ETH zürich

BACHELOR THESIS

Physical Soil Properties and Urban Lawn Health

A Case Study in Geneva

Manon Davies
Student Number 18-914-374
Bachelor's degree in Environmental Sciences

1st July 2022

Supervisor: Prof. Sebastian Dötterl
Institute of Terrestrial Ecosystems, ETH Zürich

Advisor: Dr. Silvia Tobias
Landscape Dynamics, WSL

ABSTRACT

Green spaces in cities fulfil key functions for human well-being. With climate change and the resulting increase in the Urban Heat Island effect, their ability to regulate climate will become increasingly important. However, even if vegetation relies on soil as a substrate, the link between vegetation and soils is poorly understood in the urban setting. The present study explores the link between soil properties and the greening and browning of urban lawns. Thirteen sites which were considered as showing uniform vegetation were selected in the city of Geneva. The greening and browning of the lawns was assessed by using the Normalised Difference Vegetation Index (NDVI), which is being increasingly used as a proxy for vegetation health in the urban environment. In this study, the NDVI evolution of the studied sites over a whole vegetation period was examined, focusing on two seasons, spring and summer. The soil properties of soil depth, soil texture, amount of coarse material, bulk density, gravimetric water content at -100hPa, air content at -100hPa and soil organic carbon were measured in all sites, as these properties relate to soil structure quality and the amount of water soils can store. It was found that the amount of coarse material related significantly to the NDVI of the sites in spring as well as in summer, with higher amounts of coarse material leading to lower NDVIs. The soil depth could be related to the NDVI of the sites in the summer, with shallower soils showing lower NDVIs. The bulk density and the gravimetric water content at -100hPa were related to the NDVI of the sites in spring, with higher bulk densities and lower gravimetric water content values belonging to sites with lower NDVIs. It is believed that the effect of the coarse material and the soil depth on the NDVI in summer can be related to their importance for soil water storage. Sites with shallower soils and higher amounts of coarse material drain quickly and are able to store less water than other sites, leading the sites' vegetation to be more stressed in the summer. Furthermore, no soil property related to the fine earth fraction could be shown to have an effect on the NDVI in the summer, leading to the conclusion that the amount of coarse material and the soil depth had a higher influence on the greening and browning of the vegetation than other soil properties. This finding is unique, as no other study successfully linked the amount of coarse material or soil depth to vegetation health in the urban environment. As these soil properties are only rarely assessed in soil surveys, the author stresses the importance of including these soil properties in future research on urban soils and urban vegetation health. Furthermore, it was found that the NDVI of some sites seemed to be influenced by the microclimate of the sites' locations, leading to unexpected NDVI evolutions considering the sites' soil properties. Thus, in further research, the effect of microclimate should be assessed alongside soil properties in order to understand the importance of both factors on vegetation health.

ACKNOWLEDGEMENTS

In order to be able to accomplish a work that relied on multiple different institutions, the help of many people was needed, which I want to take the time to thank here.

First, I would like to thank the two Persons who accompanied this work from start to finish, Prof. Sebastian Dötterl (Soil Resources, ETH Zürich) and Dr. Silvia Tobias (Landscape Dynamics, WSL). I am thankful to Dr. Silvia Tobias for helping me set up the concept of the bachelor thesis, as well as for the numerous and precise text reviews she offered me, and to Prof. Sebastian Dötterl for the suggestions on how to improve my work, and especially for believing that my work could deliver better results when I grew tired of looking further. Second, from the group Sols et Substrats from HEPIA, I would like to thank Prof. Pascal Boivin for letting me use the soil lab and borrow soil measuring equipment, and particularly thank Adrien Matter for the patient explanations of soil property measurements, as well as looking after my soil samples in my absence. Third, from the Soil Resources Lab in ETH Zürich, I would like to thank Dr. Marco Griepentrog and Raffaele Lanini for accompanying the lab work in Zürich. Fourth, I would also like to thank the SEVE for allowing me to take soil samples in the parks they manage, and for providing valuable GIS Layers. Last but not least, I would like to thank Sibylle Förster and Gruffydd Davies (my parents) for helping me finish the field work in time for sundown in December, and Gruffydd Davies for correcting my English, even if he might have found the subject slightly boring.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

A_{100}	Air content at -100hPa (equal to the volume of pores >15µm)
BD	Bulk Density
HEPIA	Haute école du paysage, d'ingénierie et d'architecture de Genève
NDVI	Normalised Difference Vegetation Index
SEVE	Service des espaces verts, the municipal service for green spaces in Geneva
SOC	Soil Organic Carbon
W_{100}	Gravimetric water content at -100hPa

1. INTRODUCTION

With 83% of the Swiss population living in urban areas, the urban environment is the setting in which most Swiss citizens spend their day-to-day life. To ensure human well-being, green spaces in cities are extremely important: they fulfil key functions for health and recreation, as well as for climate regulation (Bundesamt für Umwelt, 2018). Although vegetation relies on soil as a substrate, the link between soil and vegetation in the urban area is not well understood. Generally, soils in cities are not well studied: up until recently, soil mapping worldwide has been focused on agricultural soils, and urban areas appear as blanks on soil maps (Foti et al., 2021; Hiller & Meuser, 1998). In Switzerland, no soil maps have been drawn for cities, and only rare studies focus on urban soils (Amossé et al., 2016; Klaus, 2017; Tresch et al., 2018), none of which link soils to urban vegetation health. Studies linking soil properties to vegetation health are scarce, not only in Switzerland. Most of the studies linking soil properties to vegetation health focus on trees, while some other focus on herbaceous plants (Hernández-López et al., 2021; Moore et al., 2014; Mukherjee & Agrawal, 2018; Scharenbroch et al., 2018; Scharenbroch & Catania, 2012; Ugolini et al., 2020; Yu et al., 2018). None of these studies assess trees and herbaceous plants simultaneously, as all the studies (except one) determine vegetation health through direct measurements on the plants, which are difficult to generalise to all vegetation. Remote sensing data could help resolve this issue, as it can deliver indexes which can be generalised to different vegetation types, such as the Normalised Difference Vegetation Index (NDVI). The NDVI, when used on uniform vegetation, measures the greening and browning of vegetation, and is increasingly being used as a proxy for urban vegetation health. However, only one study was found which used the NDVI to understand the influence of soil properties on urban vegetation health, which focused on urban trees (Galle et al., 2021). No study has yet used NDVI as a proxy for vegetation health to understand the effect of soil properties on urban herbaceous vegetation, and generally, the influence of soil on urban herbaceous vegetation health is poorly understood.

The aim of this study is to understand the effect of soil properties on the greening and browning of urban vegetation, with the novel approach of using the NDVI as a proxy for vegetation health. Even if the NDVI could be generalised to include more than one type of vegetation, this study focuses on herbaceous vegetation, as the link between soil properties and herbaceous vegetation is still understudied in the urban context.

1.1 State of Knowledge

1.1.1 Urban Vegetation

Promoting urban vegetation is an important way to counter the high temperatures which result from the high absorption of solar energy and the high anthropogenic heat radiation in urban areas, also called the Urban Heat Island effect. Vegetation cools the air surrounding it through several processes: trees and shrubs create shade, lawns serve as surfaces for cold air formation during the night, and all vegetation evapotranspires (Bundesamt für Umwelt, 2018). However, urban areas are also a poor environment for plant growth: air pollution, degradation of soil structural quality, and the urban heat island effect itself can all affect plant health (Cârlan, Haase, et al., 2020; Kim et al., 2021; Mukherjee & Agrawal, 2018). Furthermore, urban areas, through their high degree of sealing, have more water runoff and thus less water infiltration, leading to less evapotranspiration than in natural areas (Paul & Meyer, 2001). Droughts, which will increase in intensity and frequency due to climate change, also reduce the evapotranspiration of urban vegetation, and thus the ability of plants to cool the surrounding air (Gräf et al., 2021; Rötzer et al., 2021).

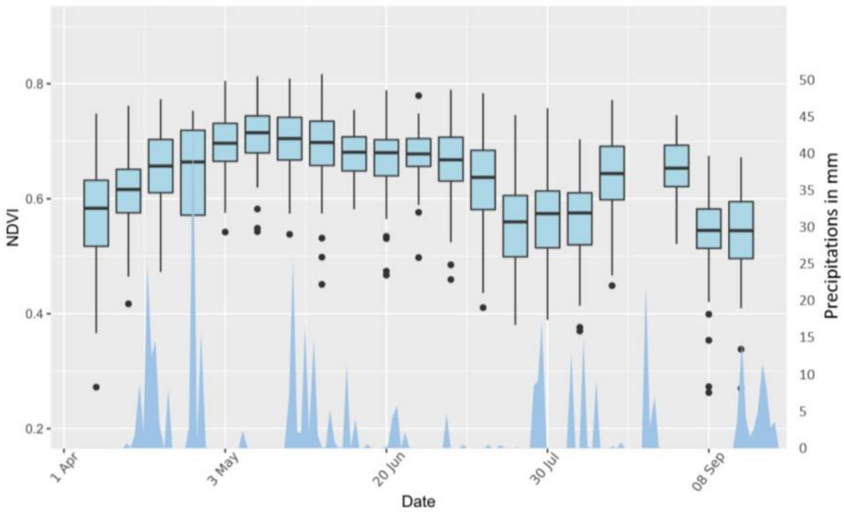
1.1.2 NDVI as a proxy for Vegetation Health

Vegetation health in urban areas has increasingly been determined using remote sensing methods, as data from remote sensing is much easier to obtain than data retrieved by field methods. The Normalised Difference Vegetation Index (NDVI) uses measurements of reflected near infrared light and red light and was designed to differentiate vegetation from other land cover types. It delivers a number between -1 and 1, with numbers closer to 1 representing vegetation. When used on uniform vegetation, the NDVI measures the greening and browning of vegetation, and is thus increasingly used in quantitative assessments to determine various factors linked to vegetation. Nouri et al. (2013) show that NDVI correlates with the evapotranspiration of plants in urban areas. Cârlan, Mihai, et al. (2020) use it as a proxy for vegetation health in a study on urban green spaces. A link between water availability and vegetation greening and browning could be seen in a study led in Geneva: NDVI values of green spaces rose after rainfall events, indicating vegetation greening, and low NDVI values could be observed during droughts and at high temperatures, indicating vegetation browning (Figure 1). The advantage of NDVI compared to other remote sensing methods is that it is openly available, meaning it is easy and inexpensive to retrieve (Imhof, 2021).

Imhof (2021) calculated mean NDVI values over 8-day periods for test sites in green spaces in the city of Geneva during the vegetation period of 2020. The data is available for each surface separately, and the values across all surfaces are visible in Figure 1. It can be observed that the NDVI values in each 8-day period have a wide range, and so that the different sites present different greening and browning trends. Imhof (2021) did not find an explanation for the difference in NDVI values across surfaces – when observing all types of vegetation, she could neither link the NDVI values to underground sealing nor to management level. One part of her study focused on grassy sites, in which she selected grassy sites in Geneva which were comparable in terms of vegetation and management. In her analysis of grassy sites, she excluded areas with underground sealing. Here again, she did not find an explanation for the difference in NDVI values. However, she did not compare the sites' soil properties in any of her analysis.

Figure 1

NDVI Evolution of Green Spaces in the City of Geneva (year 2020)



NDVI evolution across green spaces within the city of Geneva, based on 8-day medians of NDVI values of the surfaces, including all vegetation types (number of sites = 314). Filled line: precipitation in mm in spring and summer 2020. The NDVI values show a great range in each 8-day period, which could be explained neither by management regime nor by the presence of underground sealing. Adapted from Imhof, (2021).

1.1.3 Urban Soils

Urban soils are usually viewed as highly disturbed soils as they are often rearranged as a result of anthropogenic activities (Endlicher, 2012; Lal, 2018; Pouyat et al., 2010). During construction, large amounts of soil are excavated and used as filling at a later moment, and possibly in a different location (Klaus, 2017). Furthermore, urban soils often have incorporated artefacts, such as plastic, glass, building rubble, and household ash (Hiller & Meuser, 1998). As Pouyat et al.(2007) point out, however, most studies in the urban area focus on soils along streets and in highly developed areas, leading to the conclusion that all urban soil is drastically disturbed. When considering soils across the entire urban landscape, undisturbed soils and relatively undisturbed soils can also be found, mainly in old gardens or parks, leading to highly diverse soils in the urban area (Endlicher, 2012; Hiller & Meuser, 1998; Mónok et al., 2021; Pouyat et al., 2007).

1.1.4 Urban Soils and Vegetation Health

Even though studies of urban soils often warn of the possibility of urban soil properties limiting vegetation growth (Jim, 1998; Lan et al., 2019), only a few studies attempt to prove the influence of urban soils on vegetation health. Of these studies, a majority focus on urban trees (Hernández-López et al., 2021; Scharenbroch et al., 2018; Scharenbroch & Catania, 2012; Yu et al., 2018), and some examine herbaceous plants (Kim et al., 2021; Moore et al., 2014; Mukherjee & Agrawal, 2018; Ugolini et al., 2020). It has been shown that the amount of sealing around planted trees influences tree health (Yu et al., 2018), and that some soil properties correlate with tree health attributes. For irrigated trees, soil chemical parameters were found to correlate with urban tree health (Scharenbroch et al., 2018), whereas for trees that were not irrigated, chemical as well as physical properties were found to correlate to tree size and tree growth parameters (Scharenbroch & Catania, 2012). Physical soil properties are especially important during droughts, as they influence the soil structure and water retention of the soil (Kim et al., 2021), which explains why physical properties are more important for surfaces without irrigation.

For herbaceous species, it has been shown that soil moisture has a critical influence on plant growth in urban settings (Ugolini et al., 2020). Thus, physical soil properties should be important for the health of urban herbaceous species in the absence of irrigation. One study shows that herbaceous plant health was influenced by chemical as well as physical soil properties, but that the effect of air pollution was much higher than that of soil properties (Mukherjee & Agrawal, 2018). However, the study's sites were located in India, where air pollution in cities is much higher than in Switzerland (World Health Organization, 2016). Thus, in Switzerland, soil properties might have a greater effect on urban vegetation health than air pollution. As Switzerland has relatively low urban air pollution compared with other countries, the effect of soil properties on vegetation health can be studied while neglecting the effect of air pollution.

Even if the influence of sealing that surrounds urban vegetation has been studied (Yu et al., 2018), no studies were found linking underground sealing to vegetation health. Furthermore, other soil properties, such as soil depth and water content at a given matric potential, have been left out of studies linking urban soil properties to urban vegetation health.

Therefore, this work focuses on the influence of physical soil properties, and soil properties linked to soil structure, on herbaceous plant health in the absence of irrigation in a city with low air pollution.

1.1.5 Soil Properties affecting Water Availability and Rooting Space

Soil is the main water reserve for plants and, in the absence of irrigation, is therefore essential for the water supply of plants. Soil properties also determine rooting space, and thus access of plants to soil water and nutrients. Various soil properties affect soil water storage and rooting space. Here, an overview of the soil properties which will be focused on in this study is given, and for each soil property, it is discussed what soil condition is expected to be found in the urban environment.

In the urban environment, soil properties are generally measured in the upper 20 cm of soil, mainly because of the difficulty of penetrating lower layers. This has, in some studies, led to inconsistent results, as the upper 20 cm do not necessarily represent the rooting depth of all urban vegetation (Galle et al., 2021). As we will be considering lawns, however, the topsoil characteristics very probably represent the soil in which the vegetation roots, and soil properties will be measured in the 5 to 10 cm depth range. The uppermost soil, from 0 to 5 cm, will be left out, as it has too many roots to deliver consistent soil property results.

Soil Depth

When considering the total amount of water and nutrients available to a plant, the rooting depth is an important characteristic, as it defines the amount of soil with which the plant has contact. The rooting depth can vary significantly from species to species, but the maximum plant rooting depth is often restricted by soil properties rather than by the physiology of the plant (Mullins, 1991). Thus, soil depth influences the possible rooting depth of the plants, and so the total available water. In urban areas, soils have been found to be relatively shallow (Tresch et al., 2018), and it is expected that underground sealing severely limits soil depth. However, no study was found which included soils with underground sealing either to characterise soils in an urban setting, or to explain urban vegetation health.

Particle Size Distribution

How strongly water is held in a soil depends on the pore size and distribution. Water is held in pores through capillary and adsorptive forces, both of which depend on the amount of solid surface area. As small pores have more solid surface area per pore volume than large pores, they hold the water more strongly (Hillel, 2003). Soil texture describes the distribution of particles that are smaller than 2 mm. The dimensions of voids between particles depend on particle sizes but are generally two to five times smaller than particle size (Hillel, 2003). Texture thus influences the smaller pores (<50µm), which are especially important for water storage (Kretzschmar, 2017). In urban soils, particle size distribution is linked to geology, or to the geology of the parent material used as a filling, with the urban environment having little influence on the particle size distribution (Foti et al., 2021; Pouyat et al., 2007). Soil texture has been found to influence urban tree health (Scharenbroch & Catania, 2012), and influences the moisture optimum for urban herbaceous plants (Ugolini et al., 2020).

Amount of Coarse Material

The amount of coarse material (solid particles over 2mm in diameter) influences the rooting of plants and the water movement. A high amount of coarse material impedes root growth, with the limitation increasing with stone size (Jim, 1998; Mullins, 1991). The coarse material also influences the amount of large pores in a soil, which are important for water drainage, and thus for aeration (Baetens et al., 2009; Kretzschmar, 2017; Lus & Toor, 2018). In urban soils, it has been noted that a high amount of coarse material is present in soils with high artefact content (Mullins, 1991).

Bulk Density

Bulk density (BD), which represents the mass of soil per volume of soil, determines the amount of pore space, which in turn determines the total amount of space available for air and water to fill. Generally, it is assumed that through loss of the upper soil layer, filling with material from construction sites, traffic from heavy machinery used during construction, trampling, and the sometimes reduced organic carbon content, soils in urban areas have poor structure: the pore space in urban soils is reduced, and thus the bulk density is increased (Endlicher, 2012; Hernandez et al., 2018; Klaus, 2017; Pouyat et al., 2010; Prokof'eva et al., 2020). However, not all studies find high BDs in the urban area. When including soils that are not drastically disturbed in urban soil assessments, significantly lower BDs than in agricultural land can be found (Edmondson et al., 2011; Pouyat et al., 2007; Tresch et al., 2018). Consequently, high BD is common in soils which have undergone soil rearrangement, especially filling and topsoil removal, or which have been subject to external application of forces such as traffic or trampling. Nevertheless, high BD is not a common characteristic of all urban soils and depends on the degree of naturality of the soil as well as vegetation cover.

Soils with more than 10% of clay swell and shrink depending on soil water content, which means that their bulk density will vary with soil moisture (Johannes et al., 2021b). Thus, water content at the time of sampling needs to be indicated (Blake & Hartge, 1986). However, bulk density is often not accompanied by such information, making it very difficult to compare bulk densities across different studies. For this reason, Johannes et al. (2021) propose equilibrating undisturbed soil samples at a given matric potential, and to let the samples swell freely during equilibration before measuring the volume and the mass of each sample. When using this method, the measured bulk density is not dependent on water content while sampling.

Water Content and Air Content at a Given Matric Potential

Most of the time, not all the pore space is occupied by water. The water content expresses how much water is held in a soil sample at a given matric potential. It can be expressed as a ratio of masses (mass of water relative to mass of oven-dried soil) and is then called gravimetric water content, or it can be expressed as a ratio of volumes (volume of water divided by the sample volume, normally calculated by multiplying the gravimetric water content by the bulk density), when it is called volumetric water content (Hillel, 2003).

Johannes et al. (2019) compared more than 70 soil properties to a visual classification of structural soil quality (CoreVess) with the objective of identifying properties that are reliable and easy to measure for the characterisation of soil structure quality in topsoils. They concluded that the most reliable and practical properties are air content and gravimetric water content at a matric potential of -100hPa at 5 to 10 cm depth. The air content at -100hPa (A_{100}) is equal to the volume of pores with a diameter over 15µm.

In this work, water content at -100hPa (W_{100}) is defined as the water content at field capacity, which is described as the water content obtained after draining a fully saturated soil by gravity (Hillel, 2003), and thus represents the water a soil can hold in the long term. Values of the matric potential at field capacity used in Literature range from about 60 to 300hPa and depend on soil texture (Amelung et al., 2018; Lus & Toor, 2018). For operational ease, standard matric potentials are determined for field capacity. Often, the matric potential of -330 hPa is used (Foti et al., 2021; Hillel, 2003; Lan et al., 2019). German literature uses the matric potential of -60 hPa (Kretzschmar, 2017) and in the United Kingdom, the measure of -50hPa is set as a standard (Mullins, 1991).

Often, the volumetric water content is used to quantify the water content at field capacity because it indicates the pore volume filled with water. However, as we orient our work towards the soil structure quality indicators proposed by Johannes et al. (2019), which suggest the use of the gravimetric water content, the latter will be used in this work. Furthermore, this allows the water content measurements to be independent of the bulk density, as the bulk density is not used to calculate the gravimetric water content.

Due to the high amount of disturbed soils in the urban environment, and the often higher bulk density and impaired structure, it is believed that water infiltration and water-holding capacity in the root zone is negatively affected in the urban environment (Lus & Toor, 2018; Pouyat et al., 2010; Scharenbroch & Catania, 2012). However, moisture regimes in urban landscapes are complex, as irrigation and reduced drainage through abrupt textural or structural interfaces may counter the effect of poor soil structure, and the net result of the combined effects is not yet well understood (Pouyat et al., 2010).

As the indicators proposed by Johannes et al. (2019) are not yet a standard, no literature using exactly these indicators in the urban context was found. However, two studies, conducted by Foti et al. (2021) and Lan et al. (2019), used soil water characteristic curves to analyse urban topsoils. Lan et al. (2019) found that soils which had undergone foreign soil replacement had available water capacities below optimum, and Foti et al. (2021) found that the urban-rural gradient had a significant effect on the water content at field capacity as well as available water capacity in all soils. However, the influence of the gradient was not linear. Thus, the link between urbanisation and available water capacity is not yet well understood.

Soil Organic Carbon

Soil organic carbon (SOC) promotes aggregate and macropore formation, and hence is important for soil structure (Lus & Toor, 2018). Johannes et al. (2019) found that SOC content was closely related to physical soil parameters, especially water content at maximum swelling. Rawls et al. (2003) found that SOC influences soil water retention, but that the effect of SOC depends on soil texture and the amount of organic carbon present in the soil. Thus, SOC might have an influence on the capacity of a soil to hold water but should be measured alongside particle size distribution to understand its effect properly. Johannes et al. (2017) propose using the SOC:clay ratio as an indicator for soil structure, rather than just the SOC content.

SOC has been shown to correlate with urban tree health (Scharenbroch et al., 2018; Scharenbroch & Catania, 2012). Adding organic matter in the form of biochar or compost is used as a management measure to promote soil structure and soil water retention, and has been shown to have positive effects on urban trees and herbaceous plants (Kim et al., 2021; Somerville et al., 2020).

In the urban environment, SOC is often lower than outside of the urban environment (Jim, 1998; Lan et al., 2019; Mónok et al., 2021), but its level depends heavily on management regime and vegetation cover: higher amounts of leaf litter, lower plant removal or a less intensive mowing regime lead to higher SOC (Foti et al., 2021; Mónok et al., 2021; Secu et al., 2016; Tresch et al., 2018). The presence of artefacts and their type, as well as type and extent of soil rearrangement also has an influence on SOC (Hiller & Meuser, 1998; Lan et al., 2019; Mónok et al., 2021; Secu et al., 2016).

pH

Soil pH does not have a direct effect on the water storage capacity of soils. However, pH values of over 9 have been shown to affect water uptake of plants negatively (Thorup, 1969). On the other hand, soils with pH < 5 can have elevated concentrations of aluminium, which is toxic for plant roots and can inhibit root growth (Kretzschmar, 2017). pH has been shown to have correlated with urban tree health in the absence of irrigation as well as in the presence of irrigation (Scharenbroch et al., 2018; Scharenbroch & Catania, 2012), which is why it will also be measured in this study.

Summary of the Selected Soil Parameters

As such, the soil properties soil depth, particle size distribution, amount of coarse material, BD, W_{100}, A_{100} and SOC affect water storage and/or root formation, which has an influence on vegetation health. These soil properties are expected to vary within the urban landscape, with highly disturbed sites probably having less optimal soil properties for plants than more natural sites. pH, SOC, BD and texture have been shown to correlate with urban tree health by several studies (Scharenbroch et al., 2018; Scharenbroch & Catania, 2012), and have been shown to have an influence on urban herbaceous vegetation, but the interactions between the soil properties are poorly understood (Mukherjee & Agrawal, 2018). To the best of our knowledge, the effect of soil depth, the amount of coarse material, W_{100} and A_{100} on urban vegetation health has never been explored.

