 trees, a percentage dieback and/or a percentage missing crown was recorded. Three trees were found to have a percentage of missing crowns of 20%-25%, 35%-40% and 45%-50% respectively. Five other trees were found to have a percentage of missing crowns of less than 15%. Two trees were found to have crown dieback of 15%-20% and 20%-25% respectively. Another five trees were found to have crown dieback below 15%.

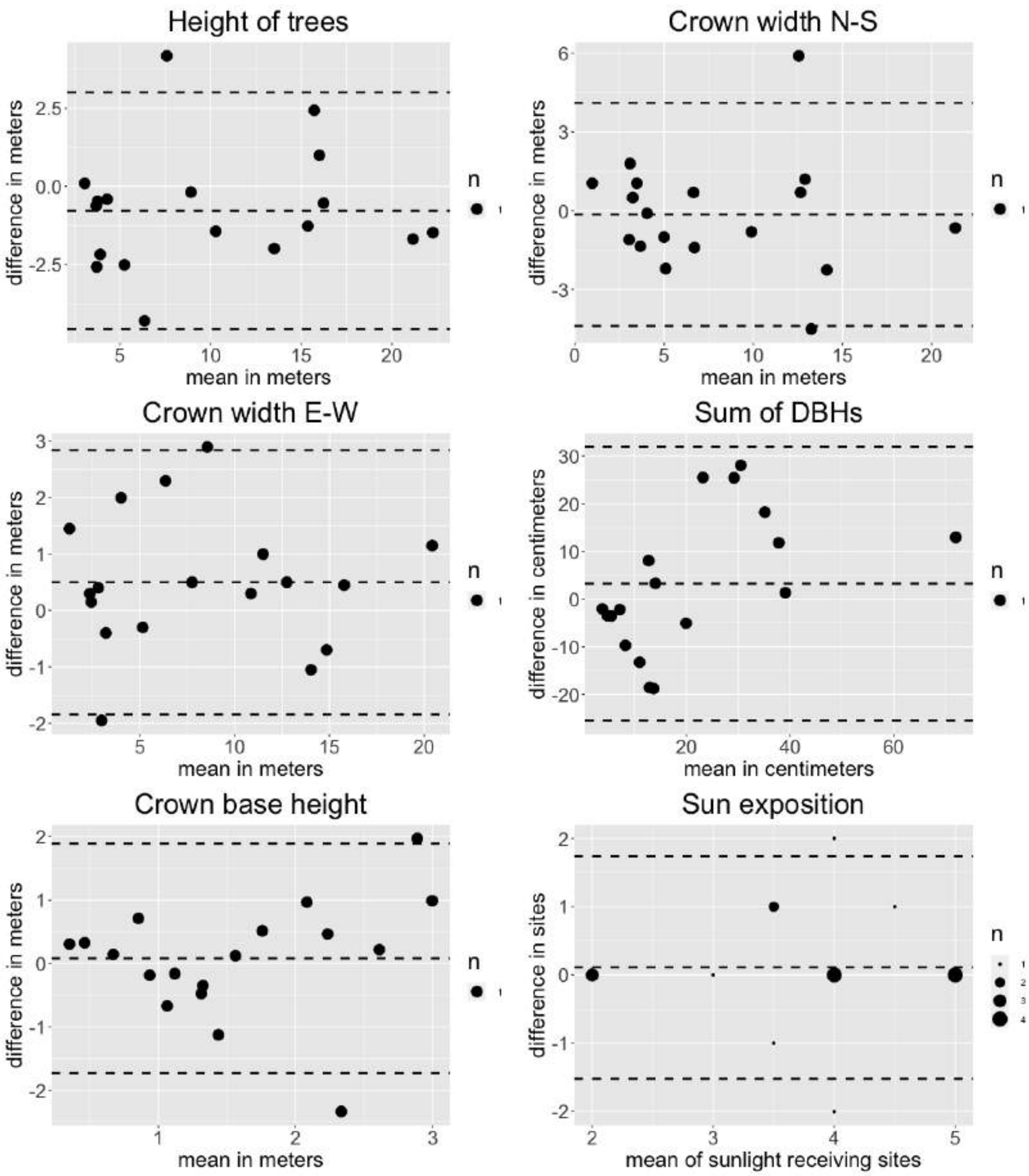

Fig. 16 Each parameter for each tree was determined both with remote sensing and field data. In the Bland-Altman plot, the x-axis shows the mean values of two measurements for a parameter of an investigated tree. The y-axis shows the difference between the value determined with remote sensing data and the field measurement. n indicates the number of trees per point. Except for sun exposure, each point corresponds to one tree. If a point is above 0, the value was higher with the remote sensing data than with the field data. The dashed lines above and below show the 95% confidence interval, but due to the small sample size no conclusions about significance are made.

3.3.2 Outputs

Tab. 3 shows the results calculated by i-Tree Eco. The software calculated the impacts of all 18 trees together. For example, depending on the data collection method, in 2018, the examined 18 trees at the site were able to reduce the stormwater runoff by 20.8 m^3 or 24.8 m^3 respectively. This is the amount of water which infiltrated into the soil or evaporated instead of running off the surface.
In addition, it was calculated that the 18 trees removed 6.5 kg or 7.5 kg respectively of air pollutants per year. In particular, the removed pollutants are NO_2, O_3 and $PM_{2.5}$. These removed pollutants do not longer contribute to air pollution and therefore not harm human health.

Furthermore, the 18 trees stored 0.95 or 3.15 tons of carbon at their stage in 2018. Depending on the approach, it was calculated that the 18 trees sequestered 64 kg or 96 kg of carbon in the year 2018. The carbon comes from CO_2 which is taken from the air and then bound to plant tissue. For the data set based on remote sensing, VOCs emission of 2.1 kg in the year of 2018 was calculated, while only 1.5 kg of VOCs emission per year were calculated based on field data. This is the amount of emitted volatile compounds being able to contribute to ozone formation.

Depending on the data collection method, different species are considered to deliver the most ecosystem services. For the remote sensing approach, the largest leaf area was calculated for the species Pinus sylvestris, Carpinus betulus and Platanus x hispanica. In the field survey approach, also these three were listed to have the largest leaf area, but instead of the Pinus sylvestris, Carpinus betulus was listed as the one with the largest canopy cover. In the i-Tree Eco report about the remote sensing project, Pinus sylvestris, Platanus x hispanica and Carpinus betulus are listed as the trees which annually sequester the most carbon and Carpinus betulus, Acer campestre and Pinus sylvestris are storing the most carbon. In the project based on the field survey, the carbon storing tree species were the same, except for Prunus serrulata listed as a larger contributor to carbon sequestration than Carpinus betulus, and Platanus x hispanica as a larger carbon storage than Pinus sylvestris. The avoided runoff was mainly intercepted by Pinus sylvestris, Carpinus betulus and Platanus x hispanica according to both reports. But while Pinus sylvestris was considered the most important in the report based on remote sensing, it was only the third most important in the report based on the field survey. Overall, the species Pinus sylvestris is less important in the outputs based on field data than in the outputs based on remote sensing.