1.2 Objectives

The objective of this study is to explore the link between the soil properties and herbaceous vegetation health in the urban environment. Soil depth, particle size distribution, amount of coarse material, BD, W_{100}, A_{100} and SOC were chosen as soil properties. As NDVI is used as a proxy for vegetation health, and an NDVI dataset for a variety of sites within the city of Geneva is available, the soil properties will be linked to NDVI, and the study sites will be located within the city of Geneva.

Furthermore, the correlation of the soil properties will be explored. Especially the correlation between SOC and W_{100} will be explored, to test whether the findings of Johannes et al. (2019) and Rawls et al.(2003) also stand true in the urban environment. As carbon is often linked to soil structure, its correlation with clay content, BD and A_{100} will also be explored. The correlation of physical soil properties, such as bulk density and coarse material, will be explored as well to understand their interactions and/or their redundancy.

Lastly, as no study focusing on the influence of underground sealing on soil properties and vegetation health in the urban environment was found, we wish to explore the effect of underground sealing on soil properties.

Thus, following three research questions (Q) and hypotheses (H) are formulated:

Question 1. Can particle size distribution, amount of coarse material, BD, W_{100}, A_{100} and SOC in the 5 to 10 cm depth range as well as soil depth explain differences in the evolution of NDVI values, NDVI being used as a proxy for vegetation health, at different sites in the city of Geneva?

Hypothesis 1. We expect soil properties to be linked to NDVI evolution, with lower soil depth, higher amount of coarse material, higher BD, lower W_{100}, lower A_{100}, and higher SOC and leading to lower NDVI values.

Question 2. Is SOC correlated to W_{100}, A_{100}, clay content and BD in the urban environment?

Hypothesis 2. We expect SOC to be positively correlated to W_{100}, as similar findings were made by Johannes et al (2019) and (Rawls et al., 2003) outside the urban environment. We also expect SOC to be correlated to BD, clay content and A_{100}, as SOC influences soil structure.

Question 3: Does underground sealing influence soil properties and NDVI evolution?

Hypothesis 3. We expect that sites with underground sealing will have lower soil depth than their counterpart sites without underground sealing. We also expect their soil structure to be more disturbed than in sites without underground sealing, leading to higher BD, lower W_{100}, lower A_{100} and higher amounts of coarse material. We expect these soil properties to negatively affect NDVI evolution.

2. METHODS

2.1. Site selection

All study sites are located within the city of Geneva, which is situated around the end of Lake Geneva, at the centre of the canton of Geneva. Counting 12’811 inhabitants per square km, it is the commune with the highest population density of Switzerland (Bundesamt für Statistik, 2021b). It is also one of the communes with the highest degree of soil sealing, with 65.5% of its surface area taken up by buildings and infrastructure (Bundesamt für Statistik, 2021a).

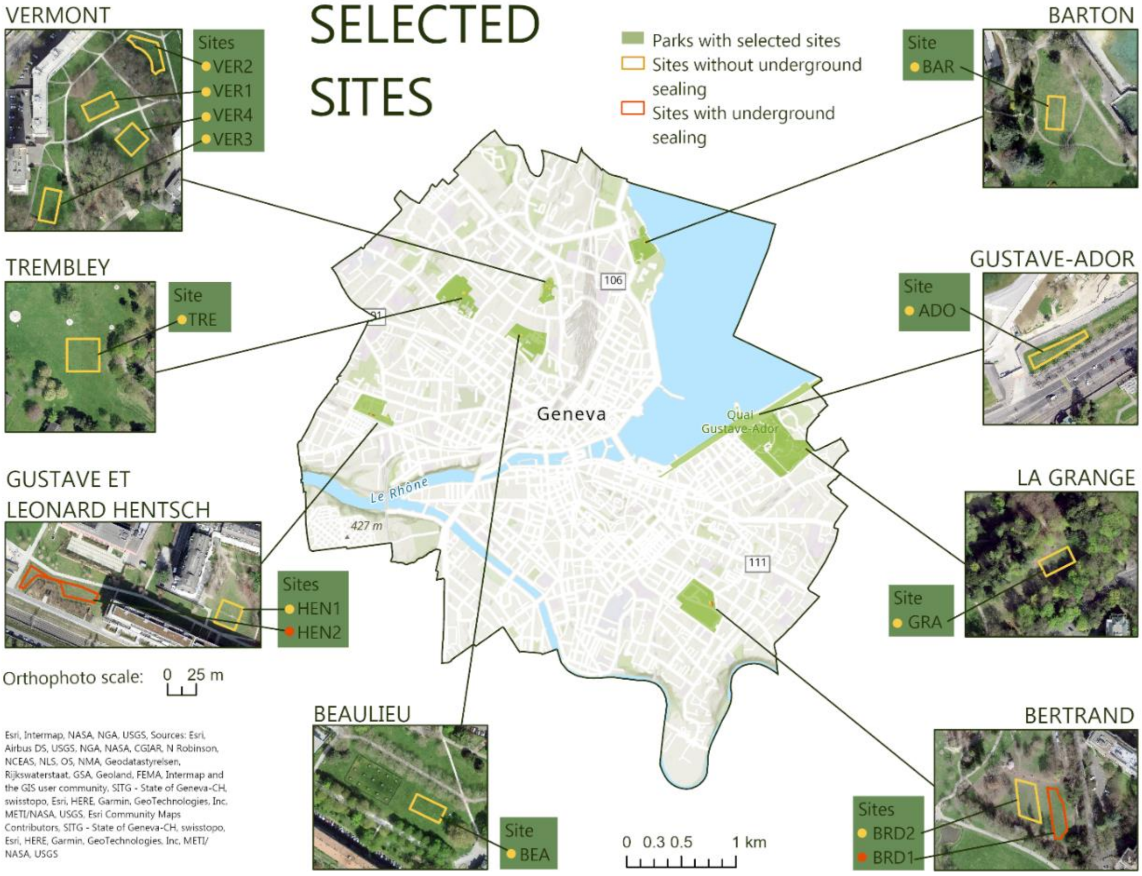
The climate of Geneva is a temperate climate. The hottest months are July and August and have an average of 6 and 7 days with maximum temperatures over 30°C. The average rainfall in a year is 946 mm. The wettest months are September and October (with average rainfalls of 91 mm and 97 mm), and the driest February, March, and April (with an average rainfall of 56, 62, and 67 mm). Between May and August, the average rainfall per month is about 80 mm (MeteoSwiss, 2021).

The site selection was done using the program ArcGIS Pro (version 2.8.0). The same criteria as used by Imhof (2021) were used in this study, except that surfaces with underground sealing were included. To ensure comparable management regimes, only sites managed by the Service des espaces verts (SEVE, the municipal service for green spaces) were selected. From a layer containing all sites managed by the SEVE, only areas with lawn vegetation were selected. Areas with high management level and areas with irrigation were excluded to limit the influence of these factors on the sites. Cemeteries were also excluded. A buffer of five metres was given to all test areas to keep the influence of surrounding surfaces to a minimum, and only areas which were over 400 square metres were kept, as 400 square metres is the minimum surface needed to yield a representative sample size of NDVI pixels. The output data was split into two groups: surfaces with underground sealing and surfaces without underground sealing. As areas with trees were still present in the selected areas, only sites with vegetation lower than one metre were selected using a vegetation height raster layer. In a last step, using an orthophoto, the selected sites were verified for the presence of trees or infrastructure. Only sites with uniform vegetation were kept. In some cases, the outlines of the sites were adjusted to obtain sites with uniform vegetation, while maintaining a surface of at least 400 square metres. The selected sites are visible in Figure 2, and the conceptual model of the ArcGIS-selection is to be found in Appendix 1.

Characteristics of each site were further specified. The soil origin (whether the soil was formed naturally or is man-made) was determined with the help of a study done by the Haute école du paysage, d’ingénierie et d’architecture de Genève (HEPIA, formerly Laboratoire cantonal d’agronomie) in 1992, in which soil profiles from different areas in city parks were studied and classified as modified soils or natural soils (Laboratoire cantonal d’agronomie, 1992). For the parks which did not figure in the study, information on the formation of the parks was retrieved from the website of the city of Geneva, or the official websites of the parks (Ville de Genève, 2021b, 2021a; Weck, n.d.). The management level was retrieved from the information given in the GIS layer of the SEVE. The area and was calculated in ArcGIS. An overview of the characteristics of all parks is given in Table 1.

Figure 2

Overview of the Selected Sites



In total, 13 sites are selected. All the selected sites are within the city of Geneva. Some sites are located within the same park as others. Two sites are above underground sealing.

Table 1

Characteristics of the Selected Sites

Park	Soil origin	Site	Underground Sealing	Management Level	Area [m^2]
Gustave Ador	Anthropogenic, created 1920s**	ADO	no	No Management	459.98
Barton	Natural*	BAR	no	Low	406.73
Beaulieu	Anthropogenic*	BEA	no	Low	406.73
Bertrand	Natural*	BRD1	yes	Moderate	457.77
		BRD2	no	Moderate	560.81
La Grange	Natural*	GRA	no	Moderate	406.73
Gustave et	Anthropogenic,	HEN1	no	No Management	402.36
Léonard Hentsch	2015****	HEN2	yes	Moderate	482.94
Trembley	Natural*	TRE	no	Moderate	804.48
Vermont	Natural***	VER1	no	Moderate	406.73
		VER2	no	Moderate	402.55
		VER3	no	Moderate	406.73
		VER4	no	Moderate	406.55

* *Indication from* Laboratoire cantonal d'agronomie (1992)

** *Indication from* Ville de Genève (2021b)

*** *Indication from* Ville de Genève (2021a)

**** *Indication from* Weck (n.d.)

2.2 Field Work

The field work was carried out between December 2021 and January 2022. Undisturbed samples at -5 to -10 cm were taken between the 14th and 17th of December 2021, and the soil depth was measured on the same dates. A snowfall event took place on the 10th of December, but the snow melted before the field work began. The temperatures during sampling were between 4°C and 10°C, and the soil was humid but not wet. The soil not being wet is important to avoid plastic deformation during sampling (Johannes et al., 2021b). Undisturbed samples from 0 to -5 cm were collected on the 21st of January 2022, where weather conditions were similar to the conditions between the 14th and 17th of December 2021.

The site corner coordinates were exported from ArcGIS Pro and imported to a GPS device, which was used in the field to find the site edges. In the field, a further 5 m buffer was kept to the corners found with the GPS device.

Per site, six to seven undisturbed samples from -5 to -10cm were taken, with care given to space the sampling points out evenly in the area. The sampling method proposed by Johannes, Weisskopf, et al. (2021a) was used. The upper layer of grass, roots and soil was carefully removed with a trowel down to -5 cm, and samples were then taken with a custom-made cylinder sampler. The difference to a traditional sampler was that the steel cylinder was replaced by a PVC-cylinder, which was split open on one side. Inside the PVC cylinder, a very thin plastic bag was placed, so that the soil sample entered the plastic bag when sampling. This made it possible to transport the soil samples without losing soil material. The soil samples, including the PVC cylinder, were put in another plastic bag to keep the samples from drying out. The PVC-cylinders were open on one side, making it possible for the undisturbed samples to be taken out of the cylinder during the lab work. One undisturbed sample between 0 and -5 cm was taken in the middle of each parcel. The top layer of grass was not removed before sampling but was removed in the lab before further analysis. The undisturbed samples were placed in a padded box for transport and stored at 4°C at the end of the sampling day until the start of the laboratory work.

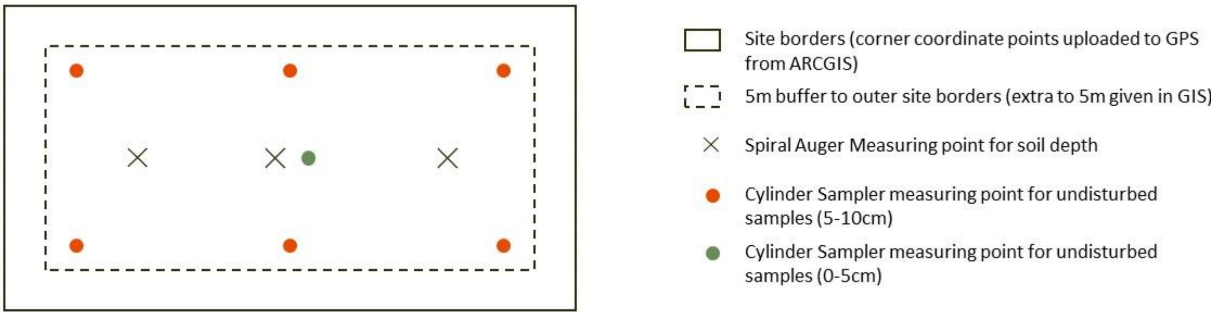
The soil depth was measured with a spiral auger (diameter of 20mm), which was bored into the ground by hand until the resistance was too high to bore further. The auger length was 120cm, and if the auger was fully driven into the ground before reaching high resistance, the soil depth was written down as >120cm. The soil depth was measured three times per site. The same operator handled the spiral auger for each site, so that the maximum resistance to which the operator bored was not dependent on the strength of the operator.

A gauge auger was used in the middle of the plot to try and characterise different soil horizons. However, as the gauge auger often did not penetrate more than 20 cm into the soil (even if the soils were sometimes more than 120 cm deep), the results of this sampling were not used in the analysis. It was decided against replacing the gauge auger with an Edelman auger, as the Edelman auger would have been too invasive for heavily frequented city parks.

The overall layout of soil sampling was set up as shown in Figure 3. This represents an ideal sampling design, and the sampling spots sometimes diverged slightly from the ideal location if stones impeded sampling, or if the site did not have a rectangular shape.

Figure 3

Idealised Soil Sampling Design of One Site



A 5 m buffer to the edge of the site, found with the coordinates imported from ARCGIS, was kept for sampling the soil. The six cylinder samples in the 5-10 cm depth range were evenly distributed within the area. The cylinder sample in the 0-5 cm depth range was taken in the middle of the site. The soil depth was measured three times, following the centre line of the site. The exact location of the sampling points diverged from the diagram when stones impeded sampling or when sites did not have a rectangular shape.

2.3 Lab Work

2.3.1 Undisturbed samples

The undisturbed samples analysed in the HEPIA laboratory in Lullier, Geneva, between January and March 2022. The samples were taken out of the plastic bags and PVC cylinders, and one of their sides trimmed to a flat surface before being put onto a water saturated plate. The water tension was set by a hanging water column, as described in Blume et al. (2010) and Hillel (2003).

First, the samples were saturated to -10hPa until equilibration. To determine equilibration, the weight of selected samples was measured every two days, and a sample was considered equilibrated if its weight changed less than 0.5 g since the last measurement. The equilibration time lasted from 11 to 15 days. Once equilibrated, all samples were weighed. Second, the samples were dried to -100hPa. The same process as at -10hPa was used to determine equilibration, with equilibration time lasting from 11 to 13 days. Once equilibrated, the samples were weighed, and their volume was determined with the plastic bag method. This method consists of placing the samples in a plastic bag, which is partially evacuated to remove air external to the sample, before holding the plastic bag in a container full of water. The container full of water is placed on a scale, and the difference in mass (measured in g) measured on the scale when the plastic bag with the sample is suspended in the water is equal to the volume of the sample and the plastic bag (in cm^3) (Boivin et al., 1990). Third, the samples were dried at 105° for 48 hours. They were weighed again, before being sieved to 2 mm. The sieving was done in two steps: first, the samples were sieved dry, then, the samples were sieved wet. The dry 2 mm fraction was kept for further analysis. The coarse fraction was sorted according to the type of material. Gravel, organic material (such as roots or wood chips), expanded clay, glass, coal, and concrete was sorted by visual estimation. Each type of material was weighed separately, and the volume of each material was determined. This was done either by putting the material in a graduated cylinder filled with water and measuring the amount of water displaced by the material (this was done for concrete, glass, and coal), or by finding a value for the density of the material (this was done for gravel and expanded clay). For gravel, the density of 2.5 g/cm^3 was used, following the measurements of Schwab & Gubler (2016). For expanded clay, the dry density of 0.4 was used, as indicated by the expanded clay producer RICOTER (2022). The mass and volume of organic material was neglected, as proposed by Schwab & Gubler (2016). The reason for using the density to determine the volume of gravel was that it is an easier way of determining the volume, and that the density of 2.5g/cm^3 is a reliable value when considering Swiss gravel (Schwab & Gubler, 2016). The reason for using the density of expanded clay is that it has a lower density than water, meaning that its volume cannot be measured by the water displacement method.

Out of the 98 undisturbed soil samples, 5 fell apart at one point during the lab work. These samples were excluded from the statistics. About a third of the samples were recorded to have earthworms inside. This did not however lead to higher porosities in the results compared to samples from the same sites without earthworms, so these samples were kept in the statistics.

2.3.2 Calculations

For each undisturbed sample, the bulk density, the gravimetric water content at -100hPa, the air content at -100hpa (corresponding to the volume of pores over 15µm), as well as the amount of coarse material was calculated using the following formulas.

Mass and Volume of Fine Particles in Urban Soils

Classically, the mass and volume of particles under 2 mm (M_{2mm} and V_{2mm}) within a sample is calculated by subtracting the mass and volume of gravel from the total mass and volume of a sample. The volume of gravel can be determined with the estimated density of gravel. In the soils analysed here, however, not all the particles over 2mm are gravel, as artefacts such as concrete and expanded clay are present in the samples. As such, the calculation of M_{2mm} and V_{2mm} takes into account the mass and volume of each of these artefact types.

$$M_{2mm} = M_{dry} - (M_{gravel} + M_{expanded\ clay} + M_{glass} + M_{coal} + M_{concrete}) \quad (1.1)$$

$$V_{2mm} = V_{sample} - (V_{gravel} + V_{expanded\ clay} + V_{glass} + V_{coal} + V_{concrete}) \quad (1.2)$$

Where:

M_{dry} = mass of sample, dried
V_{sample} = volume of sample, measured at -100hPa
M_x = mass of material x
V_x = volume of material x

Bulk Density

The bulk density was calculated for the fine earth fraction. The formula given by Soil Survey Staff (2014), which corrects bulk density for gravel, was used, but the bulk density was corrected not only for gravel, but also other coarse material types.

$$BD_{fine\ earth} = \frac{M_{2mm}}{V_{2mm}} [\frac{g}{cm^3}] \quad (2)$$

(Soil Survey Staff, 2014)

Where:

$BD_{fine\ earth}$ = bulk density of fine earth fraction [g/cm^3]
M_{2mm} = mass of particles under 2mm [g] (see equation 1.1)
V_{2mm} = volume of particles under 2mm [cm^3] (see equation 1.2)

It is to be noted that $BD_{fine\ earth}$ is not the same as the density of the fine particles, as V_{2mm} includes the pore volume of the sample.

Water content at -100hPa:

The gravimetric water content at -100hPa was computed as:

$$W_{100} = \frac{M_x - M_{dry}}{M_{2mm}} [\frac{g}{g}] \tag{3}$$

(following Hillel, 2003; Johannes et al., 2019)

Where:

W_{100} = gravimetric water content at -100hPa [g/g]
M_{100} = mass at -100hPa [g]
M_{dry} = mass of whole sample, dried at 105°C [g]
M_{2mm} = mass of particles under 2 mm [g] (see equation 1.1)

Air Content at -100hPa

The air content at -100hPa was calculated as:

$$A_{100} = (1 - \left(W_{100} - \frac{1}{2.65}\right) * BD_{fine\ earth}) * 100\ \ [\%\ by\ volume] \tag{4}$$

(following Johannes et al., 2019)

Where:

A_{100} = volumetric air content at -100hPa [% by volume]
W_{100} = gravimetric water content at -100hPa [g/g]
$BD_{fine\ earth}$ = Bulk density of fine earth fraction [g/cm^3] (see equation 2)
2.65 = density of fine earth [g/cm^3]

According to Jurin's law, A_{-100} represents the volume of pores larger than 15 µm (Johannes et al., 2019).

Amount of coarse material:

The amount of coarse material was measured as:

$$Coarse\ material = \frac{M_{coarse\ fraction}}{M_{dry}} * 100\ [\%\ by\ mass] \tag{4}$$

(Blume et al., 2010)

Where:

$M_{coarse\ fraction} = M_{gravel} + M_{expanded\ clay} + M_{glass} + M_{coal} + M_{concrete}$ [g]
M_{dry} = mass of whole dried sample [g]

2.3.3 Fine Soil Composite Samples

The dried and sieved soil (<2 mm) from each site's undisturbed samples were mixed in equal parts in order to form one composite sample per site. The composite samples were then used in the analysis described below.

Soil Texture

Soil texture was measured with a laser diffraction particle analyser (LS 13 320 Laser Diffraction Particle Size Analyzer, Beckman Coulter, Brea, CA, United States) according to Gee & Or (2002). The samples were prepared as follows: for each site, 0.5 g of soil was weighed into a glass vial. To remove organic matter, 3 ml of 6 % hydrogen peroxide (H_2O_2) was added. The glass vials were placed in a water bath between 35°C and 38°C to let the H_2O_2 evaporate. Another 3 ml of 6 % H_2O_2 was added after 24 hours and another 3 ml after 48 hours. The samples were then dried in an oven at 80°C until the H_2O_2 had evaporated entirely. To disperse the soil aggregates, 7mL of 10% Sodium hexametaphosphate $(NaPO_3)_6$ was added, the tubes were sealed, and put on a shaker for 7 hours. The glass vials were then inserted into the laser diffraction particle analyser auto-sampler, which calculated the percentage by mass of sand, silt, and clay according to the USDA classification as well as the WRB classification.

pH

The pH was determined using a $CaCl_2$ (0.01M) extraction with a soil:solution ratio of 1:5, following Hendershot et al. (2007). 3 g of dry and sieved soil from each site was added to 15 ml of 0.01M $CaCl_2$ in a falcon tube, which were shaken for 10 min, before being left to stand 24 hours. The pH was measured with the Metrohm 713 pH Meter (sensor 6.0262.100).

The idea behind using $CaCl_2$ as an extraction is that the cations of the salt solution replace the H^+ cations from the soil matrix, and the obtained pH estimates the actual pH in the environment of plant roots. The obtained pH is thus lower than the pH obtained when diluting soil sample in deionised H_2O.

Carbon and Nitrogen Content

Before estimating the carbon and nitrogen content, the dried and sieved soil samples were ground. For each site, 200 mg of ground soil was weighed into an aluminium foil. This foil was folded into a ball, which was placed into the autosampler of the CN analyser. The CN analyser used was the LECO CHN 628, LECO Corporation, St Joseph, USA. The method used was dry combustion. The samples were combusted in an environment containing only oxygen, which led to the carbon and nitrogen within the sample being oxidised to carbon dioxide (CO_2) and NO_x. CO_2 was detected in a non-dispersive infrared cell. NO_x was reduced to N_2 in a tube filled with copper. N_2 was detected in a thermal conductivity cell, after removal of CO_2. From the signal emitted by CO_2 and N_2, the computer calculated the percentage by mass of C and N in each sample (LECO Corporation, 2016).

2.4 NDVI Calculation and Classification

The calculation of the NDVI values of the sites was done by Imhof (2021). The principle resided in using NDVI data from open access sources with a 10x10m resolution and calculating the median of each pixel over 8-day periods in the vegetation period of 2020 (April through September). Then, for each site and each 8-day period, a mean of the pixels of the site was calculated. The result was, for each site, a series of NDVI means (as well as NDVI minima and maxima) over the vegetation period of 2020. Imhof (2021) cleaned the datasets for cloudy days, leading to some 8-day periods being missing for some sites.

The values obtained by Imhof (2021) were used to plot the NDVI evolution of each site using R (version 3.6.1). The NDVI plots were compared, and the sites were classified into different groups. As no reference NDVI values describing lawn vegetation health were found, the limit values distinguishing the groups (0.6 in spring and 0.5 in summer) were determined by comparing the NDVI evolution of the sites. For two periods, the start of spring and mid-summer, the sites were classified into a group with high NDVI values and a group with low NDVI values. In spring, the three 8-day periods starting on the 1.04, 9.04, and 17.04 were assessed – if one of the mean NDVI values of a site dropped under 0.6, the site was considered to have a low NDVI in spring. In summer, the months of June, July, and August were assessed (all 8-day periods from the 20th of June to the 18th of August were observed), and if the NDVI value dropped below 0.5 at some point in these months, the site was classified as having low NDVI values in the summer.

2.5. Visualisation and Statistics

The values of each soil property were combined to yield a mean value and standard deviation per site, and a plot (a boxplot or a barplot) was created for each soil property, showing the values of the soil property for each site, with the sites classified according to their NDVI class in summer and their NDVI class in spring.

2.5.1 Soil depth

The mean and standard deviation of the soil depth was calculated in Excel. For sites with three measurements of >120cm, no mean was calculated. One site had one measurement of >120cm, and two below. In this case, the measurement of >120cm was used as 120cm and used to calculate the mean and standard deviation. A barplot showing the mean values and standard deviation per site was created.

2.5.2 Undisturbed samples

As mentioned in Section 2.3.1, out of the 98 undisturbed samples, 5 were excluded from the statistics. In the 5-10 cm depth range, for each site and each property, the mean and standard deviation was calculated from the six to seven soil samples of the site. Furthermore, for each property, a boxplot was plotted, showing the differences between sites. For the 0-5 cm depth range, no mean or standard deviation was calculated, as only one sample was taken per site. The soil properties of the 0-5 cm samples are not discussed in the results or the discussion and can be found in Appendix 4.

2.5.3 Fine Soil Composite Samples

No statistical analysis was performed on properties determined with the fine earth composite samples, as only one measurement per property per site was done. Thus, no estimates of measurement errors are made. The texture class of each site was assessed, and was plotted in a texture class diagram, which can be found in Appendix 3.

2.5.4 Comparison of Means

For selected soil properties, a statistical test was performed to determine whether a significant difference in the soil property mean exists between the sites with high NDVI and the sites with low NDVI. This test was done twice for each soil property: once comparing the means of the two groups in summer and once comparing the means of the two groups in spring. To compare the means of two groups, either the Welch’s t-test or the Wilcoxon test can be used. As the Welch’s t-test assumes that the data of each group is normally distributed, the normal distribution of each soil property for each NDVI class was checked with a Shapiro test. When the Shapiro test indicated normally distributed data, the Welch’s t-test was used. When the Shapiro test indicated non-normally distributed data, a Wilcoxon test was preferred. Welch’s t-test was used for comparing the means of W_{100}, and SOC. The Wilcoxon test was used for comparing the means of soil depth, amount of coarse material, and BD.

2.5.5 Correlation of soil properties

A correlation test was performed to check the correlation between different soil properties. The correlation of SOC with BD, clay content, W_{100} and A_{100} as well as the correlation between BD and W_{100}, and BD and amount of coarse material were studied. A Pearson correlation was performed on normally distributed data, and a Spearman correlation was used for data with a non-normal distribution. Again, a Shapiro test was used to assess whether the data of each soil property followed a normal distribution.

2.6. Factsheets

For all thirteen sites, a factsheet containing the characteristics, the NDVI evolution, a photo, an orthophoto, and, if available, a soil profile image originating from the study on city parks by the Laboratoire cantonal d'agronomie (1992) was put together. A table with the characteristics of the site, the mean values and standard deviation of the physical soil properties, as well as the values of the chemical soil properties was added. These factsheets allowed a first comparison of NDVI evolution and soil properties to be done and helped in the decision of which soil properties to set a focus on. They will not be discussed further here but can be found in Appendix 2.

3. RESULTS

3.1 NDVI classification:

Through the NDVI classification, sites were placed in different groups: high or low NDVI in summer and high or low NDVI in spring. The classification placed some of the sites in the low NDVI group for both seasons, but not all sites with low NDVI in one season also had low NDVI in the other season.

Here, an overview of the NDVI evolution of each site is given, with the sites grouped according to their NDVI-class in the summer. Then, for April, a plot of the NDVI values of all sites is given, showing the difference between the two NDVI classes in spring.

3.1.1 High and low NDVI values in summer:

Sites with high NDVI in the summer:

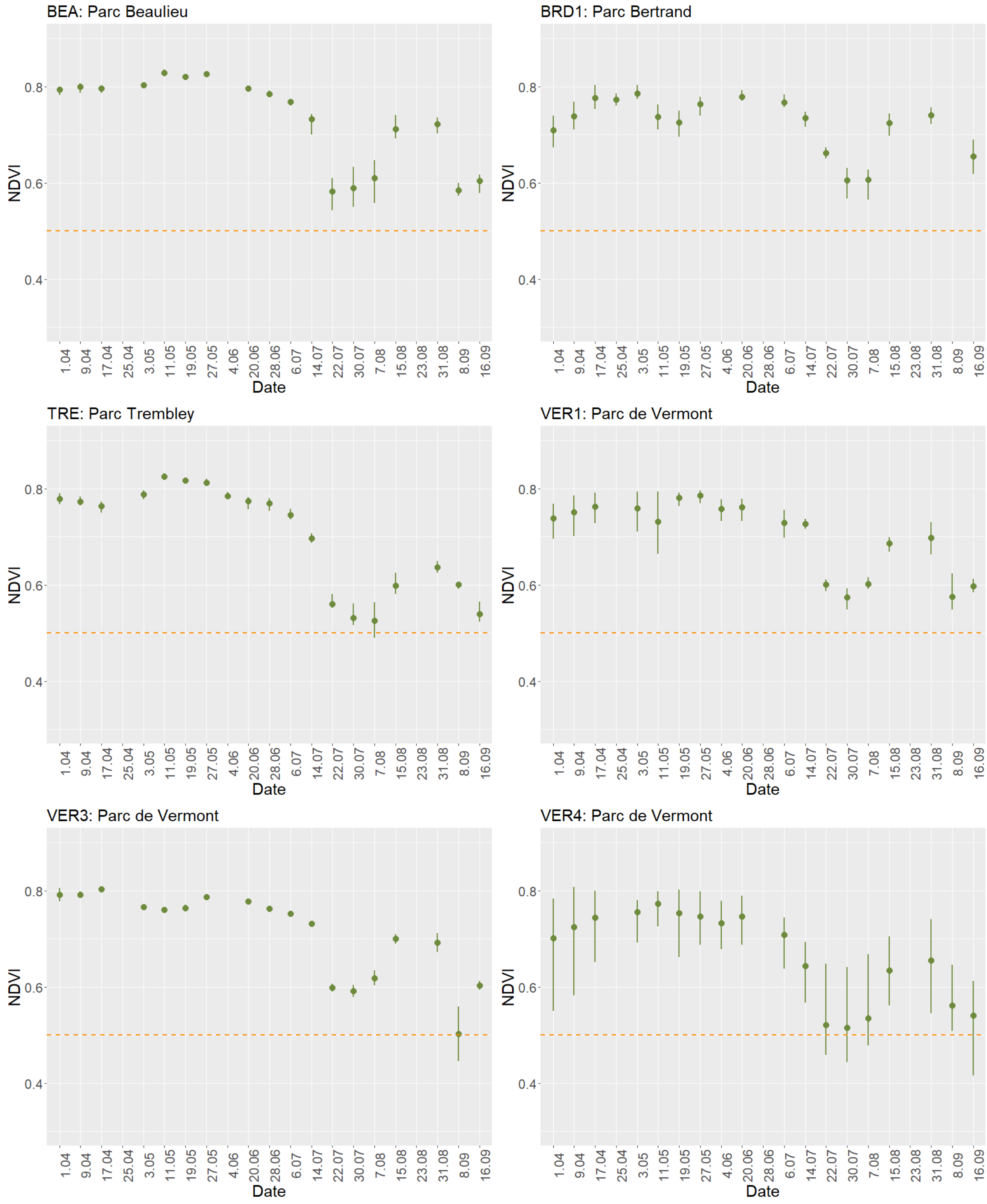
All the sites, including the sites with high NDVI in the summer, show lower NDVI values in the periods starting on the 22.07, 30.07 and 07.08 than at the start of the season. This drop can also be observed in the mean NDVI evolution over all sites and all vegetation, meaning that a drop of NDVI values in summer is to be expected in every site (Figure 1, Section 1.1.2). However, how low the NDVI dropped was site-dependent, and, as explained in the methods section (Section 2.4), sites with high NDVI in the summer were selected according to the criteria of not having a NDVI mean going underneath 0.5 in the months of June, July, and August.

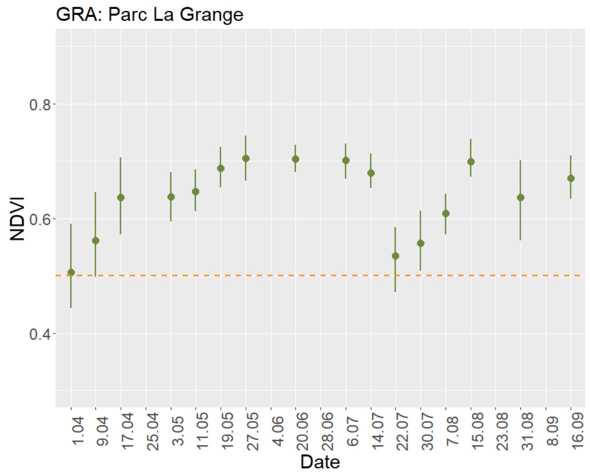
The NDVI evolutions of this class show similar patterns but are not uniform. In Figure 3 it can be observed that most of the sites which were classified as having high NDVI values in the summer have NDVI values between 0.7 and 0.9 from the start of the season up until and including the period starting on the 6th of July or on the 14th of July, where the NDVI values start to drop. One site has slightly lower NDVI values at the start of the season, with NDVI values barely exceeding 0.7. Its mean NDVI value however never goes below 0.5, which is why it is still classified as having high NDVI values in the summer (site GRA, Figure 3).

Two sites show an earlier drop of NDVI values than the others, as their NDVI values start dropping in the period beginning on the 6th of July, whereas all the other sites had a drop of NDVI starting only in the period beginning on the 14th of July. They also have slightly lower NDVI values than the other sites in the periods starting on the 14.07, 22.07 and 30.07, with their minimum NDVI values sometimes going below 0.5 (sites VER4 and TRE, Figure 3). The site which has lower NDVI values at the start of the season also has a NDVI minimum value going below the 0.5 line in the period between the NDVI-periods starting on the 14.07, 22.07 and 30.07, but its NDVI values only starts dropping in the period starting on the 14th of July (site GRA, Figure 3).

Figure 4

NDVI Evolutions of Sites with High NDVI Values in the Summer

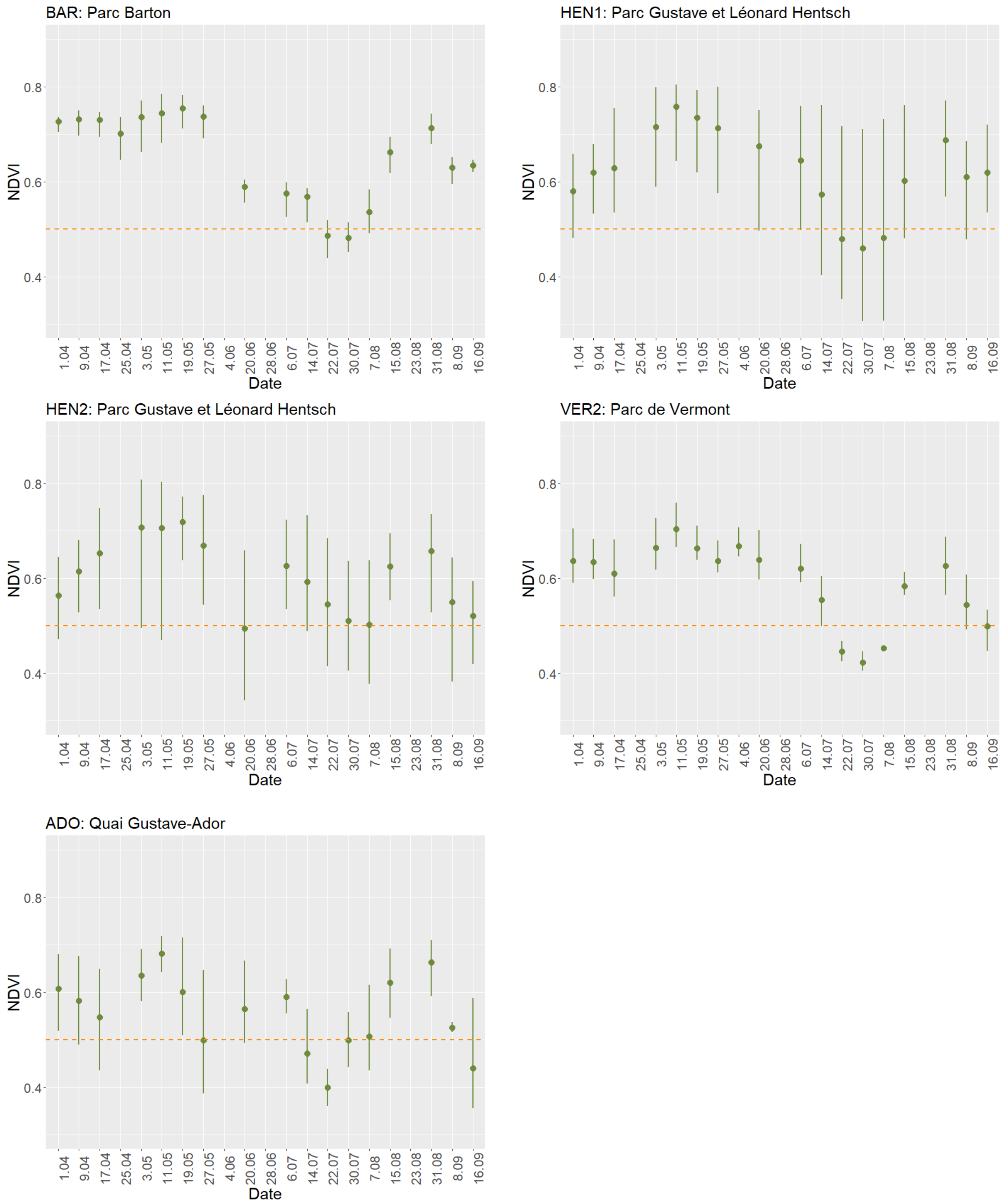




NDVI value lines (in green) represent the mean and standard deviation of the pixels of each surface, with pixels calculated as 8-day median values. All NDVI values were calculated in the vegetation period of 2020. The orange dashed line represents the limit NDVI value of 0.5. As all the mean NDVI values of these surfaces are above the 0.5 line, they were classified as having high NDVI in the summer. The NDVI evolutions show similar patterns but are not uniform.

Figure 5

NDVI Evolutions of Sites with Low NDVI Values in the Summer



NDVI value lines (in green) represent the mean and standard deviation of the pixels of each surface, with pixels calculated as 8-day median values. The orange dashed line represents the limit NDVI value of 0.5. All these sites have an NDVI mean that is under this line in July or August, which is why they were classified as having low NDVI values in the summer.

Sites with low NDVI in the Summer:

The sites with low NDVI in the summer were classified according to the criterion of having an NDVI mean of less than 0.5 in the months of June, July, or August.

It can be observed that for some parks, the NDVI drop occurs earlier in the season than in the group of sites with high NDVIs in the summer, with NDVI values starting to drop in the period beginning on the 20.06 (sites BAR and HEN1, Figure 5). For two sites, it is not possible to determine the moment at which the NDVI starts to drop, as their NDVI evolutions do not follow the same shape as the mean NDVI evolution visible in Figure 1 (HEN2 and ADO, Figure 5).

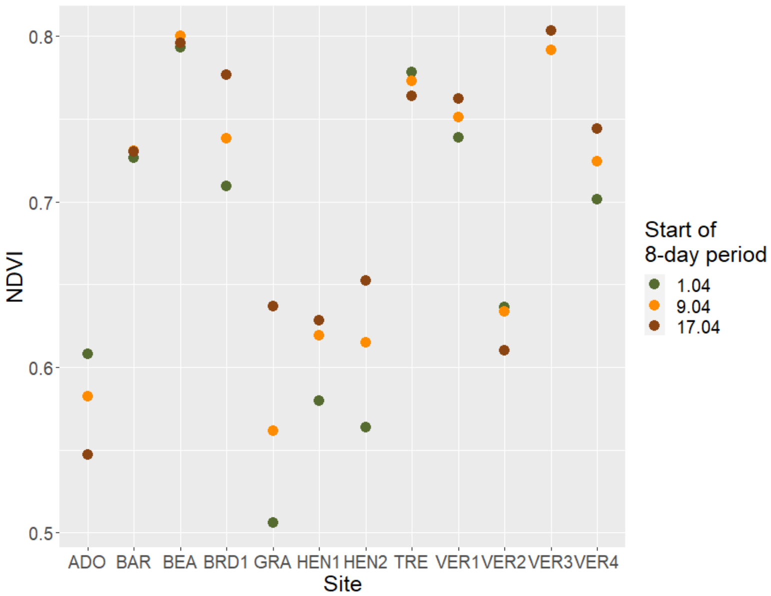
For most sites, the NDVI values that are below 0.5 are situated in the three periods of July and August in which NDVIs are low for all sites (NDVI periods starting on the 22.07, 30.07 and 07.08). There is one exception to this: one site has NDVI values staying just above 0.5 in the periods of July and August but has a mean NDVI value below 0.5 in the period starting on the 20th of June (HEN2, Figure 5). It was decided to classify this site as having a low NDVI in summer nonetheless, as the irregularity of its NDVI evolution throughout the season seemed similar to the courses of the group with low NDVI in summer.

3.1.2 High and low NDVI in Early Spring

When observing the NDVI values in the periods starting on the 1.04, 09.04 and 17.04, it is possible to distinguish two groups: one with already high NDVIs in early spring (the sites BAR, BEA, BRD1, TRE, VER1, VER3, and VER4), and one with still low NDVI values in early spring (the sites ADO, GRA, HEN1, HEN1, and VER2). The mean values of all sites in these periods are visible in Figure 6. It is to be noted that in the normal NDVI evolution (Figure 1, Section 1.1.2), the NDVI values in spring are lower, meaning that the lawn group with low NDVI in April is more representative of the general trend than the group with exceptionally high NDVI values in April.

Figure 6

NDVI Mean Values of all Sites in the Periods Beginning on the 1.04, 9.04, and 17.04



The NDVI mean values can be separated into two classes: the sites which already show high NDVI values (BAR, BEA, BRD1, TRE, VER1, VER3 and VER4) and the sites which show relatively low NDVI values (ADO, GRA, HEN1, HEN2, VER2).

3.2 Soil Properties and NDVI Classes of Each Site

In this section, the soil properties soil depth, amount of coarse material, BD, W_{100}, A_{100} and SOC of each site are shown in different plots, with colours indicating the NDVI classification of the different sites. Barplots representing the mean of each NDVI group are shown for all these soil properties excepting A_{100}. The p-values of the statistical tests comparing the two means for each season are found in the figures' notes (Welch's t-test for normally distributed data and Wilcoxon test for non-normally distributed data).

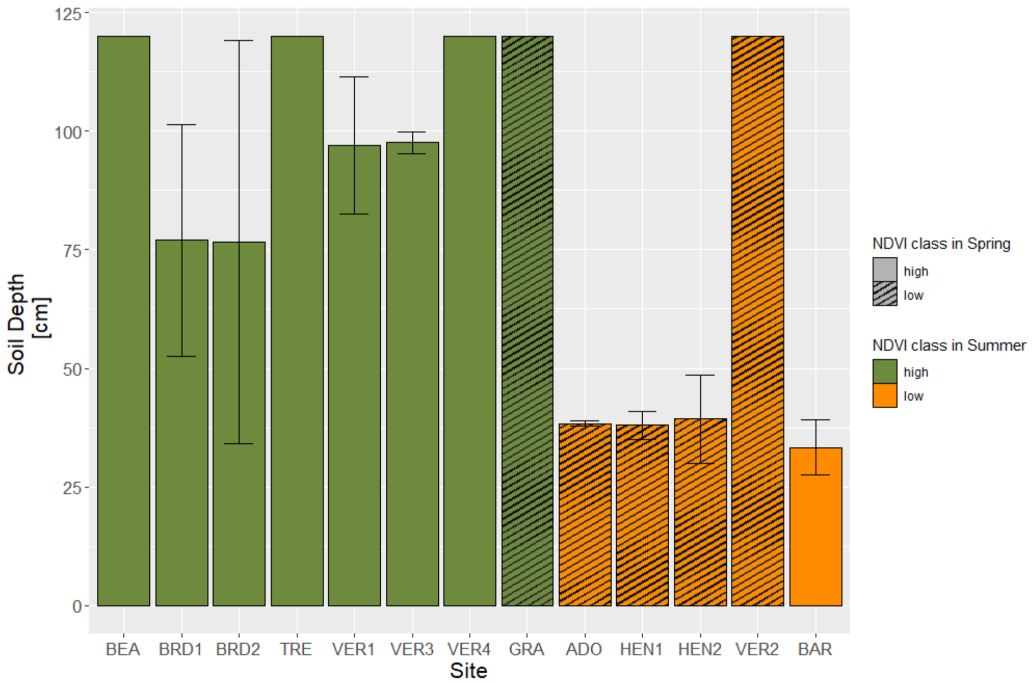
3.2.1 Soil Depth

In Figure 7, the mean soil depth of each site as well as its standard deviation is given. The soil depth measurement of five sites was above 120 cm, which is surprisingly deep (sites BEA, GRA, TRE, VER2, VER4, Figure 7). The value "over 120 cm" represents categorical data, so no standard deviation was calculated. Four sites show relatively deep soils with mean values ranging from 77 cm to 97 cm (sites BRD1, BRD2, VER1, VER3, Figure 7), and four other sites show a mean soil depth of less than 40 cm (ADO, BAR, HEN1, HEN2, Figure 7). The sites with very shallow soil all had low NDVI values in the summer. However, not all sites which had low NDVI values in the summer show low soil depth, as one site which was classified as having low NDVI values in the summer shows a soil depth of >120 cm (VER2, Figure 7).

The sites with underground sealing (BRD1 and HEN2) do not show significant differences in soil depth compared with other sites in the same parks (BRD2 and HEN1).

Figure 7

Mean Soil Depth of Each Site

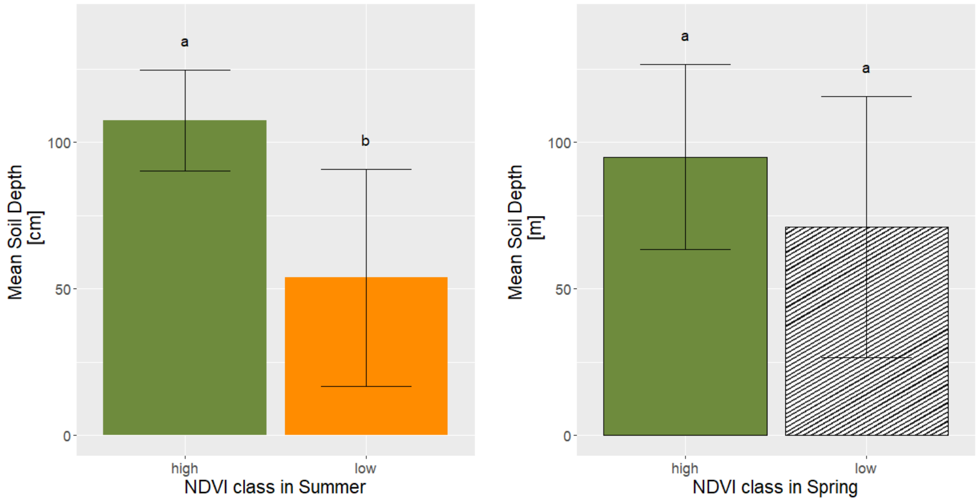


The bars represent the mean soil depth of each site, with the standard deviation visible in the whiskers. The soil depth measurements of the sites BEA, GRA; TRE, VER2 and VER4 were all >120 cm, and so no standard deviation was calculated. No difference in soil depth can be seen for the sites with underground sealing (BRD1 and HEN2) compared to sites without underground sealing located in the same parks (BRD2 and HEN1, respectively). All the sites with soil depth under 40cm have low NDVI in the summer.

A Wilcoxon test was computed to compare the mean soil depth of the sites with high NDVI in the summer with the mean soil depth of the sites with low NDVI in the summer (the Wilcoxon test was used as the data was not normally distributed). The same was done for the NDVI classes in spring. P-values of 0.043 (for the summer NDVI groups) and 0.61 (for the spring NDVI groups) were found, indicating a significant difference between the two summer groups, but not a significant difference between the spring groups. The mean soil depth of each group, as well as each group's standard deviation, are visible in Figure 8.