Table 3 Outputs by i-Tree Eco

Calculated output	**Project: Field survey**	**Project: Remote sensing**
Tree coverage of the total area	21.3%	21.6%
Leaf area in hectares	0.53	0.64
Avoided runoff in m^3 per year	20.8	24.8
Pollution removal in kg per year	6.5	7.5
Carbon storage in t	0.95	3.15
Carbon sequestration in kg per year	64	96
VOCs emissions in kg per year	1.5	2.1

All calculated results were higher for the project based on remote sensing than for the project based on the field survey. The divergence in percentage is shown in fig. 17.

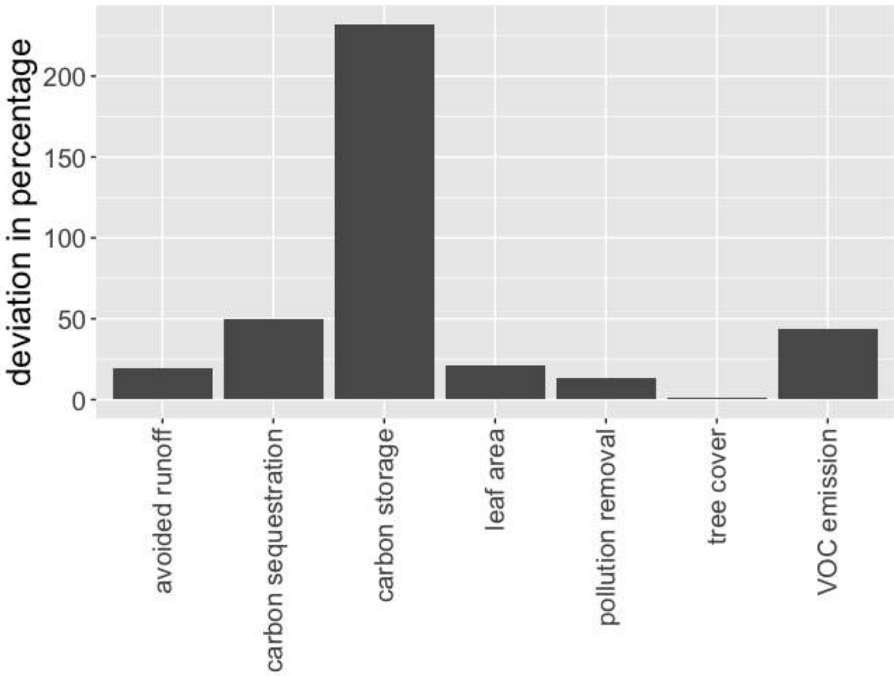

Fig. 17 The deviation of the results obtained from i-Tree Eco: The x-axis shows the calculated effects, the y-axis the deviations. The percentage by which the outputs of the remote sensing data deviate from the outputs of the field surveys is shown.

According to the forecasts run with i-Tree Eco, the number of trees will decrease in the next 30 years if no new trees are planted. According to the report based on remote sensing, nine trees will be left in 30 years. According to the report with field data, there will only be six trees left in 30 years. The ecosystem service delivery and structural compositions predicted for the two projects are shown in tab. 4.

Table 4 Predictions by the forecast function of i-Tree Eco

Prediction	**Project: Field survey**	**Project: Remote sensing**
Number of trees in 15 years	15	14
Number of trees in 30 years	6	9
Leaf area in 15 years	9521 m^2	9734 m^2
Leaf area in 30 years	6869 m^2	9294 m^2
$PM_{2.5}$ removal in 15 years	0.3 kg/year	0.4 kg/year
$PM_{2.5}$ removal in 30 years	0.3 kg/year	0.4 kg/year
O_3 removal in 15 years	7.1 kg/year	7.4 kg/year
O_3 removal in 30 years	6 kg/year	7 kg/year

3.3.3 Sensitivity analysis of the DBH

In figure 18, the results of the sensitivity analysis of i-Tree Eco concerning the DBH are shown. For this analysis, the 19 trees at Rautistrasse for which parameters were determined with remote sensing were used. Thus, there is one more tree in the sensitivity analysis than in the comparison of the methods because the tree which was removed from the site is included.

The only parameter which did not depend on varying DBH was the energy savings for buildings. The reason is mentioned in the output of the i-Tree Eco report: The calculation of the energy savings is only considering tree height, distance to buildings and the condition of the crown. Based on the energy savings, the avoided carbon is calculated. This value was 1.15% higher for the samples where the DBHs were reduced. According to the i-Tree report generated for the site, evergreen trees can lead to higher energy consumption in winter if they are on the south side of a building and prevent sunlight from reaching the front of the building. Therefore, the reason for higher avoided carbon for the reduced DBHs might be that there are less trees in the sample which prevent the sunlight from reaching buildings.

There was less pollution removal, carbon storage, carbon sequestration and avoided runoff for the samples where DBH was decreased, while the values were higher for the samples where DBH was increased. The greatest impact of varying DBH was stated for the carbon storage where the addition of 22% resulted in an increase of 57.3% in carbon storage, while the deduction of 22% of the DBH led to a decrease of 42.8% in carbon storage. Also, carbon sequestration values seem to react sensible on varying DBH. Changes between 0.9% and 4.8% were detected for the pollution removal values, changes between 1.2% and 5.8% for the avoided runoff values

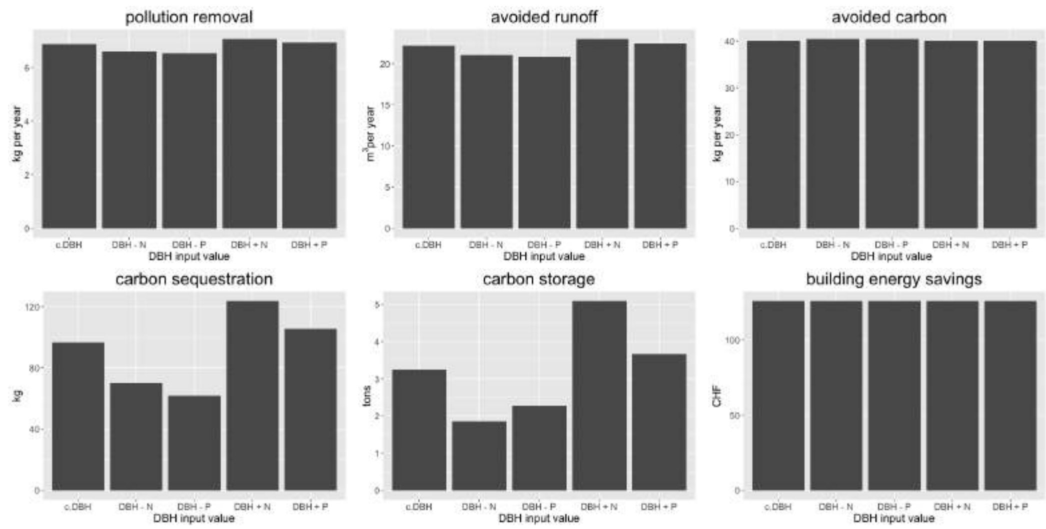

Fig. 18 Sensitivity analysis with i-Tree Eco

4 Discussion

4.1 Assessment of the changes at the 6 study sites

Based on changes in unsealed areas and tree stocks, an evaluation can be conducted whether the investigated areas are better adapted to climate change than they were before they were overbuilt. The evaluation follows the assessment schemes shown in fig. 12 and fig. 13. A summary of the evaluations is shown in fig. 19.

Rautistrasse
The changes at this site resulted in scenario C for green space and scenario 1 for trees. In general, it is beneficial that the total unsealed area has increased, but in the assessment scheme the heat mitigation effect is heavily weighted. Since roofs do not contribute to the cooling effect, the heat protection provided by green spaces might have decreased. However, the development of the tree population might have compensated for this loss.

It is not known to what extent the infiltration of water and rooting of trees is disturbed by underground structures located below 20% of unsealed soil. Further investigations would be required to make a statement about the influence of the underground structures on the provision of ecosystem services.
As the site is located on the edge of the city, ozone concentrations could be higher than in the city centre due to the lower NOx concentrations. Thus it is an advantage that there are no trees known for high BVOCs emissions contributing to ozone formation. At Rautistrasse, there might already be pollution removal due to the large number of trees, but the removal potential could be increased by implementing vertical greening or lush vegetation on the roofs.

Escherpark
With regard to the green spaces, scenario A has arrived. No information on tree species could be found, so scenarios 1,2,3 or 4 may have come true.
The green roofs are about 1 meter higher than proposed in the scheme, but it is assumed that they contribute to cooling. The only shortcoming of the green space development at this site is that about 43% of the unsealed soil is underbuilt, which could reduce the infiltration rate. However, as the site has a retention system, it is assumed that no significant surface runoff will occur.

This site is well adapted to climate change unless the trees are not suitable and emit a lot of BVOCs, which is not known. However, the risk of ozone formation at this site is lower than at other sites. Due to the proximity to the motorway, the NOx concentration is likely to be rather high. In addition, the site is close to the lake and a park, so heat island effects may not be as pronounced and the trees are therefore less exposed to stress.

Triemli
The green space development of Triemli led to scenario B. No information on tree composition could be found for this site either, which means that scenario 1,2,3 or 4 could apply.

The area is close to the forest, but also close to a major road. Therefore, the NOx concentrations could be quite high, but the heat island effect is probably not very pronounced.

For these reasons, it is assumed that this site is not an extremely stressful environment for trees. Most probably, the site is better adapted to climate change than it was before.

Hunziker Areal
In 2018, the changes at this site led to Scenario C, but without an increase in total unsealed area. However, if the unsealing carried out in 2020 is taken into account, the total unsealed area has increased compared to 2010. Nevertheless, scenario C still applies. There is some vertical greening that contributes to cooling.

If the area is assessed only on the basis of the trees whose species are known, scenario 4 applies. But it must be taken into account that these are not all trees occurring on the site. A total of 155 trees were counted, so there are 103 trees whose species are not known. However, it is known that there are BVOCs-emitting trees. Since this site is affected by urban heat islands, these trees are exposed to stress and therefore most likely contribute to ozone formation.
The site is not ideally adapted to climate change, but it is a good development that there are still efforts to further increase green spaces and unsealed areas.

Kalkbreite
Scenario F occurred for green spaces. There were many improvements, the unsealed area in general and the greened area in particular increased. However, there is less vegetated area than on average in Zurich. Green areas on mezzanine floors of the building were not taken into account, but it is assumed that they would not cover 7% of the total area, which would be required to reach the average green area in the city of Zurich.

If only the 7 trees whose species have been identified are taken into account, scenario 1 for building development applies. However, with 31 trees per hectare, this site offers the lowest tree density compared to the other study areas. Since this housing estate is located in the city centre, which is particularly affected by the urban heat island, increasing the greened area and the number of trees would certainly be beneficial.

Freilager Areal
The development at this location leads to the scenarios F and 1. There has been much improvement compared to before the superstructure was built.
However, since the green roofs are too high to contribute to heat mitigation, there is 6% less green area at this site than on average in the city of Zurich. Overall, the site benefits from more ecosystem services than before, but it would be an upgrade to green more of the unsealed area.

Rautistrasse	
Although other unsealed areas such as green roofs or gravel covered grounds increased, it is likely that the mitigation of heat islands decreased due to the decrease in vegetated ground.	This site benefits from more tree-based ecosystem services than before. It is likely that these services will be provided in the future because most trees are adapted to climate change.
If possible, more area should be unsealed and vegetated.	It is always beneficial to plant more trees, if not for ecosystem services then for biodiversity.

Escherpark	
There is more heat reduction, runoff mitigation, and air pollution reduction now than before due to the increase of unsealed and vegetated area.	The tree development could not be determined.
Climate adaption could be further improved by the implementation of vertical greening.	

Hunziker Areal	
Although other unsealed areas such as green roofs or gravel covered grounds increased, it is likely that the mitigation of heat islands decreased due to the decrease in vegetated ground.	This site benefits from more tree-based ecosystem services than before. However, most trees are not adapted to climate change and might not survive in the future. In addition, some of the trees have an adverse effect and contribute to ozone formation.
If possible, more area should be unsealed and vegetated.	It is recommended to plant new, more adapted trees or to replace damaged ones with some that are marked as suitable on the GALK list. Moreover, it is recommended to observe the local ozone concentration and to create the least possible stressed environments for trees listed in box 2 or to replace them.

Triemli	
The area of vegetated soil has increased, which is beneficial in terms of heat mitigation. The whole unsealed area increased, which reduces surface water runoff.	The tree development could not be determined.
Vertical greening or vegetated roofs could be implemented to contribute to air pollution removal.	

Kalkbreite and Freilager Areal	
It is an improvement that vegetated and unsealed but vegetation-less grounds and/or green roof area increased. There might be more heat mitigation, surface runoff reduction and even more air cleaning at the site now than before. Still, the vegetated area is below average.	This site benefits from more tree-based ecosystem services than before. It is likely that these services will be provided in the future because most trees are adapted to climate change.
It would be beneficial to increase unsealed and vegetated spaces.	It is always beneficial to plant more trees, if not for ecosystem services then for biodiversity.

Fig. 19 Assignment of the scenarios for the study areas

Summary
Not enough sites have been studied to ascertain a correlation between previous use of the site and the development of green areas. It can only be stated that vegetated spaces either increased or decreased, but the number of trees increased at all sites. In her master thesis, Wild (2013) found that for 30 sites in the city of Zurich, an increase of green spaces only occurred at industrial sites. This insight matches to the result that green space increased at Kalkbreite and Freilagerstrasse, which are former industrial sites. But in this thesis, it was also found that green space increased at the former residential area Triemli. This can be explained by the fact that densification is enabled by building in the vertical direction. That is also the reason why the green space per flat decreased on the examined sites Rautistrasse and Escherpark even though the absolute green area increased.