Figure 8

Mean Soil Depth of the NDVI Classes in Summer and in Spring



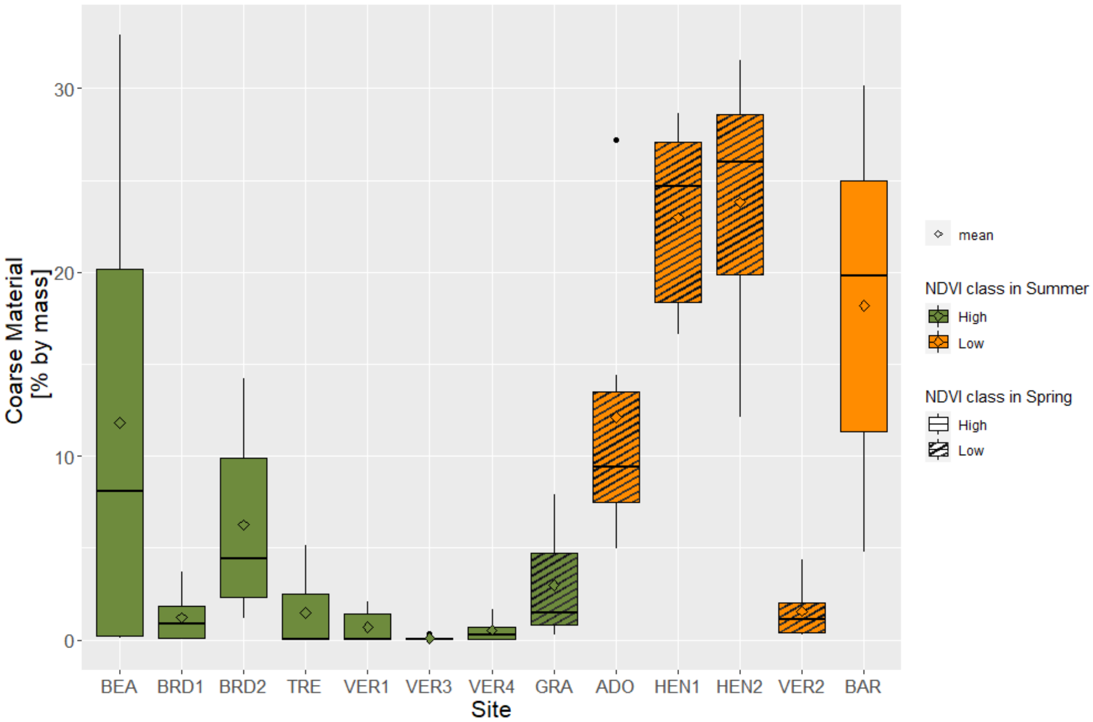
The barplots show the mean and standard deviation of soil depth of each NDVI class. If the two groups in one plot are significantly different, they show different letters above the bar. The group of sites with high NDVI in the summer has a significantly higher mean soil depth than the group of sites with low NDVI in the summer (p=0.043, Wilcoxon test). The soil depth means of the two NDVI classes in spring are not significantly different (p=0.61, Wilcoxon test).

3.2.2 Coarse material

The amount of coarse material for each site is visible in Figure 9. The amount of coarse material is quite variable, with the highest range of measurements within one site spanning from 0.1 to 32.9 % by mass (site BEA, Figure 9). It can be observed that the mean values of the five sites, which range from 11.8% to 23.8% by mass, are higher than the others (sites HEN1, HEN2, ADO, BAR, and BEA, Figure 9). Except for one (site BEA), all of these sites have low NDVIs in the summer.

Figure 9

Amount of Coarse Material for Each Site

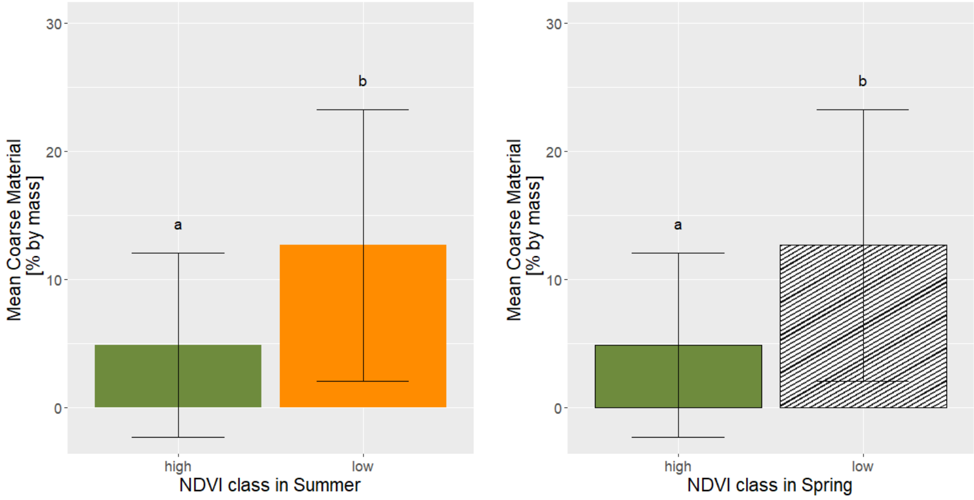


The boxplot shows the amount of coarse material for each site, with the quartiles measured from the different samples of each site. The amount of coarse material is quite variable, especially in the site BEA. Five sites show higher means than the others: HEN1, HEN2, ADO, BAR, and BEA.

The mean of sites with high NDVI in the summer was compared to the mean of sites with low NDVI in the summer with a statistical test. The same was done for the means of the NDVI classes in spring. As the data was not normally distributed, a Wilcoxon test was used. The tests yielded a p-value of 0.0101 and 0.048, respectively, meaning that in summer as well as in spring, the means of the NDVI classes were significantly different. The mean percentage of coarse material of each NDVI class, as well as its standard deviation, is visible in Figure 10. It is to be noted that even if the mean values are significantly different, the standard deviation of each group is also very large.

Figure 10

Mean Amount of Coarse Material of the NDVI Classes in Summer and in Spring



The barplots show the mean and standard deviation of coarse material of each NDVI class. If the two classes in one plot are significantly different, they show different letters above their bars. The group of sites with low NDVI in the summer has a significantly higher amount of coarse material than the group of sites with high NDVI in the summer (p=0.0101, Wilcoxon test). The same relation was found in spring: the NDVI class with low NDVI in spring also has a significantly higher amount of coarse material than the NDVI class with high NDVI in spring (p=0.048, Wilcoxon test).

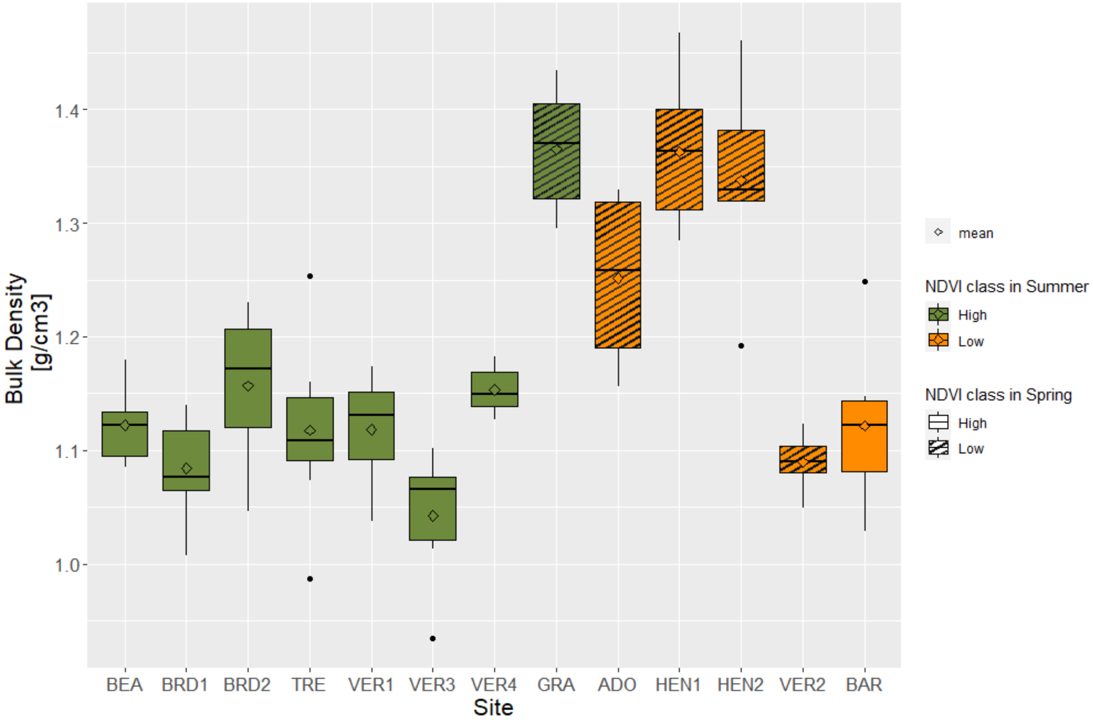
3.2.3 Bulk Density (BD)

The bulk density means range from 1.04 g/cm3 to 1.36 g/cm3 (with an overall mean of 1.18 g/cm3). In Figure 11, three sites appear to have higher BD than the others, with mean values of 1.36 g/cm^3, 1.36 g/cm^3, and 1.34 g/cm^3, all of which have low NDVI in spring (sites GRA, HEN1, and HEN2). One site, with a mean of 1.25 g/cm^3, lies slightly lower than the highest three, but can still be distinguished from the remaining nine sites, which have a maximum mean value of 1.16 g/cm^3 (site ADO). This site also has low NDVI in spring.

The two NDVI groups in summer and in spring were compared with a Wilcoxon test. The tests yielded p-values of 0.34 and 0.048, respectively, indicating a significant difference between the two groups in spring, but not in summer. The means and standard deviations can be seen in Figure 12.

Figure 11

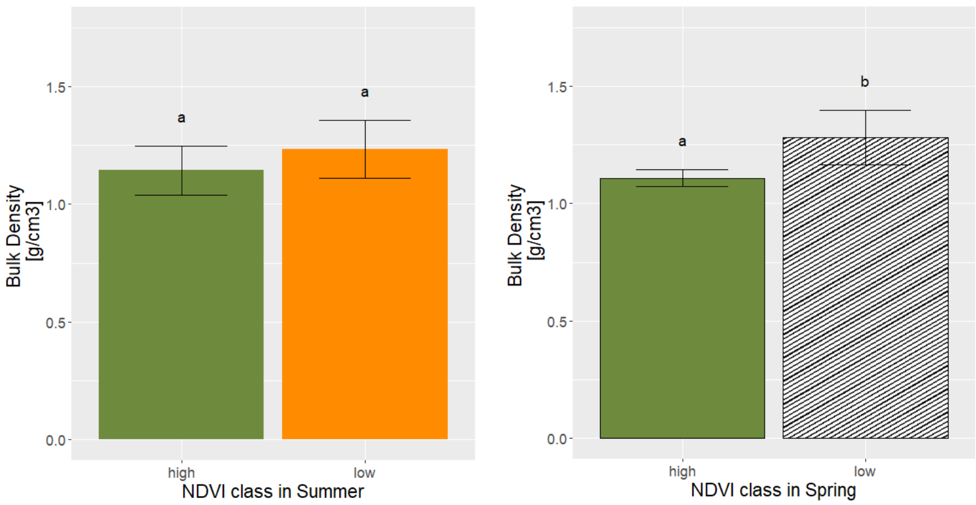
Bulk Density for Each Site



The boxplot shows the bulk density for each site, with the quartiles measured from the different samples of the sites. Three sites show higher BD values than the others (HEN1, HEN2 and GRA). One site lies slightly below these three, but above the nine other sites (ADO). These four sites all show low NDVI values in the spring.

Figure 12

Mean Bulk Density of the NDVI Classes in Summer and in Spring



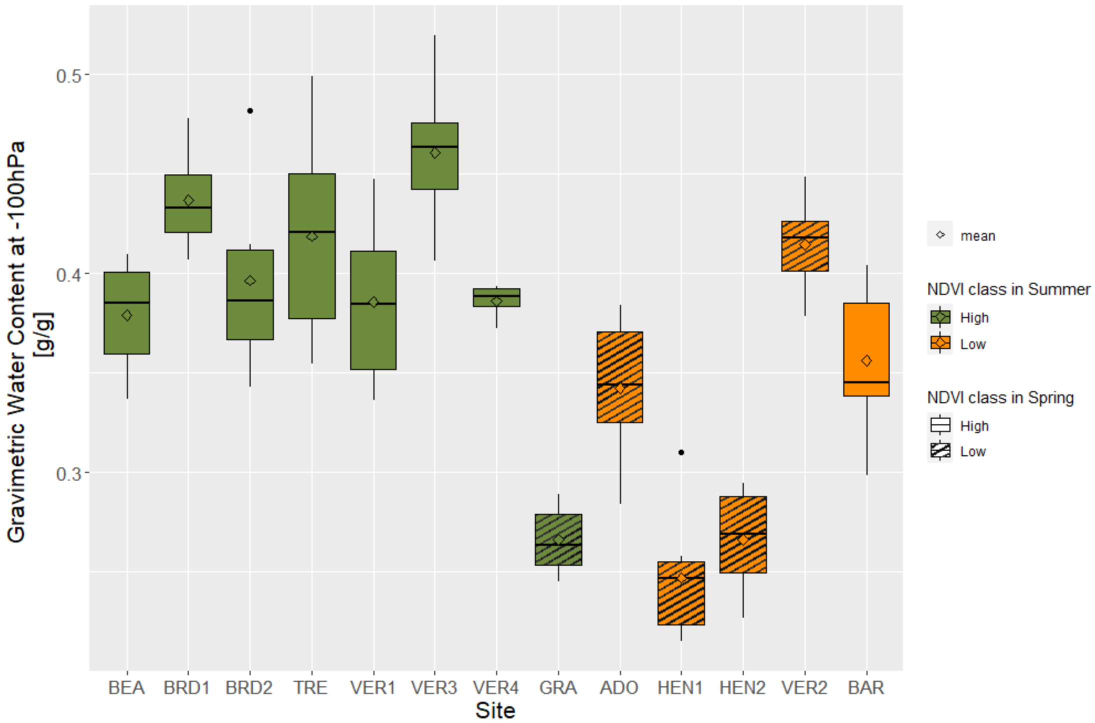
The barplots show the mean and standard deviation of BD of each NDVI class. If the two classes in one plot are significantly different, they show different letters above their bars. The two NDVI classes in summer do not have significantly different means of BD (p=0.34, Wilcoxon test). However, the two NDVI classes in the Spring do have significantly different BD means (p=0.048, Wilcoxon test).

3.2.4 Gravimetric Water Content at -100hPa (W_{100})

Three sites have lower W_{100} values than the other sites (GRA, HEN1 and HEN2, Figure 13). Interestingly, these are the same three sites that could be distinguished as having higher BDs in Figure 11. A fourth site also shows a lower W_{100} mean than the others, but its variation does not allow it to be clearly distinguished from the others (site ADO, Figure 13) This site is the same site which showed a slightly higher BD in Figure 11, while staying below the highest three. These four sites all have low NDVI in spring. The highest mean values are 0.44[g/g] and 0.46[g/g] and are found in sites with high NDVI in summer as well as in spring (sites BRD1 and VER3 Figure 13). Welch's t-test was performed both for the NDVI class in summer and the NDVI class in spring, which yielded p-values of 0.13 and 0.034, respectively, meaning a significant difference in means could be found in the spring, but not in the summer. The means and standard deviation of the NDVI classes can be found in Figure 14.

Figure 13

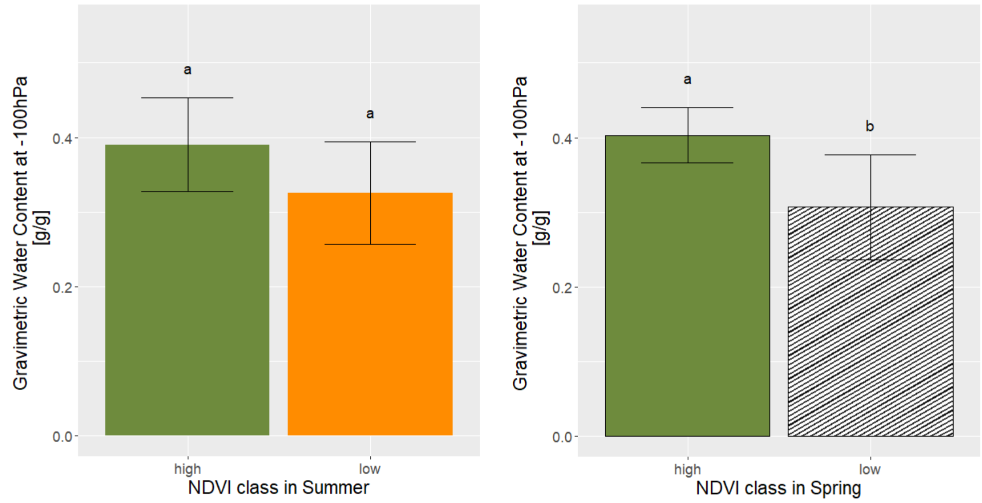
Gravimetric Water Content at -100hPa of Each Site



The boxplot shows the gravimetric water content at -100hPa for each site, with the quartiles measured from the different samples of the sites. Three sites show lower W_{100} values than the others (HEN1, HEN2 and GRA). One site lies slightly above these three, but its range doesn't allow it to be distinguished from the others (ADO). These four sites show low NDVI in spring.

Figure 14

Mean Gravimetric Water Content at -100hPa of the NDVI Classes in Summer and in Spring

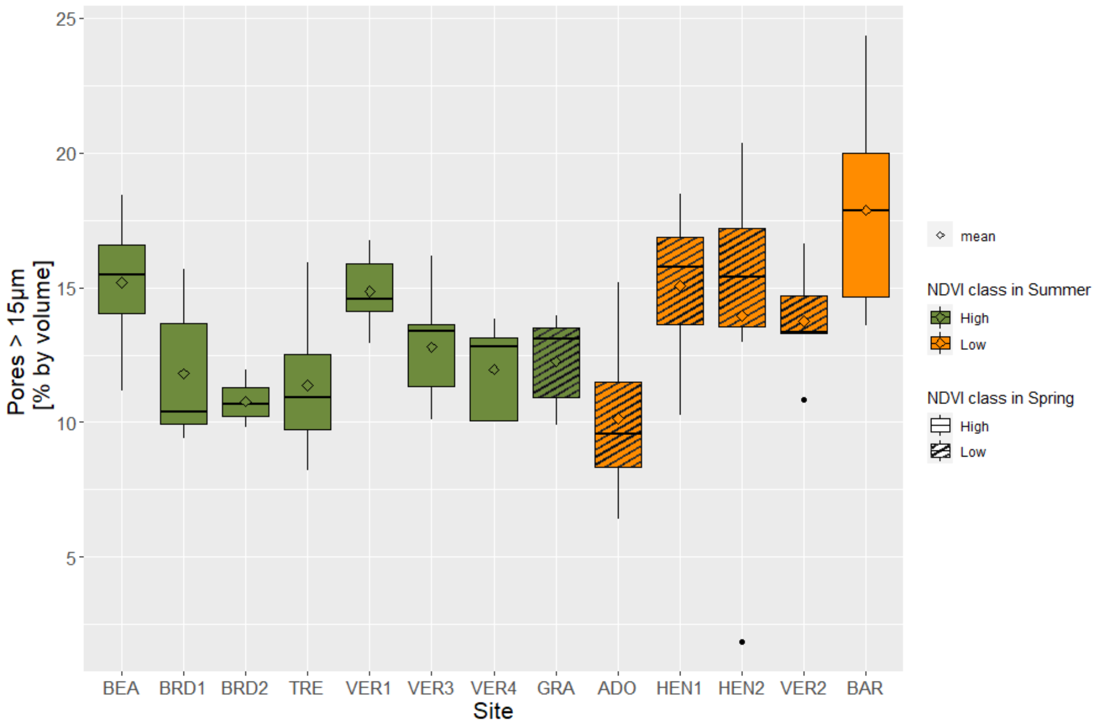


The barplots show the mean and standard deviation of W_{100} of each NDVI class. If the two classes in one plot are significantly different, they show different letters above their bars. The two NDVI classes in summer do not have significantly different means of W_{100} (p=0.13, Welch's t-test). However, the two NDVI classes in spring do have significantly different W_{100} means (p=0.034, Welch's t-test).

3.2.5 Air Content at -100hPa (A_{100}, volume of pores >15 µm)

Figure 15

Air Content at -100hPa of each Site



A_{100} means range from 10.14% to 17.86%, with no sites clearly distinguishable from the others.

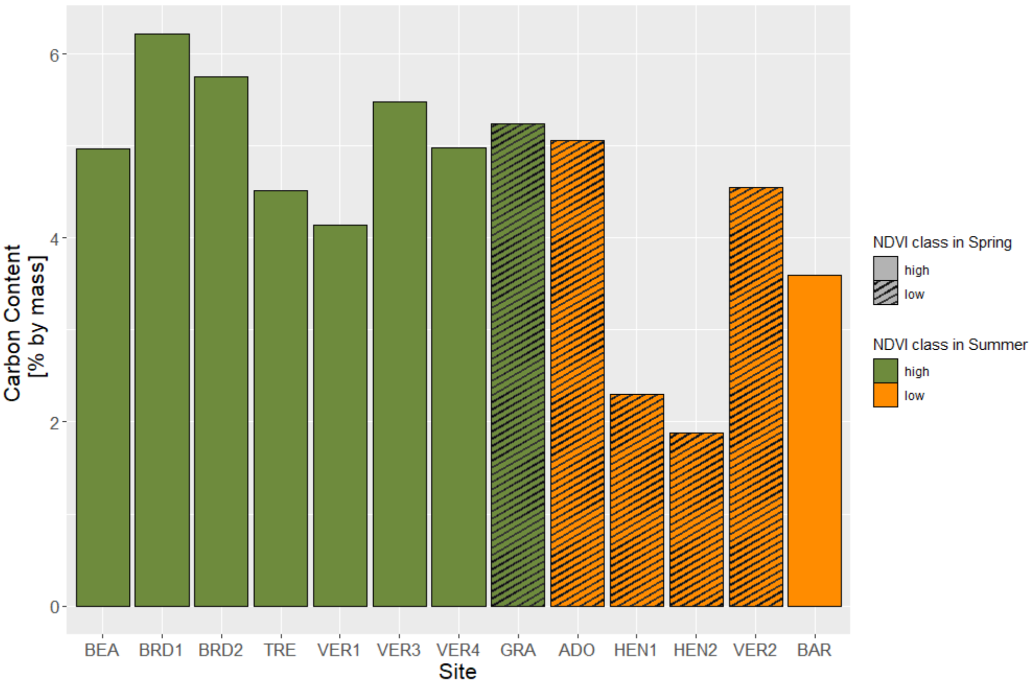
The volumetric air content at -100hPa means range from 10.14% to 17.86%. No sites appear to be clearly distinguishable from the others, and no further statistical evaluation was made.

3.2.6 Organic Carbon Content (SOC)

The organic carbon content across the sites ranges from 1.88 % to 6.21%. No standard deviation was calculated, as the SOC was measured only once per site on a composite sample. Two sites appear to have lower SOC than the others, and both sites are located in the same park (sites HEN1 and HEN2, Figure 16). These sites are expected to have anthropogenic soils, as the park was created in 2015. The mean SOC values of the NDVI classes in summer and the NDVI classes in spring were compared with Welch's t-test, yielding a p-value of 0.059 and 0.24 respectively, showing that the NDVI class means were not statistically different.

Figure 16

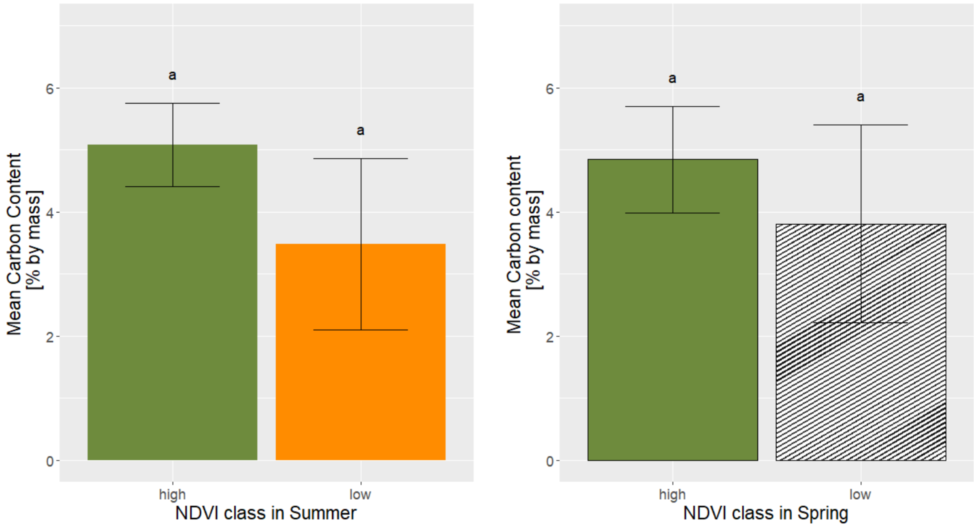
Soil Organic Carbon of each Site



The bars represent the measured SOC of each site (one measurement from a composite sample). Two sites, HEN1 and HEN2, appear to have lower SOC than the others. Both sites belong to the same park, which was created in 2015, and is assumed to have anthropogenic soils.