The fact that the number of trees has increased at all sites is considered a good sign in terms of climate adaptation. It has not been investigated what tree species were at the sites in 2010, but it seems that on the sites Rautistrasse, Escherpark and Hunziker Areal some of the old tree stocks were left. This is particularly important because newly planted, younger trees have less leaf area and therefore less effects on air quality, heat mitigation and surface runoff than old trees. In the end, however, it is most important that the newly planted trees are adapted to the site conditions and have a high life expectancy.

4.2 i-Tree Eco: Differences between the two measuring methods

4.2.1 Deviations of the input parameters

Tree height
In general, all parameters were expected to be measured larger in the field than with remote sensing data, since the LiDAR point clouds were recorded in 2018 while the field survey was conducted in 2021.
Therefore, it is explainable that especially small trees, which were planted recently, had a larger height measured in the field than with remote sensing. However, the largest observed difference might not be explicable through plant growth. Tree AL-5759, a Metasequoia glyptostroboides, was measured to be 4.3 m higher in 2021 in the field than measured with remote sensing in 2018. According to a German tree nursery, this species can only grow up to 60 cm a year (Baumschule Horstmann).
There are different reasons why trees could be measured smaller in the field than based on LiDAR points. For example, it is very probable that for tree AL-5701, which was bend below another tree, a wrong value was determined with LiDAR. Most probably a branch of the tree above was measured.

Another tree measured smaller in the field only had a very small deviation in negative direction what is explicable with the error of ±10cm for LiDAR data or also with the ±0.5 m error for the field survey.
One tree was measured to be 2.5m lower in the field than with LiDAR, another one even 4m lower.
Since most heights match or the differences are explicable with plant growth, it is concluded that measuring tree height with LiDAR data clouds is an appropriate method. The height differences of -2.5 m for tree AL-5684 and -4 m for tree AL-5701 could either be due to inaccurate field measurements or due to errors in the LiDAR point cloud.

Crown width
The difference between the crown width measurements deviates in both directions. Due to tree growth, it was expected that they are measured larger in the field survey. However, the field survey was conducted before all leaves were out, thus crowns might have been underestimated in the field. But also the LiDAR data, from which the nDOM was derived, was collected when there was little vegetation. There is an error of ±0.5 m for the determination of crown widths with nDOM, which partly explains the deviations.
However, this error does not explain several deviations above 1 m and up to almost 6 m. Some of the trees for which major deviations were observed stood next to other trees. Overlapping crowns could not be detected with nDOM, thus the error through the measurement with nDOM might have been larger than 0.5 m. Still, widths that were measured to be more than 1 m larger with nDOM than in the field were also observed for single-standing trees. An explanation might be that the trees have been pruned in the meantime. For example for tree AL-5694, for which the crown width was determined to be 6 m larger with remote sensing, a missing crown of 35%-40% was observed. However, the error of this particular tree was most probably also big because it was standing next to other trees which led to the overlapping mentioned above.

It is concluded that the method for determining crown widths based only on nDOM is not accurate enough. An improvement could be achieved by measuring crown width via profile views of LiDAR data clouds. However, it is not guaranteed that overlapping crowns could be detected by this method. In addition, it is time consuming to select the correct sequence for which a profile view should be created when dealing with groups of trees. To find overlapping crowns, the profile must be investigated from different directions.

DBH
The deviations of DBHs were expected. There are three possible error sources which could have led to the deviations between the sums of DBHs:

- The model to estimate the DBHs was not suitable.
- The deviations of the parameters used for the model (tree height and average crown width) led to error propagation and thus to results that deviate widely from the DBHs measured in the field.
- It is not appropriate to compare the sum of DBHs. Since the model cannot provide an estimation for the number of stems, it is not suitable.

To find out whether the model was simply unsuitable or whether the used parameters led to the deviations, the equation 1 was also used to calculate the DBHs based on parameters measured in the field. The results were more similar to the DBHs calculated with remote sensing data than to the DBHs determined in the field. That means that the model does not lead to more accurate DBHs even with field-measured data. It is concluded that the main reason for the discrepancies of the DBHs is that the equation 1 is not appropriate for the tree species studied.

Improvements could be achieved by adjusting the model through calibration with Swiss trees. However, the fact that many trees have several stems makes it more difficult to find a reliable model.
DBH is therefore one of the factors that most complicate the use of i-Tree based on remote

sensing data. In terms of the ecosystem services air pollution removal and surface water runoff, this parameter is not crucial, which was shown in the sensitivity analysis. However, this insight should be taken with caution because the calculated DBHs deviated more from field data than the DBHs in the sensitivity analysis.

Crown base height
The deviation of the crown base height is not surprising, as it is difficult to determine the lowest branch only by data points. The difficulty is to distinguish between tree branches and other vegetation below the tree. As mentioned above, the crown base height is used to calculate the total volume of the crown. The other parameters involved, tree height and crown width, deviated much more than the values of crown base height. Thus, this parameter is not seen as the main reason for deviating results.

Sun exposure
This parameter was determined the same way in the field and with orthophotos and point clouds. Thus, it is not surprising that for most trees these values were determined to be the same. Deviations are explicable through the fact that some light absorbing barriers were not detected on the orthophotos or because the shading of large adjacent trees was overestimated when only looking at data points.

Crown dieback and missing crown
Neglecting these two parameters led to an overestimation of crown volumes in the remote sensing based project, especially for the two trees with high missing crown percentages of over 35%. In the remote sensing data set, it was assumed that these trees have over 35% more crown and thus more leaf area. In addition, dieback also leads to a reduction in leaf area, which provides ecosystem services. Since the dieback was also neglected in the remote sensing data set, the leaf area was additionally overestimated. Furthermore, dieback affects the predictive function of i-Tree Eco as it gives information about the tree health.

To improve the method, missing crowns could be estimated with point clouds. However, this would only be possible if the trees were free-standing and had severe crown deficiencies, e.g. due to shading of an entire tree side. There is no way to determine dieback using LiDAR point clouds or orthophotos so far.
Besides DBH, these two crown-related parameters are the biggest weakness of i-Tree evaluations based on remote sensing data.

4.2.2 Deviations of the outputs

A possible reason for deviations of the calculated outputs is that crown dieback and missing crown were specified for the field data set but set to 0% in the remote sensing data set. This led, for example, to the result that for all Pinus sylvestris at Rautistrasse, the total percent leaf area was calculated to be half as big based on field data than based on remote sensing. There were four Pinus sylvestris at the study site and for two of them a missing crown percentage above 20% was determined in the field, which had a considerable impact on the calculated leaf area and ecosystem services.
To investigate how much the missing crown and crown dieback parameters influence the outputs, a third i-Tree project was set up. This project was run with the field data set, but instead of the determined values for crown health, 0% was specified for all trees like

in the project based on remote sensing.

The deviations of the results calculated with remote sensing data and those based on field data with and without crown health parameters are shown in fig. 20. The difference between the blue and yellow bars displays the deviations in the outputs that can be explained by the neglect of the crown parameters. It can be observed that the changes in the calculated canopy volume due to the consideration of missing crown and dieback have a rather small influence on carbon storage and sequestration. But it is noticeable that more than half of the discrepancies between the calculations of air pollutant removal, runoff reduction and the release of VOCs can be explained by the neglect of crown parameters in the remote sensing data set.