Figure 17

Mean Soil Organic Carbon of the sites, grouped according to their NDVI class in summer and in spring



The barplots show the mean and standard deviation of SOC of each NDVI class. If the two groups in one plot are significantly different, they show different letters above their bars. The NDVI classes do not have statistically significantly different means of SOC either in the summer (p=0.059, Welch's t-test) or in the spring (p=0.24, Welch's t-test).

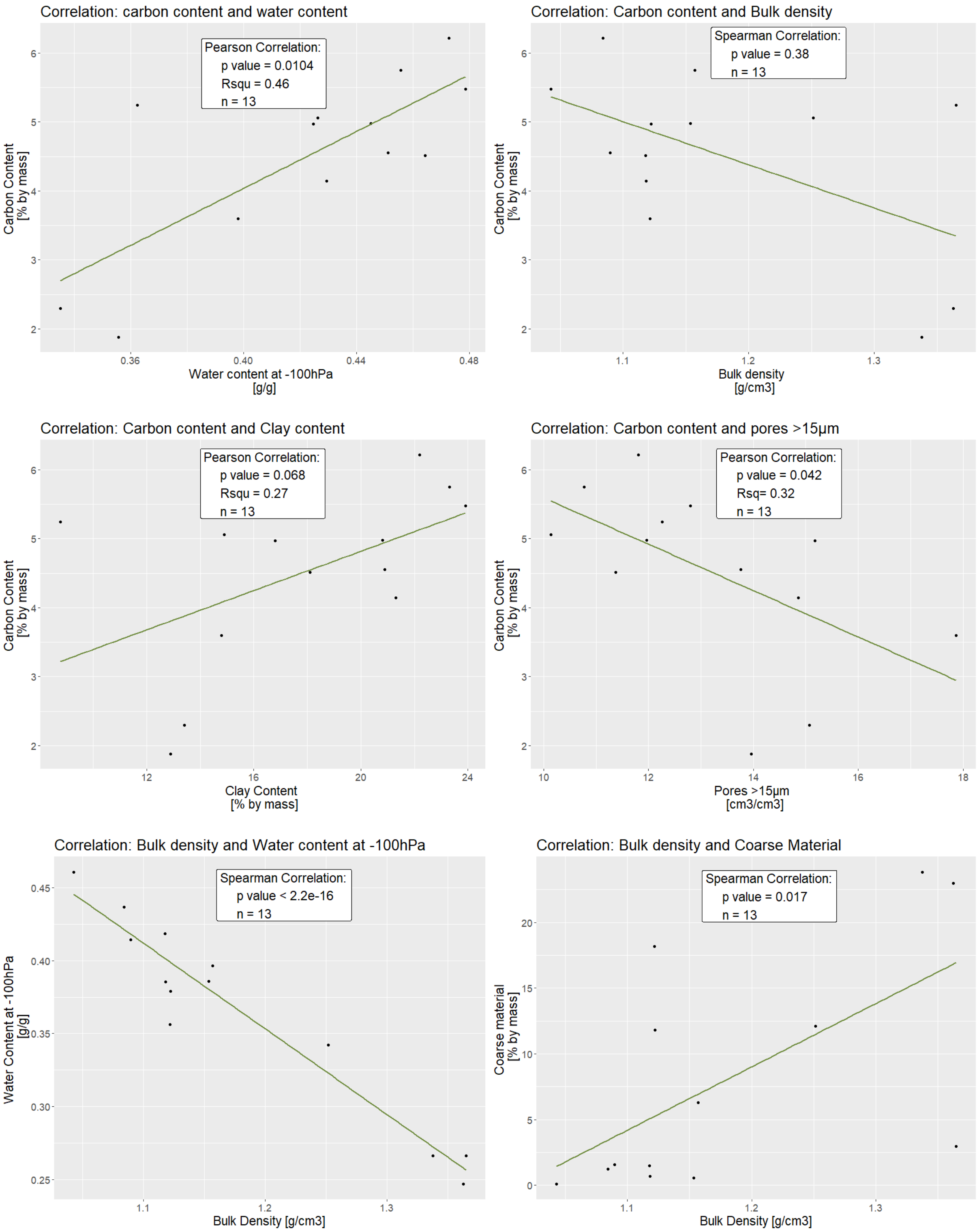
3.3 Correlations between soil properties

The correlation between SOC and the clay content, W_{100}, BD, and A_{100} was verified with Pearson tests or Spearman tests, depending on whether the soil property data followed a normal distribution. The Pearson correlation was used on normally distributed data, whereas the Spearman correlation was used on not normally distributed data. The correlation between BD and W_{100}, as well as BD and coarse material, was also tested with the Spearman correlation test. The correlations are visualised in Figure 18.

Significant results were found relating SOC to A_{100} and W_{100} (showing p-values of 0.042 and 0.0104, respectively), meaning that carbon content is correlated to these physical soil properties. Additionally, BD was found to correlate with W_{100} as well as with the amount of coarse material (showing p-values of $<2.2*10^{-16}$ and 0.017, respectively). The correlation between W_{100} and BD reflects the similarity between the two soil properties that was already noticed in Section 3.2.4.

Figure 18

Correlations of Soil Properties



The correlations were tested with the Spearman correlation or the Pearson correlation. The Pearson correlation was used on normally distributed data, whereas the Spearman correlation was used on not normally distributed data. Significant correlations were found relating SOC to A_{100} and W_{100}, as well as BD to W_{100} and the amount of coarse material.

4. DISCUSSION

4.1 NDVI Classes and Soil Properties

To answer the research question "*Can particle size distribution, amount of coarse material, BD, W_{100}, A_{100} and SOC in the 5-10 cm depth range as well as soil depth explain differences in the evolution of NDVI values, NDVI being used as a proxy for vegetation health, at different sites in the city of Geneva?*" thirteen sites within the city of Geneva were classified as having high or low NDVI courses in two seasons. For each season, a statistical test assessed whether the soil property means of the high NDVI and the low NDVI class were significantly different. It was found that coarse material related to NDVI classes in the summer as well as in the spring, and that soil depth related to NDVI class in the summer. These findings are unique, as no other study assessed whether soil depth influences urban vegetation health, and only one study measured the amount of coarse material to explain urban tree health, with inconclusive results (Scharenbroch et al., 2018). BD and W_{100} could be linked to NDVI class in spring, but not in summer, which shows that coarse fraction and soil depth probably had a higher influence on the amount of water stored in the soil in dry periods than BD and W_{100}. In spring, these properties might have influenced the root formation process, or might be linked to trampling, which would explain their link to the NDVI class. The other soil properties did not have a clear influence on the NDVI evolutions.

4.1.1 Coarse Material and Soil Depth

Both in the summer and in the spring, the high and low NDVI classes have significantly different means of coarse material, with both the summer and spring classes with low NDVI values showing high amounts of coarse material. The amount of coarse material determines how many large pores that drain water quickly exist, as well as how much space is available for plants to build roots in the soil. We suspect that in the summer, soils with a high amount of coarse material dry out quicker, and thus the plants suffer from drought earlier, and their NDVI values drop lower than in sites with little coarse material. Furthermore, the lawns on soils with a high amount of coarse material might have more trouble building large root networks, and thus have less access to water stored within the soil. In spring, the high amounts of coarse material might have a negative influence on the speed at which the lawn can reform roots, and thus the lawns become green only later in the season than at sites in which root formation is not slowed down by high amounts of coarse material.

The NDVI classes in summer also show a significant difference in soil depth, with sites with low NDVI values in the summer having shallower soils. Much like the amount of coarse material, this might be explained by the soil depth being linked to water storage, and thus the water available for plants in the long term. As the soil depth is shallower in these sites, less water is stored in total, and during the dry period of the summer, the water reserve is finished more quickly. Another way of explaining the tendency towards lower NDVI values in the summer in shallow soils could be that a lower soil depth allows for a less deep root system – even if the vegetation observed is lawn, it could be that the lawns in sites with high soil depth penetrate the soil deeper than 40 cm, which would mean that they have a larger root system, allowing them to have access to more water in times of drought. This hypothesis seems feasible, as some of the lawn sites studied by the Laboratoire cantonal d'agronomie (1992) showed roots up to 90 cm in depth.

These findings are unique in the urban environment, as no other study successfully related soil depth and the amount of coarse material to urban vegetation health. One study attempted to link the amount of coarse material to urban tree health but did not find a correlation between the two. The authors explained that they could not link this soil property or any other physical soil property to urban tree health, as the trees that they studied were all irrigated (Scharenbroch et al., 2018). Our findings support this argumentation, as the amount of coarse material was important for urban vegetation health in the absence of irrigation. No study assessing the effect of soil depth on urban vegetation health was found. The results of the present study indicate that including soil depth data could be very important for the understanding of the effect of soil on urban vegetation health, especially as urban soils have been found to be relatively shallow in other studies (Tresch et al., 2018).

4.1.2 Bulk density and Gravimetric Water Content at -100hPa

The high and low NDVI classes in spring showed a significant difference in bulk density and gravimetric water content at -100hPa, with the class with low NDVI values showing higher BD and lower W_{100}. Both soil properties are closely correlated. It is possible to explain why BD is related to the NDVI class in spring in different ways. One hypothesis is that soils with higher BD impede root growth more than soils with lower BD, leading to the root formation in early spring to be slower in these sites. Additionally, BD and the amount of coarse material are highly correlated, which further exacerbates the effect on root growth. The correlation between the amount of coarse material and BD might be explained through fine earth being washed out easily from soils with high amounts of coarse material, with the remaining fine earth clumping together, leading to high BD in the fine earth fraction. Thus, higher BDs might be a consequence of high amounts of coarse material in urban soils, and the effect of the soil properties BD and amount of coarse material might be interlinked. However, even the soils with the highest bulk densities (between 1.34 g/cm^3 and 1.36 g/cm^3) do not exceed the values at which Soil Survey Staff (2014) expects root growth to be affected (1.60 g/cm^3 for silt loams, and 1.63g/cm^3 for sandy loams and loams). A second hypothesis is that high BD leads to less coarse pores filled with air, which can lead to vegetation suffering from lack of oxygen during wet periods. However, the precipitation data of April 2020 does not seem to indicate an extremely wet spring (Figure 1, Section 1.1.2). If BD is not linked to root growth or lack of oxygen, another hypothesis is that BD might be linked to trampling over the whole sites, trampling leading to higher bulk densities, but also to more stressed vegetation, or vegetation which has more trouble developing in the spring.

The NDVI class in the summer could not be linked to bulk density or W_{100}. We would have expected there to be a link between them, as we consider the limiting factor for vegetation health in the summer to be water, and the amount of water stored in the soil should be dependent on the available pore space (determined by BD) and the capacity of a soil to hold water (determined by W_{100}). Furthermore, several previous studies have found a link between BD and urban vegetation health, with two studies reporting a negative influence of BD on vegetation health (Mukherjee & Agrawal, 2018; Scharenbroch & Catania, 2012), and one paper reporting a positive influence of BD on vegetation health (Galle et al., 2021). However, both BD and W_{100} are reported for the fine earth fraction, meaning that only the space between the coarse material is considered, and the amount of coarse material, as well as the soil depth, probably had a higher influence on how much water the soil could store as BD and W_{100} in the studied sites. The effect of BD might be more relevant in soils with less coarse material.

4.1.3 Air Content and Carbon Content

Interestingly, no clear link could be made between any NDVI classes and A_{100} or SOC. Both soil properties are, however, correlated.

SOC is also often linked to soil structure, and in the urban environment, external carbon inputs, such as biochar or compost, have been shown to have positive effects on urban vegetation health in drought periods (Kim et al., 2021; Somerville et al., 2020). SOC has also been shown to have a positive influence on urban tree health (Scharenbroch et al., 2018; Scharenbroch & Catania, 2012). For this reason, it is surprising that we did not find a link between SOC and NDVI classes. This might be explained, again, by the amount of coarse material and the soil depth (which are not influenced by SOC) having a higher influence than the structure of the fine earth fraction (which is influenced by SOC) on the amount of water stored in the soils in dry periods as well as on the root growth impedance in spring.

The low effect of SOC might also be explained by the studied soils having already good soil structure, with higher amounts of SOC not improving the soil structure quality noticeably. Limit values are given for the SOC:clay ratio and for A_{100} by Johannes et al. (2021). According to the SOC:clay ratio, all our sites are classified as having a very good soil structure. A_{100} has a limit value of 8.9 [% by volume], which is not exceeded in any of the sites. As the soils are all classified as having good soil structure, higher amounts of SOC probably did not improve the soil structure quality. However, these limit values are calculated for agricultural soils, and the limit values might be less meaningful in the urban environment.

4.1.4 Statistical Tests

The differences of means were analysed using Welch's t-test or the Wilcoxon test. Both tests assume that the observations are independent, meaning that no relationship exists between the observations. However, the sites used in this study are not completely independent, as some of them belong to the same park and are spatially nearer to one another. If the factor "park" was to be included in the statistics, a generalised linear model would need to be calculated with the data, with park and the soil property as explanatory variables. However, this test would need a higher number of observations to yield significant results. In further research, the influence of the park on the sites' soil properties should be checked with a higher number of sites, enabling more powerful statistical tests.

4.1.5 NDVI Classes

In other studies assessing urban vegetation health with NDVI, the NDVI value on one date is used, rather than the NDVI evolution or the NDVI class (Cârlan, Mihai, et al., 2020; Galle et al., 2021). While comparing the NDVI evolutions of each site, it was noticed that the NDVI evolutions were not uniform, and that the 8-day-period in which the different sites reached their minimum NDVI values in the spring and in the summer was not the same in each site. For this reason, it was preferred to use NDVI classes, which allowed the use of the NDVI values over several 8-day periods in order to assess urban vegetation health. This novel approach was extremely useful, but its correctness was not verified with vegetation data taken from the plants on the ground.

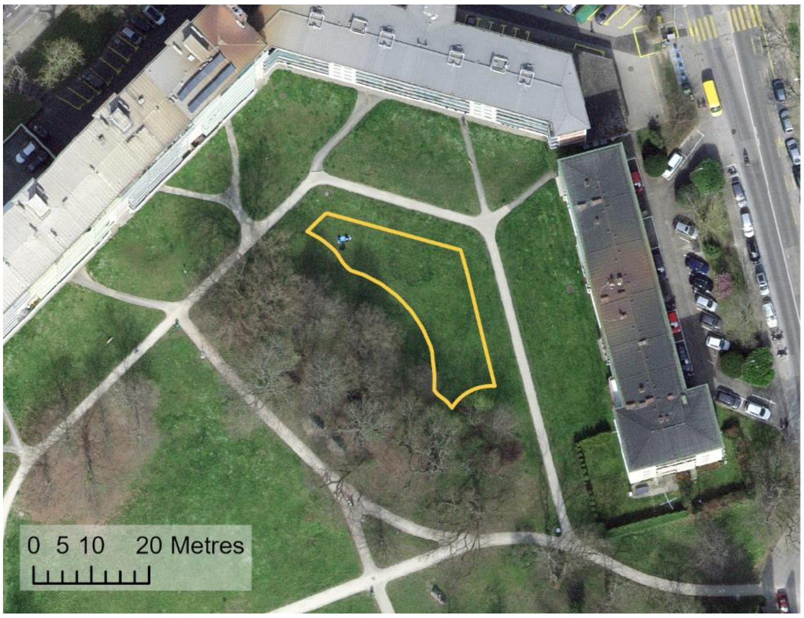
4.2 Other Factors Influencing NDVI

Even if some significant links between soil properties and NDVI classes were found, no soil property could fully explain the NDVI class of all sites. When observing the plots showing all sites, it is especially interesting to see that the site VER2, which was classified as having low NDVI in spring as well as summer, has properties which are inverse to the tendency of the classes with low NDVI. Furthermore, its soil properties are very similar to the soil properties of the other sites in the same park (VER1, VER3, and VER4), which all show high NDVI values in spring and in summer. This shows that soil properties cannot fully explain the differences in NDVI evolution in urban settings.

To try to explain why this site shows a different NDVI evolution to the other sites in the same park, the orthophoto of the site (visible in Figure 19) was observed. In the orthophoto, buildings are located towards the north and north-east of the site, meaning that the south and south-west exposed walls of the building, which heat up if sun hits them in the afternoon, probably radiate heat onto the site, creating a warm microclimate. This would lead the vegetation of the site to be exposed to much higher temperatures, especially in the summer, which might increase evapotranspiration and dry the soil out quicker. Consequently, the vegetation might show stronger browning and, thus, lower NDVI values. Furthermore, the site is situated in the corner of the park, which might mean it is more prone to be trampled, as people might use the area for short cuts. This would have an influence on the vegetation health, and thus the NDVI values, in spring as well as in summer.

Figure 19

Orthophoto of the site VER2



Buildings are located towards the north and north-east of the site, probably leading to higher temperatures in the site in summer. The site is located in a corner between footpaths, which might lead to it being trampled frequently throughout the whole year.

As discussed in section 4.1.2, we expected the W_{100} and BD to be linked to the NDVI class in the summer. The site GRA has a relatively high bulk density and low W_{100} but was classified as having high NDVI values in the summer. In its orthophoto (Figure 20), it can be observed that the site is surrounded by trees. This probably has the inverse effect of the effect of infrastructure on the site VER2; the site probably has lower temperatures in the summer than other sites, and thus the vegetation suffers less from drought, leading the NDVI values to be higher in the summer than if the trees were absent. As we observed a relatively low number of sites, it could be that the values of GRA for bulk density and W_{100} distorted the mean value of its NDVI class, leading to an insignificant statistical outcome.

Figure 20

Orthophoto of the site GRA

The site is surrounded by trees which might generate a favourable micro-climate leading to higher NDVI values in summer.

In short, even if soil properties seem to explain low NDVI values in the summer in part, surrounding infrastructure and trampling might worsen NDVI evolution in sites with poor soil conditions, and might explain low NDVI values in sites with otherwise favourable soil properties. Lack of infrastructure and trampling, as well as surrounding trees and greenery might allow sites with unfavourable soil properties still to have high NDVI values. This is supported by the evidence of Yu et al. (2018) and Carlân et al. (2020). Yu et al. (2018) showed that trees planted in highly sealed areas have lower vegetation health than trees in parks. Carlân et al. (2020), showed that land surface temperatures, distance to a lake and proximity to roads were important predictors of NDVI values in the urban environment. They did not, however, study soil properties.

Thus, in future research, the microclimate and trampling effect should be accounted for in addition to soil properties, which would enable us to differentiate between the effect of microclimate, trampling, and soil. Similarly to the study of Mukherjee & Agrawal, (2018), who studied the effect of soil properties along with the effect of air pollution and land use on roadside ground vegetation, the effect of microclimate and trampling on vegetation health should be studied alongside soil properties in future research.

4.3 NDVI and underground sealing

In the introduction, it was hypothesised that the presence of underground sealing would significantly influence the soil properties of a site, which would, in turn, influence the NDVI evolution of the site. Two site pairs, from two different parks, had one site with underground sealing, and one site without underground sealing. BRD1 and BRD2 form such a pair: both are in Parc Bertrand, with BRD1 having underground sealing and BRD2 not having underground sealing. HEN1 and HEN2 are the other pair: both are in Parc Gustave et Léonard Hentsch, HEN2 having underground sealing whereas HEN1 has not.

When comparing the soil properties of the site pairs, it is very interesting to see that the soil depth of both sites of one pair are very similar – HEN1 and HEN2 have a mean soil depth of 38 cm and 39 cm, respectively, and BRD1 and BRD2 both have a mean soil depth of 77 cm. It was expected for the sites with underground sealing to have a lower soil depth than the sites without, as it was expected that the underground sealing would limit soil depth. However, this is not the case. All other soil properties (amount of coarse material, BD, W_{100}, SOC, A_{100}) are also very similar within the site pairs. For the sites located within Parc Gustave et Léonard Hentsch, this might be explained by the fact that both sites are anthropogenic soils, which were created in the same infrastructure project in 2015. Thus, the anthropogenic site creation might have a higher influence on soil factors than the presence or absence of underground sealing.

The NDVI values of the sites located in Parc Bertrand cannot be compared, as the NDVI values for BRD2 are missing. Observing the NDVI evolution of both HEN1 and HEN2, no clear distinction can be made between the site with and the site without underground sealing. The site with underground sealing has a sudden drop of NDVI value in the period starting on the 20th of June, which the site HEN1 does not have. However, nothing indicates that this drop is linked to underground sealing. Except for the period of the 20th of June, both NDVI evolutions are very similar in form, with the site without underground sealing having slightly lower mean NDVI values in July and August.

In conclusion, underground sealing could neither indicate differences in soil properties, nor could it explain differences in NDVI evolution, leading to the hypothesis that underground sealing does not directly affect soil properties or vegetation health in lawn vegetation. However, only one site pair was assessed to determine whether underground sealing has an influence on NDVI, and the other soil properties of this park, which was created in 2015, might have a higher influence on soil NDVI evolution than the presence or absence of underground sealing. To verify the hypothesis, more parks with different formation history should be assessed. These findings cannot be compared to any literature, as no literature was found which assessed the influence of underground sealing on urban vegetation health.

4.4 SOC Correlations

To answer the research question *"Is SOC correlated to W_{100}, A_{100}, clay content and BD in the urban environment?",* the correlation between SOC and these soil parameters was calculated. SOC correlated to W_{100} and A_{100}, but not to the clay content and BD. The two first mentioned parameters are soil structure quality indicators (Johannes et al., 2021b), and so our findings support the hypothesis that SOC influences soil structure in the urban environment. However, BD is also often considered an indicator for soil structure, and we cannot provide an explanation to why SOC was not correlated to BD.

5. CONCLUSION AND OUTLOOK

13 urban sites with lawn vegetation, all located in the city of Geneva, were studied to assess the influence of soil properties on vegetation health. The measured soil properties were soil depth, particle size distribution, amount of coarse material, BD, W_{100}, A_{100} and SOC. Except for soil depth, all soil properties were measured at 5 to 10 cm depth. The vegetation health was assessed using the NDVI evolution of each site during two different seasons: spring and summer. Some soil properties were shown to be related to vegetation health.

It could be shown that the amount of coarse material related to the NDVI evolution in spring and summer and that soil depth related to the NDVI evolution in summer. In urban soils, it seems that the amount of coarse material and the soil depth have a higher influence on the amount of water stored in the soils in dry periods than any soil property relating to the fine earth fraction. These findings are unique in the urban environment, as no other study successfully related either soil depth or the amount of coarse material to urban vegetation greening and browning. The results of the present study indicate that including soil depth data as well as the amount of coarse material could be very important for understanding the effect of soil on urban vegetation health.

It could also be shown that in spring, next to the amount of coarse material, BD and W_{100} related to the NDVI, with low NDVI values relating to high BD and low W_{100}. It is believed that the impedance to root growth, as well as lack of oxygen in saturated soils, which is influenced by the amount of coarse material as well as BD, impacted vegetation health in spring. It is possible that trampling also influenced BD.

Broadly speaking, soil properties could be shown to have an influence on urban vegetation health, which was our main hypothesis. However, it was noticed that other factors, such as microclimate and trampling, might also influence vegetation health and thus NDVI values. Furthermore, the effect of the park to which the sites belonged was not accounted for, as the sample size did not allow this effect to be included in the statistical analysis. Consequently, a bigger sample size should be assessed to exclude the effect of the parks on vegetation health. In future research, it would be interesting to assess the influence of microclimate and trampling on vegetation health alongside the influence of soil properties in order to understand the importance of each individual factor on vegetation health.

This study is one of the first to use NDVI evolutions as a proxy for vegetation health while trying to link urban vegetation greening and browning to urban soil properties. The use of NDVI evolution to assess urban vegetation health is promising, especially as it can be used on different types of vegetation and the data is easy to obtain. It could be used to compare the effect of soil properties on vegetation health for a variety of different vegetation types, on much larger scales than the scales which can be achieved by individual plant sampling, which is the method used in most other studies relating soil properties to urban vegetation health. However, in this study, a novel approach of assessing the NDVI data was used, using NDVI evolution to classify the sites into vegetation health classes, instead of using the NDVI values on one date. This approach was useful, but the limit values that were used to classify the different NDVI evolution curves were determined by comparing the NDVI evolution of several sites and are not generalisable to other sites. In future research, limit values of NDVI for different vegetation types could be assessed by comparing NDVI values to data of directly sampled vegetation data, making this approach generalisable.

BIBLIOGRAPHY:

Amelung, W., Blume, H.-P., Fleige, H., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., & Wilke, B.-M. (2018). *Scheffer/Schachtschabel Lehrbuch der Bodenkunde* (17th ed.). Springer Spektrum. https://doi.org/10.1007/978-3-662-55871-3

Amossé, J., Dózsa-Farkas, K., Boros, G., Rochat, G., Sandoz, G., Fournier, B., Mitchell, E. A. D., & Le Bayon, R. C. (2016). Patterns of earthworm, enchytraeid and nematode diversity and community structure in urban soils of different ages. *European Journal of Soil Biology*, *73*. https://doi.org/10.1016/j.ejsobi.2016.01.004

Baetens, J. M., Verbist, K., Cornells, W. M., Gabriels, D., & Soto, G. (2009). On the influence of coarse fragments on soil water retention. *Water Resources Research*, *45*(7). https://doi.org/10.1029/2008WR007402

Blake, G. R., & Hartge, K. H. (1986). Bulk Density. In A. Klute (Ed.), *Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods* (2nd ed., pp. 363–376). American Society of Agronomy, Inc., Soil Science Society of America, Inc.

Blume, H.-P., Stahr, K., & Leinweber, P. (2010). Bodenkundliches Praktikum. In *Bodenkundliches Praktikum*. Spektrum Akademischer Verlag. https://doi.org/10.1007/978-3-8274-2733-5

Boivin, P., Brunet, D., & Guascuel-Odoux, C. (1990). Densité apparente d'échantillon de sol: méthode de la poche plastique. In *Milieux Poreux et Transferts Hydriques, Bulletin du Groupe Français d'Humidimétrie Neutronique n°28* (pp. 57–71).

Bundesamt für Statistik. (2021a). *Arealstatistik Land Cover - Versiegelte Flächen der Gemeinden*. https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/bodennutzung-bedeckung/siedlungsflaechen/versiegelungsgrad.assetdetail.19805723.html

Bundesamt für Statistik. (2021b). *Regional portraits 2021: key data of all communes*. https://www.bfs.admin.ch/bfs/en/home/statistics/regional-statistics/regional-portraits-key-figures/communes.assetdetail.15864443.html

Bundesamt für Umwelt. (2018). Hitze in Städten. Grundlage für eine klimaangepasste Siedlungsentwicklung. *Umwelt-Wissen*, 108.

Cârlan, I., Haase, D., Große-Stoltenberg, A., & Sandric, I. (2020). Mapping heat and traffic stress of urban park vegetation based on satellite imagery - A comparison of Bucharest, Romania and Leipzig, Germany. *Urban Ecosystems*, *23*(2). https://doi.org/10.1007/s11252-019-00916-z

Cârlan, I., Mihai, B. A., Nistor, C., & Große-Stoltenberg, A. (2020). Identifying urban vegetation stress factors based on open access remote sensing imagery and field observations. *Ecological Informatics*, *55*. https://doi.org/10.1016/j.ecoinf.2019.101032

Edmondson, J. L., Davies, Z. G., McCormack, S. A., Gaston, K. J., & Leake, J. R. (2011). Are soils in urban ecosystems compacted? A citywide analysis. *Biology Letters*, *7*(5). https://doi.org/10.1098/rsbl.2011.0260

Endlicher, W. (2012). *Einführung in die Stadtökologie*. Eugen Ulmer.

Foti, L., Barot, S., Gignoux, J., Grimaldi, M., Lata, J. C., Lerch, T. Z., Nold, F., Nunan, N., Raynaud, X., Abbadie, L., & Dubs, F. (2021). Topsoil characteristics of forests and lawns along an urban–rural gradient in the Paris region (France). *Soil Use and Management*, *37*(4). https://doi.org/10.1111/sum.12640

Galle, N. J., Brinton, W., Vos, R., Basu, B., Duarte, F., Collier, M., Ratti, C., & Pilla, F. (2021). Correlation of WorldView-3 spectral vegetation indices and soil health indicators of individual urban trees with exceptions to topsoil disturbance. *City and Environment Interactions*, *11*. https://doi.org/10.1016/j.cacint.2021.100068

Gee, G. W., & Or, D. (2002). Particle-Size Analysis. In J. H. Dane & C. G. Topp (Eds.), *Methods of Soil Analysis, Part 4, Physical Methods* (pp. 255–294). Soil Science Society of America, Inc.

Gräf, M., Immitzer, M., Hietz, P., & Stangl, R. (2021). Water-stressed plants do not cool: Leaf surface temperature of living wall plants under drought stress. *Sustainability*, *13*(7). https://doi.org/10.3390/su13073910

Hendershot, W. H., Lalande, H., & Duquette, M. (2007). Soil Reaction and Exchangeable Acidity. In M. R. Carter & E. G. Gregorich (Eds.), *Soil Sampling and Methods of Analysis, Second Edition* (pp. 173–178). Taylor and Francis Group.

Hernández-López, P., Mohedano-Caballero, L., Rodríguez-Trejo, D. A., & Martínez-Trinidad, T. (2021). Root growth of Taxodium mucronatum Ten. Planted in an urban area. *Revista Chapingo, Serie Ciencias Forestales y Del Ambiente*, *27*(1). https://doi.org/10.5154/R.RCHSCFA.2019.08.064

Hernandez, L., Levin, M., Calus, J., Galbraith, J., Muñiz, E., Ryan, K., Riddle, R., Shaw, R. K., Dobos, R., Peasle, S., Southard, S., Surabian, D., & Lindbo, D. (2018). Urban Soil Mapping through the United States National Cooperative Soil Survey. In R. Lal & B. A. Stewart (Eds.), *Urban Soils* (pp. 15–60). Taylor and Francis Inc. https://doi.org/10.1201/9781315154251

Hillel, D. (2003). Introduction to Environmental Soil Physics. In *Introduction to Environmental Soil Physics*. https://doi.org/10.1016/B978-0-12-348655-4.X5000-X

Hiller, D. A., & Meuser, H. (1998). *Urbane Böden*. Springer. https://doi.org/10.1007/978-3-642-72064-2

Imhof, C. (2021). *Testing NDVI as a proxy of soil water holding capacity in the urban context - a pilot study*.

Jim, C. Y. (1998). Urban soil characteristics and limitations for landscape planting in Hong Kong. *Landscape and Urban Planning*, *40*(4). https://doi.org/10.1016/S0169-2046(97)00117-5

Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P. C., & Boivin, P. (2017). Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma*, *302*. https://doi.org/10.1016/j.geoderma.2017.04.021

Johannes, A., Weisskopf, P., & Boivin, P. (2021a). *Probenahme von ungestörten Bodenproben ohne Stahlzylinder*.

Johannes, A., Weisskopf, P., & Boivin, P. (2021b). *Soil structure degradation evaluation for environmental legislation (STRUDEL)*.

Johannes, A., Weisskopf, P., Schulin, R., & Boivin, P. (2019). Soil structure quality indicators and their limit values. *Ecological Indicators*, *104*. https://doi.org/10.1016/j.ecolind.2019.05.040

Kim, Y. J., Hyun, J., Yoo, S. Y., & Yoo, G. (2021). The role of biochar in alleviating soil drought stress in urban roadside greenery. *Geoderma*, *404*. https://doi.org/10.1016/j.geoderma.2021.115223

Klaus, G. (2017). Boden in der Schweiz. Zustand und Entwicklung. Stand 2017. *Umwelt-Zustand*, *1721*.

Kretzschmar, R. (2017). *Pedosphäre Polybook: Pedosphäre. Einführung in die Bodenkunde*.

Laboratoire cantonal d'agronomie. (1992). *Etude des parcs de la ville de Genève*.

Lal, R. (2018). Urban agriculture in the 21st century. In R. Lal & B. A. Stewart (Eds.), *Urban Soils* (pp.

1–14). Taylor and Francis Inc. https://doi.org/10.1201/9781315154251

Lan, T., Guo, S. W., Han, J. W., Yang, Y. L., Zhang, K., Zhang, Q., Yang, W., & Li, P. F. (2019). Evaluation of physical properties of typical urban green space soils in Binhai Area, Tianjin, China. *Urban Forestry and Urban Greening*, *44*. https://doi.org/10.1016/j.ufug.2019.126430

LECO Corporation. (2016). *628 Series Elemental Determinators Specification Sheet*.

Lus, M. G., & Toor, G. S. (2018). Optimizing the hydrological properties of urban soils. In R. Lal & B. A. Stewart (Eds.), *Urban Soils* (pp. 199–213). Taylor and Francis Inc. https://doi.org/10.1201/9781315154251

MeteoSwiss. (2021). *Climate normals Genève / Cointrin, Reference period 1991−2020*. https://www.meteoswiss.admin.ch/product/output/climate-data/climate-diagrams-normal-values-station-processing/GVE/climsheet_GVE_np9120_e.pdf

Mónok, D., Kardos, L., Pabar, S. A., Kotroczó, Z., Tóth, E., & Végvári, G. (2021). Comparison of soil properties in urban and non-urban grasslands in Budapest area. *Soil Use and Management*, *37*(4). https://doi.org/10.1111/sum.12632

Moore, K. A., Shober, A. L., Hasing, G., Wiese, C., & West, N. G. (2014). Effect of soil type and nitrogen rate on growth of annual and perennial landscape plants in Florida. *HortTechnology*, *24*(6). https://doi.org/10.21273/horttech.24.6.724

Mukherjee, A., & Agrawal, M. (2018). The influence of urban stress factors on responses of ground cover vegetation. *Environmental Science and Pollution Research*, *25*(36). https://doi.org/10.1007/s11356-018-3437-5

Mullins, C. E. (1991). Physical Properties of Soils in Urban Areas. In P. Bullock & P. J. Gregory (Eds.), *Soils in the Urban Environment* (pp. 87–118). Blackwell Scientific Publications. https://doi.org/10.1002/9781444310603.ch6

Nouri, H., Beecham, S., Anderson, S., & Nagler, P. (2013). High spatial resolution WorldView-2 imagery for mapping NDVI and its relationship to temporal urban landscape evapotranspiration factors. *Remote Sensing*, *6*(1). https://doi.org/10.3390/rs6010580

Paul, M. J., & Meyer, J. L. (2001). Streams in the urban landscape. In *Annual Review of Ecology and Systematics* (Vol. 32). https://doi.org/10.1146/annurev.ecolsys.32.081501.114040

Pouyat, R., Szlávecz, K., Yesilonis, I. D., Groffman, P., & Schwarz, K. (2010). Chemical, physical, and biological characteristics of urban soils. In J. Aitkenhead-Peterson & A. Volder (Eds.), *Urban ecosystem ecology* (pp. 119–152). American Society American society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc. https://doi.org/https://doi.org/10.2134/agronmonogr55.c7

Pouyat, R., Yesilonis, I. D., Russell-Anelli, J., & Neerchal, N. K. (2007). Soil Chemical and Physical Properties That Differentiate Urban Land-Use and Cover Types. *Soil Science Society of America Journal*, *71*(3). https://doi.org/10.2136/sssaj2006.0164

Prokof'eva, T., Umarova, A., Bykova, G., Suslenkova, M., Ezhelev, Z., Kokoreva, A., Gasina, A., & Martynenko, I. (2020). Morphological and physical properties in diagnostics of urban soils: Case study from Moscow, Russia. *Soil Science Annual*, *71*(4). https://doi.org/10.37501/soilsa/131598

Rawls, W. J., Pachepsky, Y. A., Ritchie, J. C., Sobecki, T. M., & Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. *Geoderma*, *116*(1–2). https://doi.org/10.1016/S0016-7061(03)00094-6

RICOTER. (n.d.). *Argile expansée drainage*. 2022. https://www.ricoter.ch/fr/bac-toiture/materiau-de-drainage/argile-expansee-drainage.php

Rötzer, T., Moser-Reischl, A., Rahman, M. A., Hartmann, C., Paeth, H., Pauleit, S., & Pretzsch, H. (2021). Urban tree growth and ecosystem services under extreme drought. *Agricultural and Forest Meteorology*, *308–309*. https://doi.org/10.1016/j.agrformet.2021.108532

Scharenbroch, B. C., & Catania, M. (2012). Soil quality attributes as indicators of Urban Tree performance. *Arboriculture and Urban Forestry*, *38*(5). https://doi.org/10.48044/jauf.2012.030

Scharenbroch, B. C., Fite, K., Kramer, E., & Uhlig, R. (2018). Pedogenic Processes and Urban Tree Health in Engineered Urban Soils in Boston, Massachusetts, USA. *Soil Science*, *183*(4). https://doi.org/10.1097/SS.0000000000000231

Schwab, P., & Gubler, A. (2016). Methoden zur Bestimmung physikalischer Begleitparameter an Bodenproben. In *Agroscope Science* (Vol. 40). Agroscope.

Secu, C. V., Breaban, I. G., Juravle, D. T., & Lesenciuc, C. D. (2016). Human impact on urban soil properties from Bahlui Foodplain, Iasi, Romania. *Journal of Environmental Protection and Ecology*, *17*(1).

Soil Survey Staff. (2014). Soil Survey Field and Laboratory Methods Manual. In R. Burt and Soil Survey Staff (Ed.), *Soil Survey Investigations Report* (Number 51). U.S. Department of Agriculture, Natural Resources Conservation Service.

Somerville, P. D., Farrell, C., May, P. B., & Livesley, S. J. (2020). Biochar and compost equally improve urban soil physical and biological properties and tree growth, with no added benefit in combination. *Science of the Total Environment*, *706*. https://doi.org/10.1016/j.scitotenv.2019.135736

Thorup, J. T. (1969). pH Effect on Root Growth and Water Uptake by Plants. *Agronomy Journal*, *61*(2). https://doi.org/10.2134/agronj1969.00021962006100020016x

Tresch, S., Moretti, M., Le Bayon, R.-C., Mäder, P., Zanetta, A., Frey, D., & Fliessbach, A. (2018). A Gardener's Influence on Urban Soil Quality. *Frontiers in Environmental Science*, *6*. https://doi.org/10.3389/fenvs.2018.00025

Ugolini, F., Baronti, S., Lanini, G. M., Maienza, A., Ungaro, F., & Calzolari, C. (2020). Assessing the influence of topsoil and technosol characteristics on plant growth for the green regeneration of urban built sites. *Journal of Environmental Management*, *273*. https://doi.org/10.1016/j.jenvman.2020.111168

Ville de Genève. (2021a). *Parc de Vermont*. https://www.geneve.ch/fr/parc-vermont

Ville de Genève. (2021b). *Quai Gustave-Ador*. https://www.geneve.ch/fr/quai-gustave-ador

Weck, P. de. (n.d.). *Parc Gustave et Léonard Hentsch, Inauguration*. http://www.parc-hentsch.ch/#inauguration

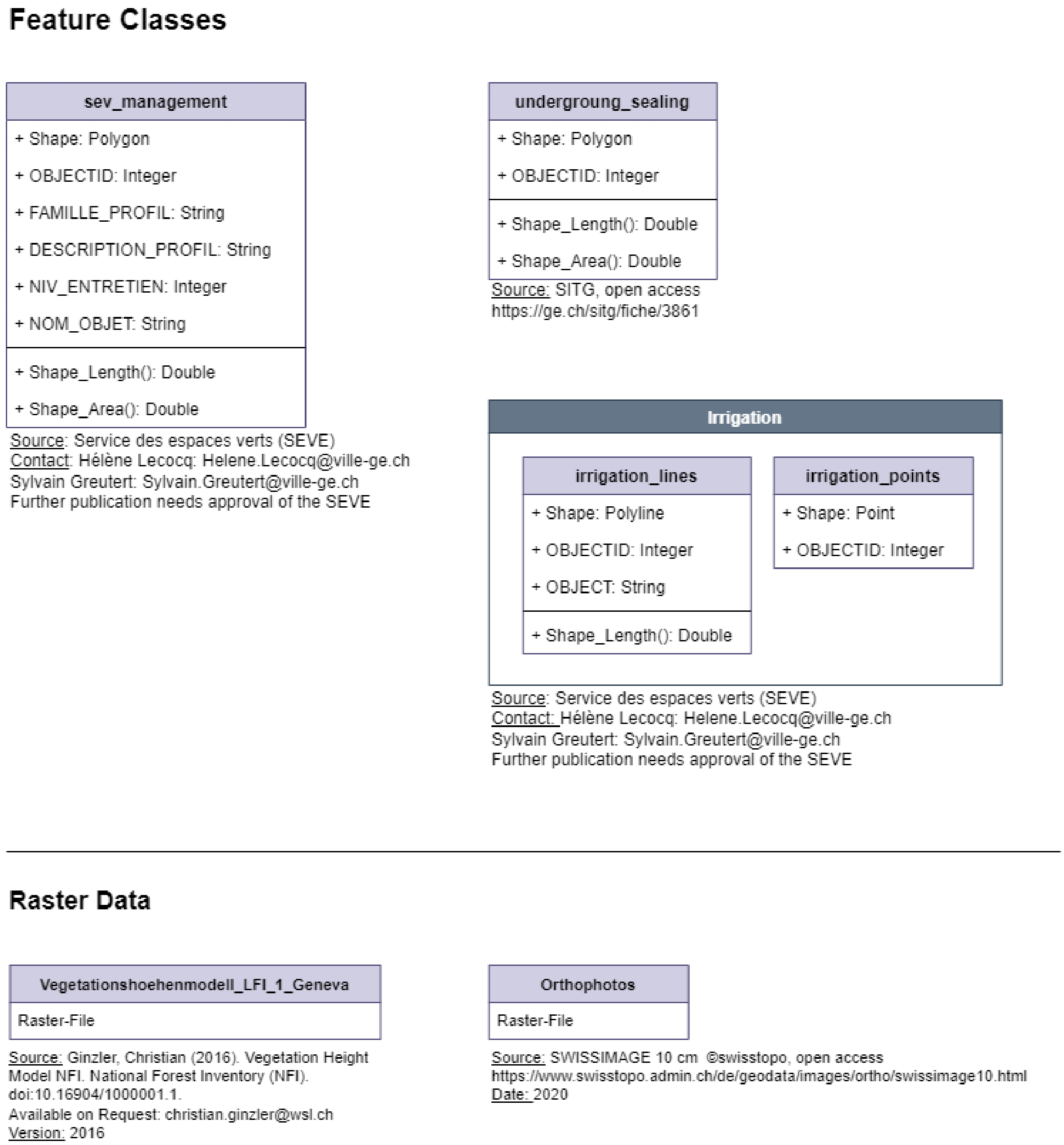
World Health Organization. (2016). *Ambient air pollution data*. https://www.who.int/data/gho/data/themes/air-pollution/ambient-air-pollution

Yu, K., Van Geel, M., Ceulemans, T., Geerts, W., Ramos, M. M., Sousa, N., Castro, P. M. L., Kastendeuch, P., Najjar, G., Ameglio, T., Ngao, J., Saudreau, M., Honnay, O., & Somers, B. (2018). Foliar optical traits indicate that sealed planting conditions negatively affect urban tree health. *Ecological Indicators*, *95*. https://doi.org/10.1016/j.ecolind.2018.08.047

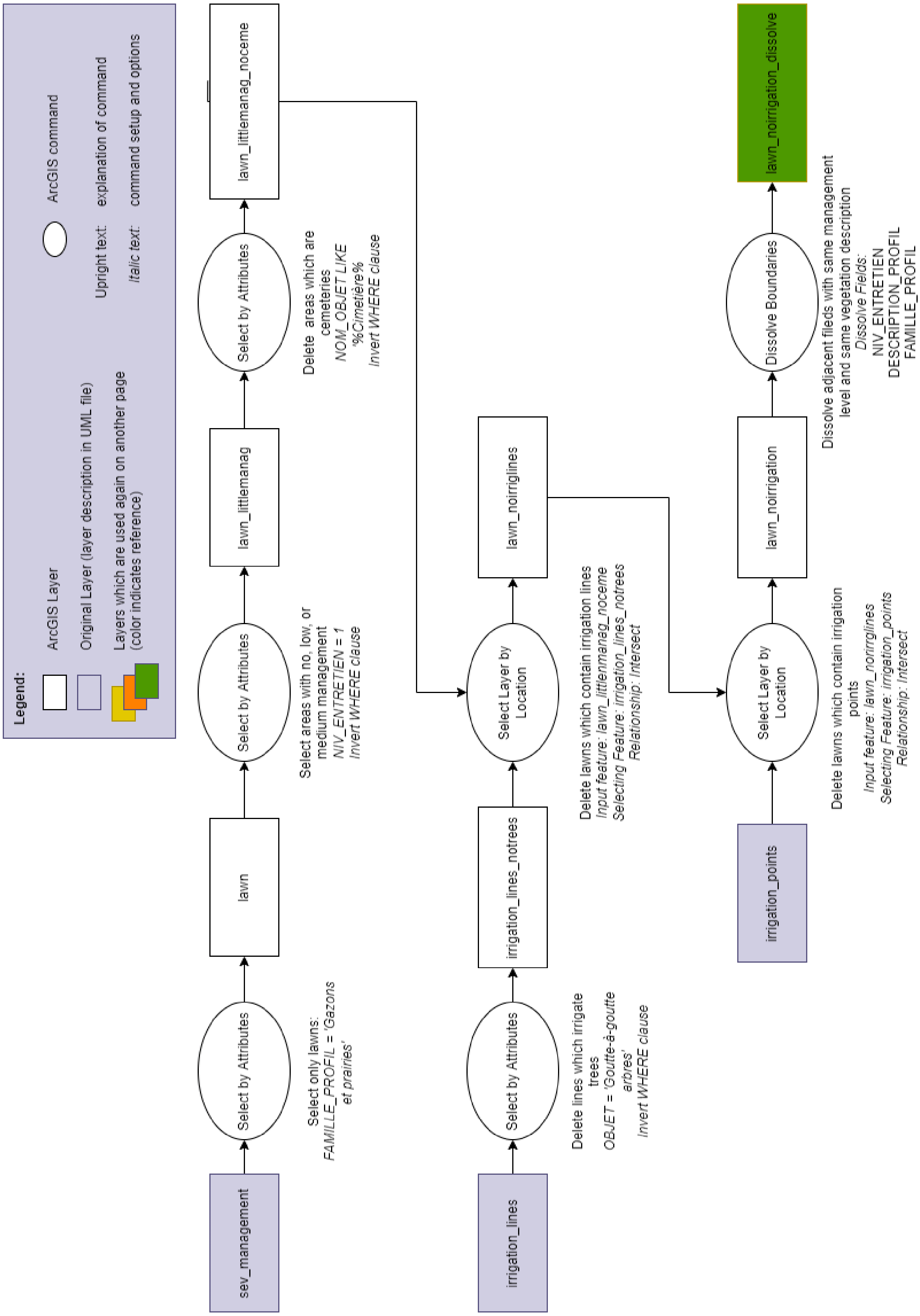
APPENDIX

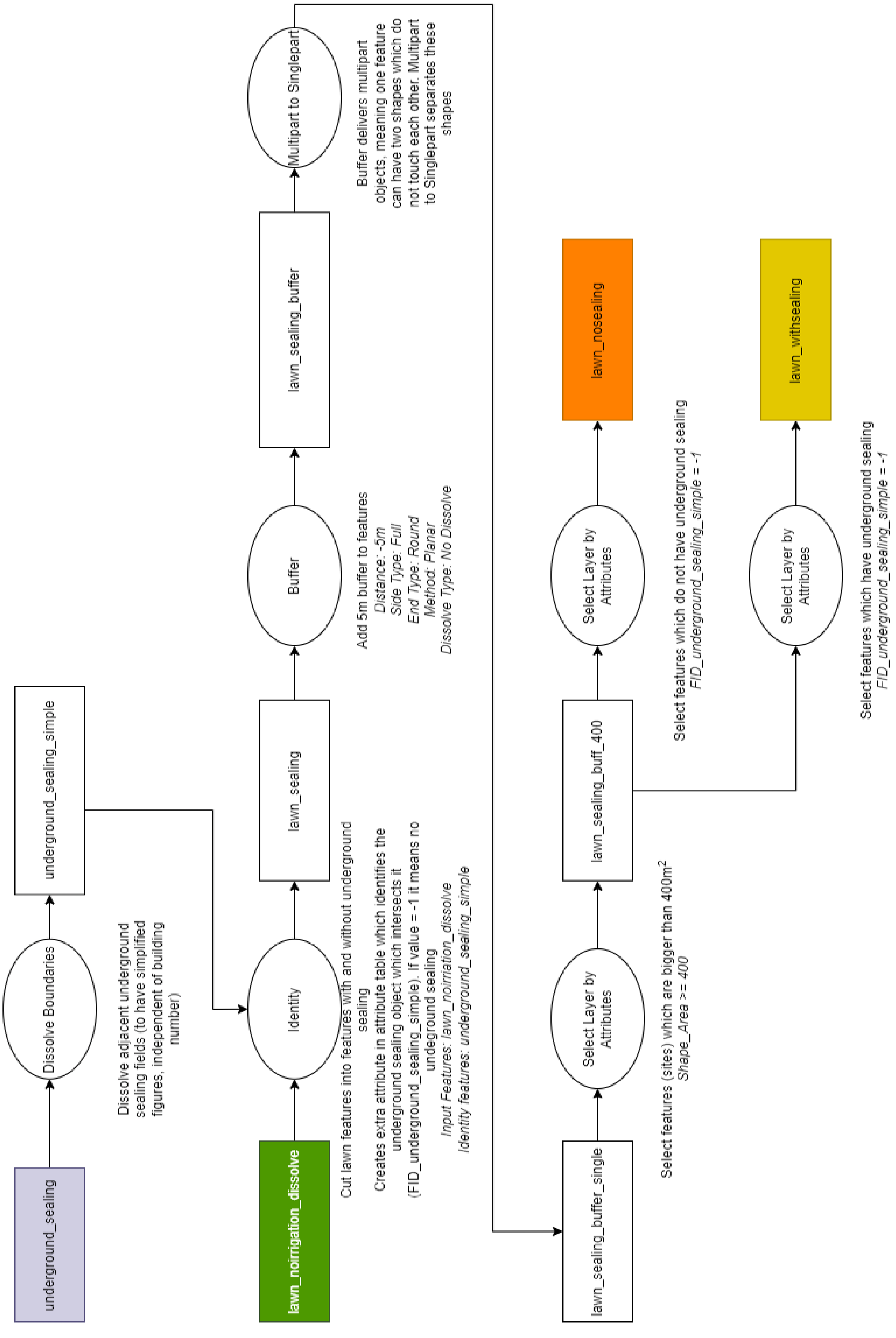
Appendix 1. Conceptual Model of the Site Selection