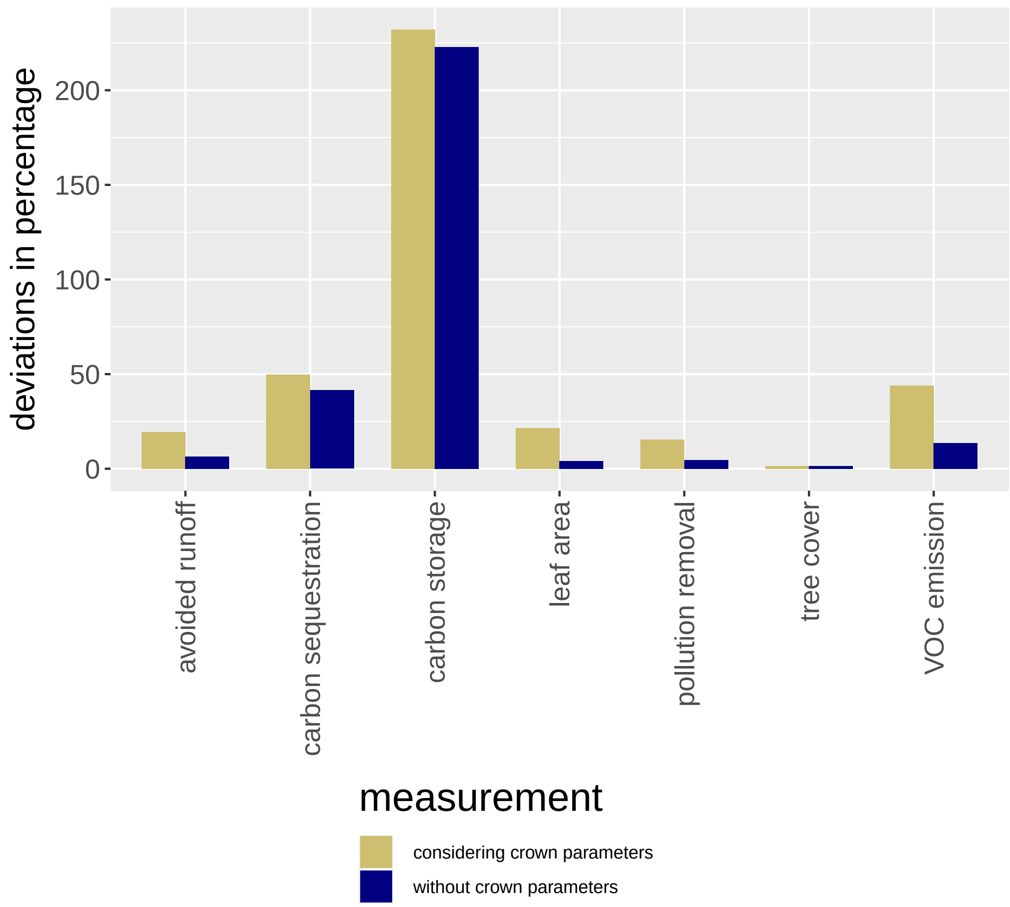

Fig. 20 The yellow bars show the percentage deviation of results obtained with remote sensing data from the result obtained with field measurements including information about missing crown and crown dieback. These are the same bars like in fig. 17. The blue bars in contrary show the percentage deviation of the results calculated based on remote sensing data from the results based on field measured data without consideration of crown missing and crown dieback. Thus the blue bars show the deviation in the outputs if crown health and volume losses are neglected in both measuring methods.

For the calculation of the ecosystem services pollution removal, avoided runoff and for disadvantageous VOCs emission, crown dieback and missing crown seem to be the crucial parameters for discrepancies. In contrary, carbon-related effects are not heavily depending on the crown input parameters. Combined with the findings from the sensitivity analysis, it can be deduced that deviating DBHs are the main reasons for large differences in calculated carbon storage and sequestration capacity.

The remaining differences have to be led back to the deviations in the other input parameters. It cannot be deduced from this experiment whether the field measurement or the remote sensing data are closer to the real values. However, since all other parameters have less influence on the calculation of ecosystem services than missing crown, crown dieback and DBH, the following can be concluded:
With the tested method, it is not possible to accurately calculate air pollutant removal, surface runoff reduction and VOCs release with i-Tree Eco only based on remote sensing data. Even if all parameters except the crown health and volume related ones were the same as measured in the field, there would still be deviations of 27% for VOC release, 12% of avoided runoff and 10% of pollution removal compared to the results calculated with a data set considering missing crown and crown dieback.
Whenever the carbon related ecosystem services of a tree stock are of interest, it is not recommended to conduct an analysis with i-Tree Eco without a field survey. The large deviations of the results and the sensitivity analysis show that an accurately measured DBH is crucial for these calculations.

The predictions of the forecast function led to similar results like the analysis itself: Ecosystem services are predicted to be higher for the project with remote sensing data, even in the future. Furthermore, the number of trees in the forecast decreases more on the basis of the field survey than on the basis of the remote sensing. Most likely, this is due to the neglect of crown dieback, which indicates the health status of a tree. Especially if a forecast is carried out to predict the composition of the tree stock in the future, a field survey must be conducted to take crown dieback into account.

4.2.3 Assessment of the tree composition at the site

50% of the examined tree species have their origin in Europe or Asia, so there is a mix of native species and neophytes.
Reading the i-Tree Eco reports, it is noticeable that the tree species Carpinus betulus, Pinus sylvestris, Acer campestre and Platanus x hispanica are made most responsible for the ecosystem services delivered by the 18 investigated trees. These are also the trees for which the largest leaf areas were calculated in both reports.

The i-Tree reports of this project state that 89% or 93% respectively of the VOCs emissions are caused by Pinus sylvestris and Platanus x hispanica. Thus, even though these species are delivering valuable ecosystem services, it might not be appropriate to plant more of them.

In order to assess the tree composition at Rautistrasse, the ecosystem service delivery of the 18 trees at Rautistrasse should be compared to other complete inventories carried out with i-Tree Eco. The results calculated based on field data are used for the comparison since this is the established method of data collection. Ecosystem services are given per 10 trees in tab. 5 to account for different sample sizes.

In the city center of Bern, at Bundesgasse, a complete inventory with 145 trees of 24 species was conducted. Two third of the examined trees had DBHs smaller than 30 cm, the remaining trees had DBHs up to 142 cm. (Bernasconi et al. (2018))

An i-Tree Eco complete inventory with 683 trees was conducted in Ridge Park in South Australia, which is an urban park in the city of Unley. In this park, more than 4% of the trees had very large DBHs of over 100cm. (City of Unley (2016)

The 18 examined trees at Rautistrasse all have DBHs smaller than 45 cm, the tree stock is consisting of 11 tree species.

Table 5 This table shows a comparison of the ecosystem services provision at three different locations. At Rautistrasse, a total of 18 trees was investigated, at Bundesgasse it was a total of 145 trees and in Ridge Park a total of 683 trees.