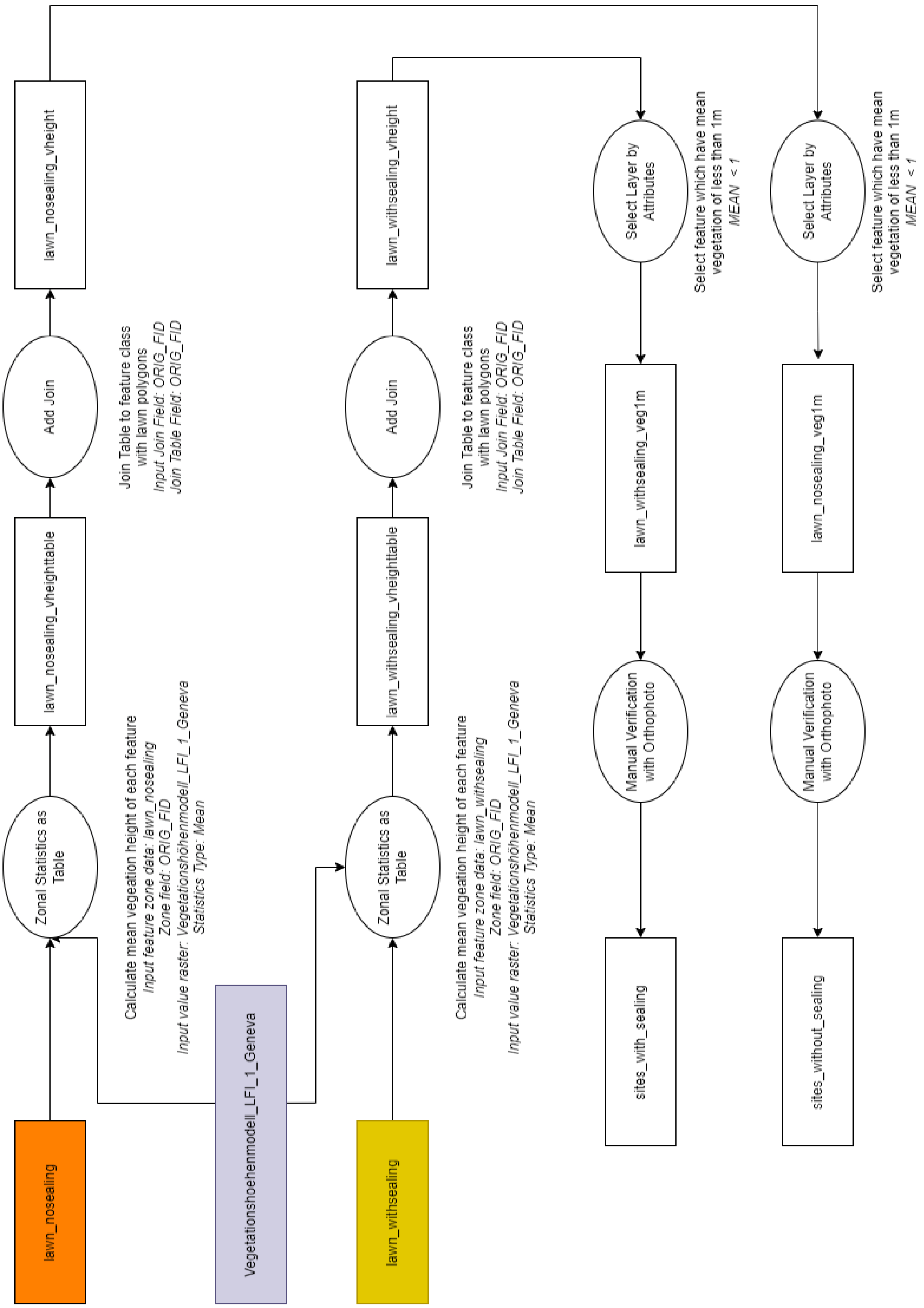
Appendix 1.1 UML Visualisation of the Individual Layers



Appendix 1.2 Conceptual Model of the Site Selection




underground_sealing
Dissolve Boundaries
underground_sealing_simple
Dissolve adjacent underground sealing fields (to have simplified figures, independent of building number)
lawn_noirrigation_dissolve
Identity
lawn_sealing
Buffer
lawn_sealing_buffer
Multipart to Singlepart
Cut lawn features into features with and without underground sealing
Creates extra attribute in attribute table which identifies the underground sealing object which intersects it (FID_underground_sealing_simple). If value = -1 it means no underground sealing
Input Features: lawn_noirriation_dissolve
Identity features: underground_sealing_simple
Add 5m buffer to features
Distance: -5m
Side Type: Full
End Type: Round
Method: Planar
Dissolve Type: No Dissolve
Buffer delivers multipart objects, meaning one feature can have two shapes which do not touch each other. Multipart to Singlepart separates these shapes
lawn_sealing_buffer_single
Select Layer by Attributes
lawn_sealing_buff_400
Select Layer by Attributes
lawn_nosealing
Select Layer by Attributes
lawn_withsealing
Select features (sites) which are bigger than 400m2
Shape_Area >= 400
Select features which do not have underground sealing
FID_underground_sealing_simple = -1
Select features which have underground sealing
FID_underground_sealing_simple = -1


lawn_nosealing
Vegetationshoehenmodell_LFI_1_Geneva
lawn_withsealing
Zonal Statistics as Table
Calculate mean vegeation height of each feature
Input feature zone data: lawn_nosealing
Zone field: ORIG_FID
Input value raster: Vegetationshöhenmodell_LFI_1_Geneva
Statistics Type: Mean
Zonal Statistics as Table
Calculate mean vegeation height of each feature
Input feature zone data: lawn_withsealing
Zone field: ORIG_FID
Input value raster: Vegetationshöhenmodell_LFI_1_Geneva
Statistics Type: Mean
lawn_nosealing_vheighttable
lawn_withsealing_vheighttable
Add Join
Join Table to feature class with lawn polygons
Input Join Field: ORIG_FID
Join Table Field: ORIG_FID
Add Join
Join Table to feature class with lawn polygons
Input Join Field: ORIG_FID
Join Table Field: ORIG_FID
lawn_nosealing_vheight
lawn_withsealing_vheight
Select Layer by Attributes
Select feature which have mean vegetation of less than 1m
MEAN < 1
Select Layer by Attributes
Select feature which have mean vegetation of less than 1m
MEAN < 1
lawn_withsealing_veg1m
lawn_nosealing_veg1m
Manual Verification with Orthophoto
Manual Verification with Orthophoto
sites_with_sealing
sites_without_sealing

Appendix 2. Factsheets of the Sites

SITE: ADO

Park: Quai Gustave-Ador

Centre Coordinates	2'501'720.327, 1'118'283.029

Characteristics:

Relief	level
Vegetation	turf, bulb flowers
Soil origin	anthropogenic, created 1920s (Ville de Genève, 2021)
Land Use	parc
Underground Sealing	no
Management level	no management
Area [m^2]	459.98

Results – Chemical Parameters

SOC	[% by mass]	5.058
SOC:Clay		0.34
N	[% by mass]	0.3461
pH		6.97

Results – Physical Parameters

Texture fractions	[% by mass]	Clay:	14.9	Silt:	56.8	Sand:	28.3
Texture class		Silty Loam					

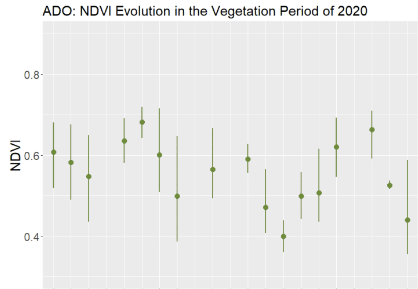
		Mean	Sd
Soil Depth	[cm]	38.33	0.58
Coarse fraction	[% by mass]	12.12	8.06
Bulk density	[g/cm^3]	1.25	0.08
Water content at -10hPa	[g/g]	0.42	0.05
Water content at -100hPa	[g/g]	0.34	0.04
Porosity	[% volume]	52.77	2.94
Pores over 15µm	[% volume]	10.14	3.12
Pores 15-150µm	[% volume]	9.30	2.36

Results – NDVI classification

Spring	low
Summer	low

Top: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Bottom: Photo, 2021, Gruffydd Davies



SITE: BAR

Park: Barton

Centre Coordinates	2'500'661.063, 1'119'852.652

Characteristics:

Relief	foot of slope
Vegetation	turf
Soil origin	natural (Laboratoire cantonal d'agronomie, 1992)
Land Use	parc
Underground Sealing	no
Management level	low
Area [m^2]	406.73

Results – Chemical Parameters

SOC	[% by mass]	3.598
SOC:Clay		0.24
N	[% by mass]	0.3074
pH		6.67

Results – Physical Parameters

Texture fractions	[% by mass]	Clay:	14.8	Silt:	41.7	Sand:	43.5
Texture class		Loam					

		Mean	Sd
Soil Depth	[cm]	33.33	5.86
Coarse fraction	[% by mass]	18.19	9.50
Bulk density	[g/cm^3]	1.12	0.07
Water content at -10hPa	[g/g]	0.46	0.05
Water content at -100hPa	[g/g]	0.36	0.04
Porosity	[% volume]	57.67	2.67
Pores over 15µm	[% volume]	17.86	3.96
Pores 15-150µm	[% volume]	11.55	2.05

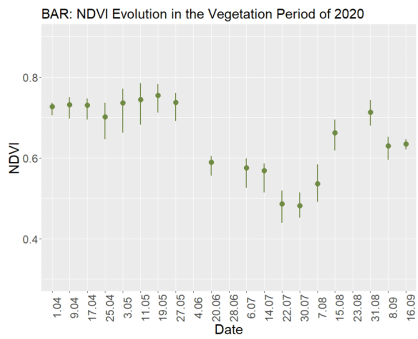
Results – NDVI classification

Spring	high
Summer	low

Top left: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Top right: Photo, 2021, Gruffydd Davies

Bottom left: Profile picture, 1991 from Laboratoire cantonal d'agronomie (1992)



SITE: BEA

Park: Beaulieu

Centre Coordinates	2'499'532.003, 1'119'003.621

Characteristics:

Relief	level
Vegetation	turf
Soil origin	Anthropogenic (Laboratoire cantonal d'agronomie, 1992)
Land Use	parc
Underground Sealing	no
Management level	low
Area [m^2]	406.73

Top left: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Top right: Photo, 2021, Gruffydd Davies

Bottom left: Profile picture, 1991 from Laboratoire cantonal d'agronomie (1992)

Results – Chemical Parameters

SOC	[% by mass]	4.970
SOC:Clay		0.30
N	[% by mass]	0.4095
pH		6.64

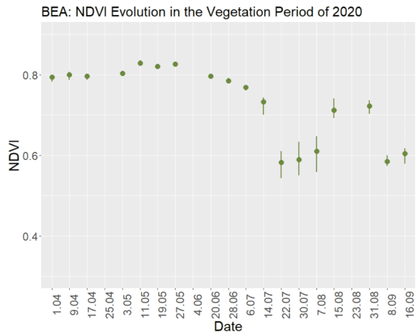
Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 16.8	Silt: 58.4	Sand: 24.8
Texture class		Silty Loam		

		Mean	Sd
Soil Depth	[cm]	>120	-
Coarse fraction	[% by mass]	11.82	13.86
Bulk density	[g/cm^3]	1.12	0.03
Water content at -10hPa	[g/g]	0.47	0.04
Water content at -100hPa	[g/g]	0.38	0.03
Porosity	[% volume]	57.65	1.31
Pores over 15µm	[% volume]	15.18	2.53
Pores 15-150µm	[% volume]	10.39	1.42

Results – NDVI classification

Spring	high
Summer	high



SITE: BRD1

Park: Bertrand

Centre Coordinates	2'501'279,548; 1'116'544.954

Characteristics:

Relief	slight slope
Vegetation	turf
Soil origin	natural (Laboratoire cantonal d'agronomie, 1992)
Land Use	dog parc
Underground Sealing	yes
Management level	moderate
Area [m^2]	457.77

Top left: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Top right: Photo, 2021, Gruffydd Davies

Bottom left: Profile picture, 1991 from Laboratoire cantonal d'agronomie (1992) – Remark: might have changed since then, as there is underground sealing under the site. Same picture as BRD2, as classified as same area in the 1992 study.

Results – Chemical Parameters

SOC	[% by mass]	6.214
SOC:Clay		0.28
N	[% by mass]	0.4738
pH		6.84

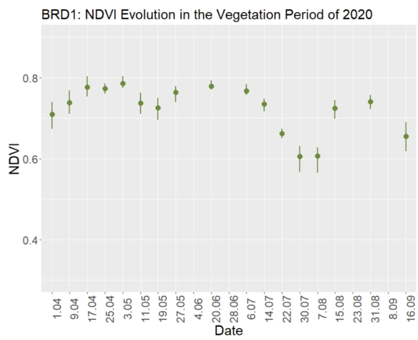
Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 22.2	Silt: 58.6	Sand: 19.2
Texture class		Silty Loam		

		Mean	Sd
Soil Depth	[cm]	77	24.43
Coarse fraction	[% by mass]	1.22	1.42
Bulk density	[g/cm^3]	1.08	0.04
Water content at -10hPa	[g/g]	0.52	0.03
Water content at -100hPa	[g/g]	0.44	0.03
Porosity	[% volume]	59.09	1.69
Pores over 15µm	[% volume]	11.81	2.47
Pores 15-150µm	[% volume]	9.27	0.75

Results – NDVI classification

Spring	high
Summer	high



SITE: BRD2

Park: Bertrand

Centre Coordinates 2'501'253.631, 1'116'556.099

Characteristics:

Relief	level
Vegetation	turf
Soil origin	natural*
Land Use	dog parc
Underground Sealing	no
Management level	moderate
Area [m²]	560.81

Results – Chemical Parameters

SOC	[% by mass]	5.747
SOC:Clay		0.25
N	[% by mass]	0.4441
pH		6.75

Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 23.3	Silt: 62.2	Sand: 14.5
Texture class		Silty Loam		

		Mean	Sd
Soil Depth	[cm]	76.67	42.52
Coarse fraction	[% by mass]	6.27	5.34
Bulk density	[g/cm³]	1.16	0.07
Water content at -10hPa	[g/g]	0.48	0.06
Water content at -100hPa	[g/g]	0.4	0.05
Porosity	[% volume]	56.34	2.63
Pores over 15µm	[% volume]	10.77	0.8
Pores 15-150µm	[% volume]	10.05	1.44

Results – NDVI classification

Spring	No classification
Summer	No classification

Top left: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Top right: Photo, 2021, Gruffydd Davies

Bottom left: Profile picture, 1991 from Laboratoire cantonal d'agronomie (1992) – Remark: Same picture as BRD1, as classified as same area in the 1992 study.

No NDVI data available

SITE: GRA

Park: La Grange

Centre Coordinates 2'502'147.374, 1'117'951.055

Characteristics:

Relief	slight slope
Vegetation	turf
Soil origin	Natural*
Land Use	dog parc
Underground Sealing	no
Management level	Moderate
Area [m²]	406.73

Results – Chemical Parameters

SOC	[% by mass]	5.243
SOC:Clay		0.6
N	[% by mass]	0.2523
pH		6.98

Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 8.78	Silt: 27.52	Sand: 63.7
Texture class		Sandy Loam		

		Mean	Sd
Soil Depth	[cm]	>120	-
Coarse fraction	[% by mass]	2.97	3.04
Bulk density	[g/cm³]	1.36	0.05
Water content at -10hPa	[g/g]	0.33	0.02
Water content at -100hPa	[g/g]	0.27	0.02
Porosity	[% volume]	48.5	2.05
Pores over 15µm	[% volume]	12.26	1.69
Pores 15-150µm	[% volume]	8.69	0.65

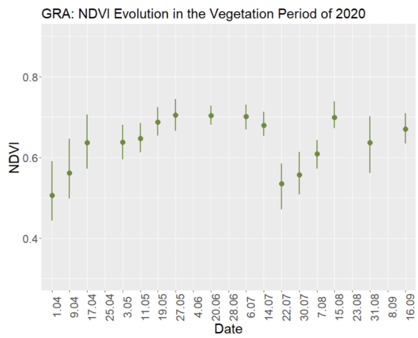
Results – NDVI classification

Spring	low
Summer	high

Top left: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Top right: Photo, 2021, Gruffydd Davies

Bottom left: Profile picture, 1991 from Laboratoire cantonal d'agronomie (1992)



SITE: HEN1

Park: Gustave et Léonard Hentsch

Centre Coordinates	2'498'306.393, 1'118'251.046

Characteristics:

Relief	level	
Vegetation	turf	
Soil origin	anthropogenic, 2015****	
Land Use	parc	
Underground Sealing	no	
Management level	no management	
Area [m²]		402.36

Results – Chemical Parameters

SOC	[% by mass]	2.299
SOC:Clay		0.17
N	[% by mass]	0.1599
pH		7.01

Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 13.4	Silt: 28.3	Sand: 38.3
Texture class		Loam		

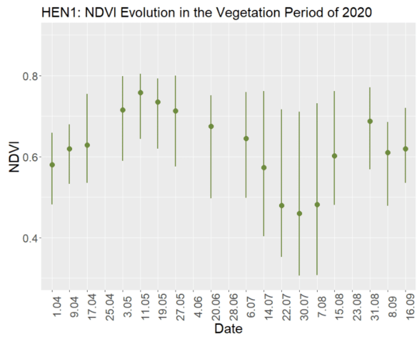
		Mean	Sd
Soil Depth	[cm]	38.00	39.33
Coarse fraction	[% by mass]	22.97	23.81
Bulk density	[g/cm³]	1.36	1.34
Water content at -10hPa	[g/g]	0.31	0.34
Water content at -100hPa	[g/g]	0.25	0.27
Porosity	[% volume]	48.58	49.52
Pores over 15µm	[% volume]	15.07	13.96
Pores 15-150µm	[% volume]	9.13	10.02

Results – NDVI classification

Spring	low
Summer	low

Top: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Bottom: Photo, 2021, Gruffydd Davies



SITE: HEN2

Park: Gustave et Léonard Hentsch

Centre Coordinates	2'498'153.388, 1'118'281.687

Characteristics:

Relief	top of slope	
Vegetation	turf	
Soil origin	anthropogenic, 2015****	
Land Use	parc	
Underground Sealing	yes	
Management level	moderate	
Area [m²]		482.94

Results – Chemical Parameters

SOC	[% by mass]	1.876
SOC:Clay		0.15
N	[% by mass]	0.1635
pH		6.5

Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 12.9	Silt: 52.2	Sand: 34.9
Texture class		Silty Loam		

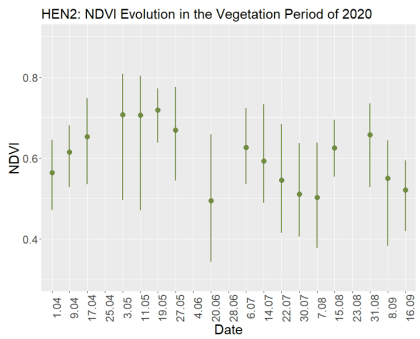
		Mean	Sd
Soil Depth	[cm]	39.33	9.29
Coarse fraction	[% by mass]	23.81	7.30
Bulk density	[g/cm³]	1.34	0.09
Water content at -10hPa	[g/g]	0.34	0.04
Water content at -100hPa	[g/g]	0.27	0.03
Porosity	[% volume]	49.52	3.39
Pores over 15µm	[% volume]	13.96	6.42
Pores 15-150µm	[% volume]	10.02	2.18

Results – NDVI classification

Spring	low
Summer	low

Top: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Bottom: Photo, 2021, Gruffydd Davies



SITE: TRE

Park: Trembley

Centre Coordinates	2'499'001.052, 1'119'389.366

Characteristics:

Relief	slope
Vegetation	turf
Soil origin	natural*
Land Use	parc
Underground Sealing	no
Management level	moderate
Area [m²]	804.48

Results – Chemical Parameters

SOC	[% by mass]	4.51
SOC:Clay		0.25
N	[% by mass]	0.4452
pH		6.38

Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 18.1 Silt: 64.9 Sand: 17
Texture class		Silty Loam

		Mean	Sd
Soil Depth	[cm]	>120	-
Coarse fraction	[% by mass]	1.48	2.18
Bulk density	[g/cm³]	1.12	0.08
Water content at -10hPa	[g/g]	0.50	0.06
Water content at -100hPa	[g/g]	0.42	0.05
Porosity	[% volume]	57.82	3.07
Pores over 15µm	[% volume]	11.38	2.62
Pores 15-150µm	[% volume]	9.07	0.62

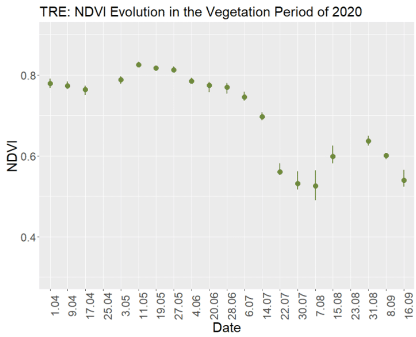
Results – NDVI classification

Spring	high
Summer	high

Top left: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Top right: Photo, 2021, Gruffydd Davies

Bottom left: Profile picture, 1991 from Laboratoire cantonal d'agronomie (1992)



SITE: VER1

Park: der Vermont

Centre Coordinates	2'499'760.448, 1'119'456.157

Characteristics:

Relief	slight slope
Vegetation	turf
Soil origin	natural***
Land Use	parc
Underground Sealing	no
Management level	moderate
Area [m²]	406.73

Results – Chemical Parameters

SOC	[% by mass]	4.14
SOC:Clay		0.19
N	[% by mass]	0.4097
pH		5.49

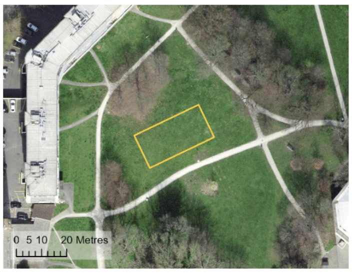
Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 21.3 Silt: 65.2 Sand: 13.5
Texture class		Silty Loam

		Mean	Sd
Soil Depth	[cm]	97.00	14.53
Coarse fraction	[% by mass]	0.69	1.01
Bulk density	[g/cm³]	1.12	0.05
Water content at -10hPa	[g/g]	0.48	0.06
Water content at -100hPa	[g/g]	0.39	0.04
Porosity	[% volume]	57.80	1.92
Pores over 15µm	[% volume]	14.86	1.43
Pores 15-150µm	[% volume]	10.91	1.81