Effect	**Rautistrasse**	**Bundesgasse**	**Ridge Park**
Avoided runoff in m^3/y per 10 trees	11.5	6.7	3.6
Pollution removal in kg/y per 10 trees	3.6	2.5	3
Carbon sequestration in kg/y per 10 trees	35.6	117.2	146.4
Carbon storage in kg per 10 trees	527.8	4275.9	5007.3

The tree composition at Rautistrasse seems to be suitable to reduce runoff and remove pollutants, there is more removal and runoff reduction per tree at Rautistrasse than at the other sites. When it comes to carbon effects, the tree composition observed in Bern and Australia provides much higher absorption and storage rates. One possible reason is that in Bern and Unley there are larger DBHs, which means thicker trunks, that clearly store more carbon. Moreover, the carbon sequestration is higher where there are several large trees with big canopies. At Rautistrasse, 40% of the trees were smaller than 6 meters, while the trees with the large DBHs at the other sites were most probably higher. However, the difference in carbon sequestration capacity per tree might also be due to the tree composition, the age of the trees, the health condition or due to location features or climatic conditions. It is assumed that the climatic conditions were similar for the sites Rautistrasse and Bern, but very different at the site in Australia.

4.2.4 Information provision by i-Tree Eco

i-Tree Eco reports indicate which species sequester and store the most carbon, which ones avoid the most surface runoff and which ones emit the most VOCs. Moreover, there is the forecast function in i-Tree Eco. Therefore, i-Tree Eco is useful to plan appropriate tree compositions for a certain site.
However, except for the emissions of BVOCs, i-Tree does not provide any information on potential risks of tree species like for example the breaking of branches, which might be hazardous for pedestrians. In addition, i-Tree does not evaluate the potential of allergens or damage through rooting. If this information is needed, it can be gained from the German database citree.

As the literature review showed, trees can not only contribute to better local conditions but also suffer from drought, heat stress or air pollutants. Besides the information provided by i-Tree Eco, table 1 in a factsheet of HAFL can help to determine climate fitness of urban trees (HAFL (b)). For the twenty most common tree species in Bern, drought tolerance, winter tolerance and urban stress tolerance are expressed as values between -1 and 1, where 1 means that a tree is well adapted.
The advantage is that these suggestions are made specifically for Switzerland and thus

can also be used for Zurich. But the disadvantage is that for example of the tree species recorded at Rautistrasse, only two species are included in the list.
If the species of interest are not covered by the list, also the tree development assessment scheme created in this thesis can be used to classify whether trees are appropriate for urban sites, like it was done for the six study sites in Zurich.

4.3 Discussion of the methods

4.3.1 Measurements and assessments of the study sites

Green and unsealed spaces

The greened and unsealed areas were determined manually, therefore it is possible that certain areas were overlooked and thus not counted.
Especially on the Hunziker Areal, solar panels restricted the view of green roofs, which made it difficult to record exact sizes. One approach to determine green spaces more objectively would be based on the NDVI (Normalised Difference Vegetation Index), which was done for example by Felber (2020) in her master thesis about green space development at the municipal level. However, her analysis was done for a much larger area and with data sets with spatial resolutions between 10 and 30 metres, which is a lower resolution than the one of the raster data analyzed in this thesis. Moreover, the NDVI approach involves more steps and would not have been suitable for this work. Furthermore, the NDVI analysis does not provide information on the composition of the green spaces. In contrast, with the method chosen in this thesis it was possible to distinguish between shrubs, trees and meadow.

The angle of the orthophotos can cause tall buildings to hide parts of the area. This problem of the so-called nadir angle was also mentioned in Wild (2013). Since the conditions for determining green areas were the same for 2007/2010 and 2018, the results are subject to the same possible error. Thus, conclusions can be drawn as to whether the green area has increased or decreased, although some areas might not have been recorded.

A strong limitation of the chosen method of green space determination is that little can be learned about soil properties. Nothing can be said about the permeability of the soil. It is not known how deep the soil layers are and thus whether underground structures affect surface runoff or evapotranspiration rates. But for this extension of data collection, a method must be found to quickly identify the underbuilt area as well as the depth of the soil layers. Also, the effects of underground structures on vegetation and infiltration would have to be clearer.
The most critical point of the assessment scheme is the reference value of what percentage of the area is vegetated. The reference value of the average vegetated soil in Zurich should be replaced by a value that describes what percentage of vegetated soil is aimed for in the cities or settlements. Such a value was not found. Moreover, the scheme would be more accurate if the underbuilt area was included. For example the Hunziker Areal might have been rated better if this component was considered since there is little underground structure disturbing infiltration or plant growth at this site. If a more social aspect of green spaces is to be assessed, the vegetated ground per person could be taken into account in addition to the total vegetated area.

Overall, the evaluation of the developments with the applied measurement method and the assessment scheme is useful in order to roughly classify the development of overbuilt areas.

Assessment of tree stocks
The method used in this work to identify the trees was not ideal because two different approaches were taken for different years. It was planned to evaluate both years with vegetation height models, but the resolution of the VHM was too low for the years before 2010. Therefore, LiDAR data was used to determine the number of trees in 2018, while only orthophotos could be used for 2010 and 2007.

It is assumed that the error for the determined number of trees for the sites in 2007/2010 is subject to a larger error, as less can be detected on the orthophotos than with LiDAR data. But according to Wild (2013), trees can be identified quite well from orthophotos. In a linear regression analysis, she found that the adjusted R^2 of trees identified with orthophotos compared to field surveys was 0.9422, which is a high correlation. In this thesis it was not verified whether the number of trees counted for 2007/2010 is correct or not.

For the Freilager Areal, only 278 of the at least 401 planted trees were counted with LiDAR for 2018. Also for the site Rautistrasse, only 93 of the recorded 101 trees were identified for 2018. During a field inspection at Freilager Areal, it was noted that many trees were planted around bicycle shelters. They were not identified as trees with LiDAR because it was not visible that they were trees. Another reason for the divergence in tree numbers is probably that all trees under 2.5 m height were not counted. This leads to the conclusion that even trees counted with point clouds can differ greatly from the true number.
It should be mentioned that there were a considerable number of trees outside the property boundaries that were not counted. In most cases these were street trees, which obviously also provide ecosystem services locally. In further studies, trees from adjacent properties could also be included in the analysis. However, for answering the questions of this work, the chosen approach was suitable, as only changes on the property itself were asked for.

Since not all trees have the same environmental impact, it is not sufficient to compare only the number of trees to assess whether an area is more or less adapted to the problems associated with climate change. The evaluation of the tree stock development with the assessment scheme is a simplified approach. However, the tree species have to be known. If the assessment is conducted without field survey and tree species determination at the site, the tree record or websites about the housing estates need to contain information about the species.
If more should be learned about the actual impact of present trees, an i-Tree Eco analysis is appropriate.

4.3.2 The analysis with i-Tree Eco

One weakness of the experiment with i-Tree Eco is that the field survey was not carried out in the same year as the LiDAR point cloud was recorded. Furthermore, the results might have been more accurate if the field survey had been conducted in late spring or summer when all trees had their leaves.

In terms to figure out whether the differences between the results obtained with field data and remote sensing are significant, the sample size needs to be larger. For further studies, trees from different locations should be investigated in case the LiDAR data acquisition of a certain area was disturbed for some reason. One challenge of further studies is to find a method to determine DBHs of trees more accurately without field surveys. Further studies also require a better tool to identify missing crown with remote sensing. Research could be conducted to find whether there are possibilities to gain more information about the crown properties with LiDAR data. Nevertheless, it will most likely remain impossible to determine crown dieback without field surveys.

5 Conclusion

The results of this thesis do not support the assumption that densification necessarily leads to a reduction in ecosystem services provided by vegetation.
Nonetheless, based on the evaluations of the six study areas, it can be said that the full potential of the vegetation was not utilised in all of them. Appropriate implementation of vegetation is crucial for the microclimate. For example, it needs to be considered that high roofs do not mitigate heat effect, thus they cannot fully compensate for the loss of vegetated grounds. Moreover, care must be taken to ensure that trees are planted in constellations that allow for a high life expectancy.

For trees in particular, it is recommended that planners carefully select tree species and composition to achieve the best possible results in improving microclimate and air quality. Scheme 13 presented in this thesis, which refers to the German GALK list and the database citree, can be used for orientation.
With regard to the calculation of ecosystem services of an existing tree population, the i-Tree Eco software allows a broad estimation of impacts. However, for the calculation of air pollutant removal, avoided runoff and VOCs emissions, the use of the remote sensing approach is only recommended if overestimations of up to 50% can be tolerated. Further research in the usage of remote sensing could lead to faster and more accurate ecosystem service calculations which would allow more frequent use of i-Tree Eco also for large construction projects in cities. For example, such i-Tree analyses could help to identify single trees or tree groups that should absolutely be maintained during a construction project. In terms to calculate carbon sequestration and carbon storage of trees, it is recommended to choose the field survey approach.

In conclusion, ecosystem services provided by greened areas, unsealed surfaces and trees are important for maintaining a pleasant microclimate in cities. Further efforts should be made to maintain or even increase adequate vegetation on residential properties, which is possible and necessary in view of the densification process.

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Appendices

study area	year	category	total shape (m^2)
Escherpark	2010	vegetated	7504.626179
Escherpark	2018	vegetated	6775.264086
Escherpark	2010	unsealed	0
Escherpark	2018	unsealed	1004.115741
Escherpark	2010/2018	total area	12598.40545
Escherpark	2018	underground structures	3350.152458
Escherpark	2018	green roof	3594.08583
Triemli	2007	vegetated	9367.185641
Triemli	2018	vegetated	9601.033282
Triemli	2007	unsealed	0
Triemli	2018	unsealed	1265.428806
Triemli	2007/2018	total area	18411.78278
Triemli	2018	underground structures	2231.181924
Triemli	2018	green roof	4364.325367
Rautistrasse	2010	vegetated	7764.856174
Rautistrasse	2018	vegetated	6642.590592
Rautistrasse	2010	unsealed	0
Rautistrasse	2018	unsealed	353.5866942
Rautistrasse	2010/2018	total area	11581.80911
Rautistrasse	2018	underground structures	2293.939561
Rautistrasse	2018	green roof	1564.394238
Freilager Areal	2010	vegetated	3247.72569
Freilager Areal	2018	vegetated	11327.18404
Freilager Areal	2010	unsealed	710.6873857
Freilager Areal	2018	unsealed	7922.072542
Freilager Areal	2010/2018	total area	70474.87754
Freilager Areal	2018	underground structures	11554.94646
Freilager Areal	2018	green roof	16941.87748
Kalkbreite	2010	vegetated	170.8710461
Kalkbreite	2018	vegetated	996.3960376
Kalkbreite	2010	unsealed	89.06889614
Kalkbreite	2018	unsealed	637.2913545
Kalkbreite	2010/2018	total area	6723.842308
Kalkbreite	2018	underground structures	28.27725231
Kalkbreite	2018	green roof	0
Hunziker Areal	2010	unsealed	708.1287614
Hunziker Areal	2018	unsealed	3831.902792
Hunziker Areal	2010	vegetated	15398.50976
Hunziker Areal	2018	vegetated	7952.007042
Hunziker Areal	2010/2018	total area	40173.53275
Hunziker Areal	2018	underground structures	69.12932472
Hunziker Areal	2018	green roof	4311.857935
Hunziker Areal	2020	unsealed area	4281.902792

Fig. 21 Raw data: Green spaces on study areas

study area	year	number of trees
Escherpark	2010	42
Escherpark	2018	87
Rautistrasse	2010	32
Rautistrasse	2018	93
Triemli	2007	37
Triemli	2018	95
Freilager	2010	8
Freilager	2018	278
Hunziker Areal	2010	14
Hunziker Areal	2018	155
Kalkbreite	2010	9
Kalkbreite	2018	31

study area	identified species present in 2018
Escherpark	0
Rautistrasse	Acer campestre
	Alnus glutinosa
	Carpinus betulus
	Cladrastis kentukea
	Davidia involucrata
	Ginkgo biloba
	Liriodendron tulipifera
	Magnolia spec.
	Malus domestica cv.
	Metasequoia glyptostroboides
	Pinus sylvestris
	Platanus x hispanica
	Prunus avium
	Prunus serrulata
	Pyrus communis cv.
	Salix fragilis
Triemli	0
Freilager	Syringa
	Betula pendula
	Carpinus betulus
	Tilia eur. ‚Pallida‘
Hunziker Areal	Fraxinus excelsior
	Acer platanoides
	Cydonia oblonga cv.
	Juglans regia cv.
	Populus tremula
	Prunus avium
	Prunus avium cv.
	Prunus domestica cv.
	Prunus domestica domestica 'Ariel'
	Prunus domestica domestica cv.
	Prunus domestica syriaca 'Mirabelle de Nancy'
	Pyrus communis cv.
	Robinia pseudoacacia
	Salix alba
	Salix alba 'Chermesina'
	Acer saccharinum
	Acer pseudoplatanus
	Cotoneaster salicifolius
	Populus nigra
Kalkbreite	Prunus serrulata 'Kanzan'

Fig. 22 Raw data: Trees on study areas

input parameters i-Tree Eco

parameter	tree ID	field survey	remote sensing data
tree height	AL-5677	4.5	4.09
	AL-5760	5	2.43
	AL-5755	5	2.83
	AL-5759	8.5	4.21
	AL-5683	3	3.10
	AL-5752	4	3.53
	AL-5756	4	3.38
	AL-5757	6.5	3.99
	AL-5702	11	9.57
	AL-5700	9	8.82
	AL-5680	23	21.52
	AL-5701	5.5	9.67
	AL-5697	15.5	16.50
	AL-5694	14.5	12.52
	AL-5685	16	14.73
	AL-5687	22	20.32
	AL-5703	16.5	15.97
	AL-5684	14.5	16.93
crown base height	AL-5677	1.2	1.04
	AL-5760	0.2	0.51
	AL-5755	1.5	1.63
	AL-5759	0.3	0.63
	AL-5683	1.03	0.85
	AL-5752	1.55	1.08
	AL-5756	2	0.88
	AL-5757	0.6	0.75
	AL-5702	1.4	0.73
	AL-5700	3.5	1.17
	AL-5680	2.5	2.72
	AL-5701	1.5	1.15
	AL-5697	1.9	3.87
	AL-5694	1.6	2.57
	AL-5685	0.5	1.21
	AL-5687	1.5	2.02
	AL-5703	2.5	3.49
	AL-5684	2	2.47

Fig. 23 Raw data: i-Tree Eco input parameters

input parameters i-Tree Eco

parameter	tree ID	field survey	remote sensing data
crown width N-S	AL-5677	0.45	1.5
	AL-5760	3	3.5
	AL-5755	2.2	4
	AL-5759	4.35	3
	AL-5683	2.95	4
	AL-5752	4.1	4
	AL-5756	3.6	2.5
	AL-5757	5.5	4.5
	AL-5702	6.2	4
	AL-5700	7.4	6
	AL-5680	21.65	21
	AL-5701	6.3	7
	AL-5697	15.5	11
	AL-5694	9.6	15.5
	AL-5685	15.25	13
	AL-5687	10.3	9.5
	AL-5703	12.3	13
	AL-5684	12.3	13.5
crown width W-E	AL-5677	0.55	2
	AL-5760	2.6	3
	AL-5755	2.2	2.5
	AL-5759	3.95	2
	AL-5683	2.35	2.5
	AL-5752	3.4	3
	AL-5756	3	5
	AL-5757	5.3	5
	AL-5702	7.1	10
	AL-5700	7.5	8
	AL-5680	19.85	21
	AL-5701	5.2	7.5
	AL-5697	15.55	16
	AL-5694	11	12
	AL-5685	14.55	13.5
	AL-5687	10.7	11
	AL-5703	15.2	14.5
	AL-5684	12.5	13

Fig. 24 Raw data: i-Tree Eco input parameters

input parameters i-Tree Eco

parameter	tree ID	field survey	remote sensing data
missing crown	AL-5677	0	0
	AL-5760	0	0
	AL-5755	0	0
	AL-5759	0	0
	AL-5683	0	0
	AL-5752	0	0
	AL-5756	0%-5%	0
	AL-5757	0	0
	AL-5702	0	0
	AL-5700	5%-10%	0
	AL-5680	0%-5%	0
	AL-5701	0%-5%	0
	AL-5697	0	0
	AL-5694	35%-40%	0
	AL-5685	0	0
	AL-5687	45%-50%	0
	AL-5703	10%-15%	0
	AL-5684	20%-25%	0
crown dieback	AL-5677	0%-5%	0
	AL-5760	0	0
	AL-5755	10%-15%	0
	AL-5759	0	0
	AL-5683	20%-25%	0
	AL-5752	0	0
	AL-5756	0	0
	AL-5757	0	0
	AL-5702	0	0
	AL-5700	15%-20%	0
	AL-5680	0%-5%	0
	AL-5701	10%-15%	0
	AL-5697	0%-5%	0
	AL-5694	0%-5%	0
	AL-5685	0	0
	AL-5687	0	0
	AL-5703	10%-15%	0
	AL-5684	0	0

Fig. 25 Raw data: i-Tree Eco input parameters

input parameters i-Tree Eco

parameter	tree ID	field survey	remote sensing data
sun exposition	AL-5677	5	5
	AL-5760	2	2
	AL-5755	5	3
	AL-5759	3	4
	AL-5683	4	4
	AL-5752	5	5
	AL-5756	5	5
	AL-5757	4	4
	AL-5702	2	2
	AL-5700	2	2
	AL-5680	4	4
	AL-5701	4	4
	AL-5697	3	4
	AL-5694	4	5
	AL-5685	3	3
	AL-5687	3	5
	AL-5703	4	3
	AL-5684	5	5
sum of DBHs	AL-5677	4.79	2.74
	AL-5760	6.48	2.97
	AL-5755	13.07	3.36
	AL-5759	7.31	3.75
	AL-5683	22.18	3.61
	AL-5752	23.04	4.27
	AL-5756	17.60	4.35
	AL-5757	8.21	6.03
	AL-5702	8.67	16.74
	AL-5700	12.36	15.67
	AL-5680	65.49	78.44
	AL-5701	22.45	17.37
	AL-5697	26.01	44.24
	AL-5694	10.40	35.91
	AL-5685	38.42	39.77
	AL-5687	16.47	41.91
	AL-5703	31.92	43.73
	AL-5684	16.43	44.51

Fig. 26 Raw data: i-Tree Eco input parameters

i-Tree Eco outputs

effect	field survey	remote sensing	field without crown parameters
tree cover	21.3	21.6	21.3
pollution removal	6.508	7.509	7.174
carbon storage	0.947	3.145	0.9743
carbon sequestration	64.05	95.99	67.85
avoided runoff	20.78	24.81	23.31
VOC emission	1.476	2.126	1.87
leaf area	0.5258	0.6388	0.6132

Fig. 27 Raw data: i-Tree Eco outputs

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Eigenständigkeitserklärung

Die unterzeichnete Eigenständigkeitserklärung ist Bestandteil jeder während des Studiums verfassten Semester-, Bachelor- und Master-Arbeit oder anderen Abschlussarbeit (auch der jeweils elektronischen Version).

Die Dozentinnen und Dozenten können auch für andere bei ihnen verfasste schriftliche Arbeiten eine Eigenständigkeitserklärung verlangen.

Ich bestätige, die vorliegende Arbeit selbständig und in eigenen Worten verfasst zu haben. Davon ausgenommen sind sprachliche und inhaltliche Korrekturvorschläge durch die Betreuer und Betreuerinnen der Arbeit.

Titel der Arbeit (in Druckschrift):

Measuring change in ecosystem service-providing vegetation on densified areas

Verfasst von (in Druckschrift):

Bei Gruppenarbeiten sind die Namen aller Verfasserinnen und Verfasser erforderlich.

Name(n):	Vorname(n):
Lauber	Chiara Isabel

Ich bestätige mit meiner Unterschrift:

- Ich habe keine im Merkblatt „Zitier-Knigge“ beschriebene Form des Plagiats begangen.
- Ich habe alle Methoden, Daten und Arbeitsabläufe wahrheitsgetreu dokumentiert.
- Ich habe keine Daten manipuliert.
- Ich habe alle Personen erwähnt, welche die Arbeit wesentlich unterstützt haben.

Ich nehme zur Kenntnis, dass die Arbeit mit elektronischen Hilfsmitteln auf Plagiate überprüft werden kann.

Ort, Datum	Unterschrift(en)
27.05.2021	Clau

Bei Gruppenarbeiten sind die Namen aller Verfasserinnen und Verfasser erforderlich. Durch die Unterschriften bürgen sie gemeinsam für den gesamten Inhalt dieser schriftlichen Arbeit.