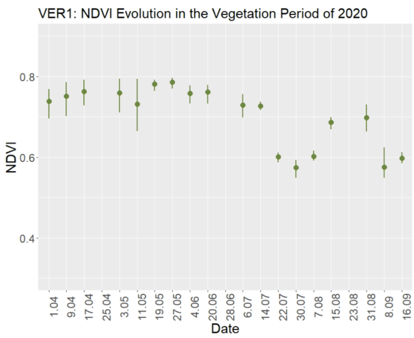
Results – NDVI classification

Spring	high
Summer	high



Top: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Bottom: Photo, 2021, Gruffydd Davies



SITE: VER2

Park: der Vermont

Centre Coordinates	2'499'805.135, 1'119'506.054

Characteristics:

Relief	foot of slope
Vegetation	turf
Soil origin	natural***
Land Use	parc
Underground Sealing	no
Management level	moderate
Area [m^2]	402.55

Results – Chemical Parameters

SOC	[% by mass]	4.552
SOC:Clay		0.22
N	[% by mass]	0.4682
pH		6.62

Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 20.9	Silt: 65.5	Sand: 13.6
Texture class		Silty Loam		

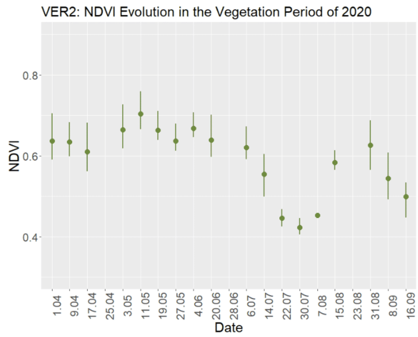
		Mean	Sd
Soil Depth	[cm]	>120	-
Coarse fraction	[% by mass]	1.56	1.58
Bulk density	[g/cm^3]	1.09	0.03
Water content at -10hPa	[g/g]	0.51	0.02
Water content at -100hPa	[g/g]	0.41	0.02
Porosity	[% volume]	58.88	0.94
Pores over 15µm	[% volume]	13.76	1.96
Pores 15-150µm	[% volume]	10.51	1.42

Results – NDVI classification

Spring	low
Summer	low

Top: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Bottom: Photo, 2021, Gruffydd Davies



SITE: VER3

Park: der Vermont

Centre Coordinates	2'499'716.394, 1'119'369.747

Characteristics:

Relief	level
Vegetation	turf
Soil origin	natural***
Land Use	parc
Underground Sealing	no
Management level	moderate
Area [m^2]	406.73

Results – Chemical Parameters

SOC	[% by mass]	5.474
SOC:Clay		0.23
N	[% by mass]	0.5164
pH		6.77

Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 23.9	Silt: 64.8	Sand: 11.3
Texture class		Silty Loam		

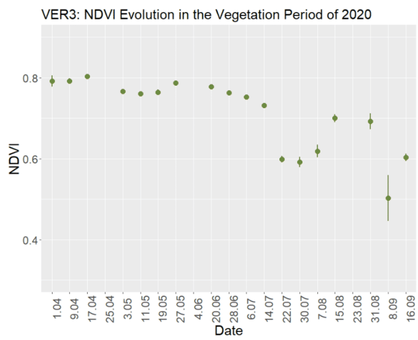
		Mean	Sd
Soil Depth	[cm]	97.67	2.31
Coarse fraction	[% by mass]	0.10	0.11
Bulk density	[g/cm^3]	1.04	0.06
Water content at -10hPa	[g/g]	0.55	0.04
Water content at -100hPa	[g/g]	0.46	0.04
Porosity	[% volume]	60.66	2.12
Pores over 15µm	[% volume]	12.8	2.10
Pores 15-150µm	[% volume]	9.38	2.05

Results – NDVI classification

Spring	high
Summer	high

Top: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Bottom: Photo, 2021, Gruffydd Davies



SITE: VER4

Park: der Vermont

Centre Coordinates: 2'499'787.942, 1'119'427.283

Characteristics:

Relief	slight slope
Vegetation	turf
Soil origin	natural***
Land Use	parc
Underground Sealing	no
Management level	moderate
Area [m^2]	406.55

Results – Chemical Parameters

SOC	[% by mass]	4.975
SOC:Clay		0.24
N	[% by mass]	0.4791
pH		6.16

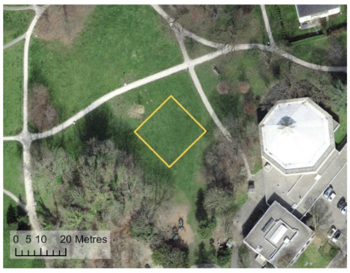
Results – Physical Parameters

Texture fractions	[% by mass]	Clay: 20.8 Silt: 66.3 Sand: 12.9
Texture class		Silty Loam

		Mean	Sd
Soil Depth	[cm]	>120	-
Coarse fraction	[% by mass]	0.55	0.7
Bulk density	[g/cm^3]	1.15	0.02
Water content at -10hPa	[g/g]	0.47	0.01
Water content at -100hPa	[g/g]	0.39	0.01
Porosity	[% volume]	56.47	0.85
Pores over 15µm	[% volume]	11.97	1.8
Pores 15-150µm	[% volume]	9.5	0.69

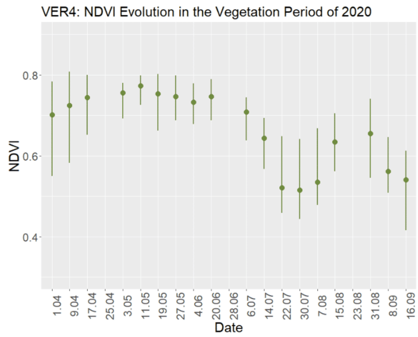
Results – NDVI classification

Spring	high
Summer	high

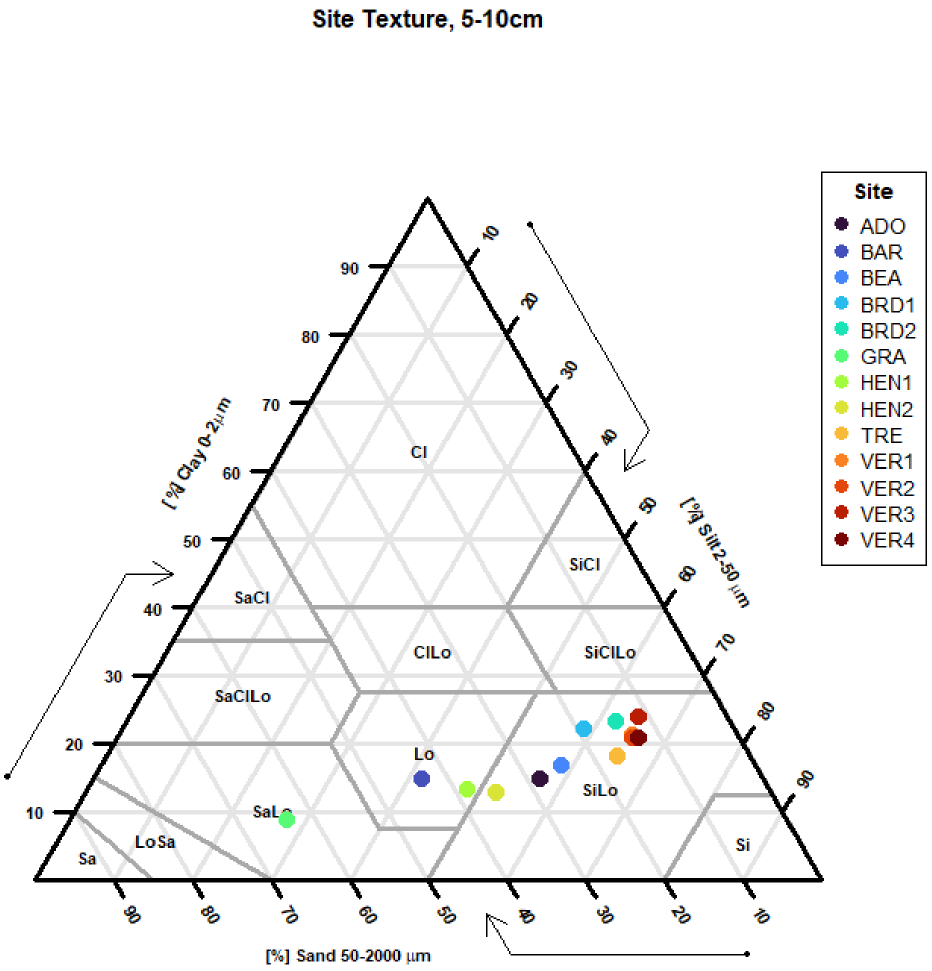


Top: Orthophoto, 2020 adapted from SWISSIMAGE 10cm ©swisstopo

Bottom: Photo, 2021, Gruffydd Davies



Appendix 3. Soil Texture Diagram



Appendix 4. Data from 0-5cm Depth Range

Site	Sand [% by mass]	Silt [% by mass]	Clay [% by mass]	Nitrogen [% by mass]	Carbon [% by mass]	pH	BD [g/cm^3]	W_{10} [g/g]	W_{100} [g/g]	A_{100} [% by volume]	Coarse Fraction [% by mass]
ADO	33.3	50.3	16.4	0.3219	5.142	6.78	1.19	0.41	0.33	0.13	19.72
BAR	29.6	54.5	15.9	0.4344	4.484	6.48	0.82	0.75	0.50	0.35	1.34
BEA	33.5	53.4	13.1	0.5616	7.46	6.65	0.93	0.60	0.49	0.21	0.97
GRA	61	29.72	9.28	0.3143	5.678	6.87	-	-	-	-	-
HEN1	48.1	37.7	14.2	0.2394	3.478	6.96	1.22	0.36	0.28	0.16	15.33
TRE	25.5	62.4	12.1	0.5944	6.61	6.25	0.99	0.60	0.51	0.13	0.00
VER1	27.7	50.1	22.2	0.6355	6.785	5.64	0.87	0.73	0.57	0.20	-0.01
VER2	34.9	45.7	19.4	0.5195	5.204	6.15	0.95	0.62	0.50	0.17	0.09
VER3	24.9	61	14.1	0.6401	6.966	6.34	0.83	0.67	0.52	0.31	0.00
VER4	12.2	67.7	20.1	0.6471	6.738	5.24	0.99	0.58	0.48	0.16	0.08

The sample of the site GRA broke while being equilibrated at -100hPa, which is why no data retrieved from the undisturbed sample is included.

Appendix 5. R-Script

Appendix 5.1 Visualisation of Data from Undisturbed Samples

```
############################################################
##                                                        ##
##    Descriptive Statistics, undisturbed samples         ##
##                                                        ##
############################################################
# April 2022, Manon Davies

#######################################################
#####             Import Data                     #####
#######################################################

#Set working directory
setwd("…")

#load libraries
library("ggplot2")
library("ggpattern")


#Import Data
undist <- read.csv("Data_Undist_Clean.csv", header=TRUE, sep = ",")

undist_5_10 <- undist [undist$Depth==5,] #Samples from 5 to 10cm
undist_0_5 <- undist [undist$Depth==0,] #Samples from 0 to 5cm

#######################################################
#####       Dataframe: Mean and Sd                #####
#######################################################

#values for fact sheets - mean and sd for each parc
library(data.table)

factsheet <- subset(undist_5_10, select = c(Site, BDcorr, Pcorr, W10, WV10, W100, WV100, A1
00, AV100, Grobporen, Skelett.content))
factsheet <- data.table(factsheet)
fs_Mean <- factsheet[ , lapply(.SD, mean), by = Site] #Calculate Mean

fs_Sd <- factsheet[ , lapply(.SD, sd), by = Site] #Calculate standard deviation
fs_Sd <- setnames(fs_Sd, c("Site","SdBDcorr", "SdPcorr", "SdW10", "SdWV10", "SdW100","SdWV1
00", "SdA100", "SdAV100", "SdMegapores", "SdSkelett"))


#mergetables
factsheet_all <- merge(fs_Mean, fs_Sd,by="Site")
factsheet_all

#export to csv
#write.csv(…)



#######################################################
##                 BOXPLOTS                          ##
#######################################################
# read to rearrange order of sites according to NDVi class in summer:
#low first
undist_5_10$Site <- factor(undist_5_10$Site, levels=c("ADO", "HEN1", "HEN2","VER2", "BAR",
"GRA", "BEA", "BRD1", "BRD2", "TRE", "VER1", "VER3", "VER4"))
#high first
undist_5_10$Site <- factor(undist_5_10$Site, levels=c("BEA", "BRD1", "BRD2", "TRE", "VER1",
"VER3", "VER4", "GRA", "ADO", "HEN1", "HEN2","VER2", "BAR"))
```

```
#######################################################
#####                  BD                         #####
#######################################################

BD_plot <- ggplot(undist_5_10, aes(x = Site, y = BDcorr, fill=NDVI_Class_Summer)) +
  geom_boxplot_pattern(
    aes(pattern= NDVI_Class_Spring),
    colour  = 'black',
    pattern_fill = "black",
    pattern_density= 0.2,
    pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  stat_summary(fun.y="mean",color="black", shape=23)+
  theme(axis.text=element_text(size=13),
        axis.title=element_text(size=16))+
  labs(x="Site", y="Bulk Density \n [g/cm3]", fill="NDVI class in Summer", pattern="NDVI cl
ass in Spring")+
  geom_point(aes(shape="mean"), alpha = 0)+
  guides(shape=guide_legend(title=NULL, order=2, override.aes = list(shape= 23, alpha = 1))
)
BD_plot

#######################################################
#####             Porosity                        #####
#######################################################

#boxplot porosities 2mm
Pcorr <- ggplot(undist_5_10, aes(x = Site, y = Pcorr)) +
  geom_boxplot() +
  labs(title="Porosity of each site, 5-10cm", x="Site", y="Corrected Porosity")
Pcorr #not kept in final study, as nearly same as BD


#### WATER CONTENT ####

#######################################################
#####     Water content at -10hPa                 #####
#######################################################


##GRAVIMETRIC WATER CONTENT
W10 <- ggplot(undist_5_10, aes(x = Site, y = W10)) +
  geom_boxplot() +
  labs(title="Gravimetric water content at -10hPa for each site", x="Site", y="gravimetric
Water content -10hPa [g/cm3]")
W10

#not kept



#######################################################
#####      Water content at -100hPa               #####
#######################################################


#GRAVIMETRIC WATER CONTENT

#Boxplot  with colors/texture according to NDVI class in spring and summer
W100_plot <- ggplot(undist_5_10, aes(x = Site, y = W100, fill=NDVI_Class_Summer)) +
  geom_boxplot_pattern(
    aes(pattern= NDVI_Class_Spring),
```

```
    colour  = 'black',
    pattern_fill = "black",
    pattern_density= 0.2,
    pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  stat_summary(fun.y="mean",color="black", shape=23)+
  theme(axis.text=element_text(size=13),
        axis.title=element_text(size=16))+
  labs(x="Site", y="Gravimetric Water Content at -100hPa \n [g/g]", fill="NDVI class in Sum
mer", pattern="NDVI class in Spring") +
  geom_point(aes(shape="mean"), alpha = 0)+ #have a legend for the mean
  guides(shape=guide_legend(title=NULL, order=2, override.aes = list(shape= 23, alpha = 1))
)

#######################################################
#####      Air content at -100hPa                #####
#######################################################

#Boxplot  with colors/texture according to NDVI class in spring and summer
AV100_colors <- ggplot(undist_5_10, aes(x = Site, y = AV100, fill=NDVI_Class_Summer)) +
  geom_boxplot_pattern(
    aes(pattern= NDVI_Class_Spring),
    colour  = 'black',
    pattern_fill = "black",
    pattern_density= 0.2,
    pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  stat_summary(fun.y="mean",color="black", shape=23)+
  geom_point(aes(shape="mean"), alpha = 0)+
  guides(shape=guide_legend(title=NULL, order=2, override.aes = list(shape= 23, alpha = 1))
)+
  theme(axis.text=element_text(size=13),
        axis.title=element_text(size=16))+
  labs(x="Site", y="Pores > 15µm \n [% by volume]", fill="NDVI class in Summer", pattern="N
DVI class in Spring")

#######################################################
#####    Coarse fraction and Artefacts            #####
#######################################################


##Coarse fraction Content (all >2mm, = gravel + artefacts) ##

#Boxplot  with colors/texture according to NDVI class in spring and summer

coarse_plot <- ggplot(undist_5_10, aes(x = Site, y = Skelett.content, fill=NDVI_Class_Summe
r)) +
  geom_boxplot_pattern(
    aes(pattern= NDVI_Class_Spring),
    colour  = 'black',
    pattern_fill = "black",
    pattern_density= 0.2,
    pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  stat_summary(fun.y="mean",color="black", shape=23)+
  geom_point(aes(shape="mean"), alpha = 0)+
  guides(shape=guide_legend(title=NULL, order=2, override.aes = list(shape= 23, alpha = 1))
```

```
)+
  theme(axis.text=element_text(size=13),
        axis.title=element_text(size=16))+
  labs( x="Site", y="Coarse Material \n [% by mass]", fill="NDVI class in Summer", pattern=
"NDVI class in Spring")

## Gravel Content
Gravel <- ggplot(undist_5_10, aes(x = Site, y = Gravel.content)) +
  geom_boxplot() +
  labs(title="", x="Site", y="weight % of Gravel")
Gravel

##Artefact content
Artefact <- ggplot(undist_5_10, aes(x = Site, y = Artefact.content)) +
  geom_boxplot() +
  labs(title="", x="Site", y="weight % of Artefacts")
Artefact

#not kept separate as only one site with significant amounts of artefacts
```

Appendix 5.2 Visualisation of data from disturbed samples and soil depth

```
#################################################################
##               VISUALISATION of DISTURBED SAMPLES            ##
##                       and SOIL DEPTH                        ##
#################################################################
# Manon Davies
# 03.2022
# Soil texture triangle adapted from a script by Laura Summerauer (01.2020)

#set working directory
setwd("…")


#################################################################
##                     TEXTURE TRIANGLE                        ##
#################################################################

####  Read files    ####

#import files
texture_data <- read.csv("texture_data_summarized_withdepth.csv", header=TRUE, sep=",")

#run for 5-10 samples:
texture_data <- texture_data[texture_data$depth==5,]

#run for 0-5 samples:
#texture_data <- texture_data[texture_data$depth==0,]



####  Visualization in a texture triangle     ####

#install.packages("soiltexture")
# load package
library(soiltexture)

## Warning: package 'soiltexture' was built under R version 3.6.3

# prepare data as required by the package and it's functions
tt_data <- data.frame(texture_id = texture_data[,"texture_id"])
tt_data$CLAY = texture_data$usda_clay
tt_data$SILT = texture_data$usda_silt
tt_data$SAND = texture_data$usda_sand
```

```
#set color theme
library(viridis)

## Loading required package: viridisLite

## Warning: package 'viridisLite' was built under R version 3.6.3

## Registered S3 methods overwritten by 'tibble':
##   method     from
##   format.tbl pillar
##   print.tbl  pillar

colors <- turbo(13, alpha = 1, begin = 0, end = 1, direction = 1)


#Texture triangle:

TT.plot(class.sys = "USDA.TT",
        tri.data = tt_data,
        main = "Site Texture, 5-10cm",
        col = colors,
        frame.bg.col = "white", #background color
        class.line.col = "dark grey", #line color
        class.lab.col ="black", #color of texture class names
        pch = 16, #dots as markers
        cex.lab = 0.7, cex = 1.5, cex.axis = 0.7, cex.main = 1,  # edit text/labels sizes
        lwd.lab = 1)

# The legend:
legend(
        x = 100,
        y = 90,
        title = expression(bold("Site")),
        legend = tt_data$texture_id, #names next to dots
        #text.font = 2,
        col = colors,
        pt.cex = 1.3, #how big dots are
        pch = 19, #shape of dots
        bty = "o",
        bg = NA,
        #box.col = NA, # Uncomment this to remove the legend box
        text.col = "black",
        text.font = 1,
        cex = 0.9 #general scaling of legend
)

#################################################################
##             BARPLOTS for Disturbed Soil Properties          ##
#################################################################
#libraries
library(ggplot2)
library(ggpattern)

#reorder Sites by NDVI class in summer
#low first
#texture_data$texture_id <- factor(texture_data$texture_id, levels=c("ADO", "HEN1", "HEN2",
"VER2", "BAR", "GRA", "BEA", "BRD1", "BRD2", "TRE", "VER1", "VER3", "VER4"))
#high first
texture_data$texture_id <- factor(texture_data$texture_id, levels=c("BEA", "BRD1", "BRD2",
"TRE", "VER1", "VER3", "VER4", "GRA", "ADO", "HEN1", "HEN2","VER2", "BAR"))

#################################################################
##                  C and N Visualisation                      ##
#################################################################

## C ##
```

```
carbon_plot <- ggplot(texture_data, aes(x = texture_id, y = carbon, fill=NDVI_Class_Summer)
) +
        geom_col_pattern(
                aes(pattern= NDVI_Class_Spring),
                colour  = 'black',
                pattern_fill = "black",
                pattern_density= 0.2,
                pattern_spacing = 0.01) +
        scale_pattern_manual(
                values = c("none", "stripe"),
                guide = guide_legend(override.aes = list(fill = "grey70")))+
        scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                          guide = guide_legend(override.aes = list(pattern = "none")))+
        theme(axis.text=element_text(size=13),
              axis.title=element_text(size=16))+
        labs(x="Site", y="Carbon Content \n [% by mass]", fill="NDVI class in Summer", patt
ern="NDVI class in Spring")

carbon_plot



## N ##

nitrogen_plot <- ggplot(texture_data, aes(x = texture_id, y = nitrogen, fill=NDVI_Class_Sum
mer)) +
        geom_col_pattern(
                aes(pattern= NDVI_Class_Spring),
                colour  = 'black',
                pattern_fill = "black",
                pattern_density= 0.2,
                pattern_spacing = 0.01) +
        scale_pattern_manual(
                values = c("none", "stripe"),
                guide = guide_legend(override.aes = list(fill = "grey70")))+
        scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                          guide = guide_legend(override.aes = list(pattern = "none")))+
        theme(axis.text=element_text(size=13),
              axis.title=element_text(size=16))+
        labs(x="Site", y="Nitrogen Content \n [% by mass]", fill="NDVI class in Summer", pa
ttern="NDVI class in Spring")

nitrogen_plot

## C:N ratio ##

CN_plot <- ggplot(texture_data, aes(x = texture_id, y = CN, fill=NDVI_Class_Summer)) +
        geom_col_pattern(
                aes(pattern= NDVI_Class_Spring),
                colour  = 'black',
                pattern_fill = "black",
                pattern_density= 0.2,
                pattern_spacing = 0.01) +
        scale_pattern_manual(
                values = c("none", "stripe"),
                guide = guide_legend(override.aes = list(fill = "grey70")))+
        scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                          guide = guide_legend(override.aes = list(pattern = "none")))+
        theme(axis.text=element_text(size=13),
              axis.title=element_text(size=16))+
        labs(x="Site", y="C/N ratio", fill="NDVI class in Summer", pattern="NDVI class in S
pring")

CN_plot
```

```
################################################################
##                  Soil Depth Visualisation                  ##
################################################################

sdepth_plot <- ggplot(texture_data, aes(x = texture_id, y = soil_depth, fill=NDVI_Class_Sum
mer)) +
        geom_col_pattern(
                aes(pattern= NDVI_Class_Spring),
                colour  = 'black',
                pattern_fill = "black",
                pattern_density= 0.2,
                pattern_spacing = 0.01) +
        scale_pattern_manual(
                values = c("none", "stripe"),
                guide = guide_legend(override.aes = list(fill = "grey70")))+
        scale_fill_manual(values=c("darkolivegreen4", "darkorange"),
                          guide = guide_legend(override.aes = list(pattern = "none")))+
        theme(axis.text=element_text(size=13),
              axis.title=element_text(size=16))+
        geom_errorbar(aes(ymin=soil_depth-soil_depth_sd, ymax=soil_depth+soil_depth_sd), wi
dth=0.5)+
        labs(x="Site", y="Soil Depth \n [cm]", fill="NDVI class in Summer", pattern="NDVI c
lass in Spring")

sdepth_plot
```

Appendix 5.3 Comparison of Means and Correlations

```
################################################################
##     Correlation between chemical and physical parameters    ##
##     T-tests Soil Properties and NDVI value classes          ##
################################################################
# Manon Davies, Mai 2022

#use ggplot
library(ggplot2)
library(ggpattern)

#set working directory
setwd("C:/Users/manon/OneDrive - ETHZ/Desktop/ETH/7. Semester/Bachelorarbeit/Data_und_Stati
stik")

#read data
dt<- read.csv("mean_sd__allproperties.csv", header=TRUE, sep=",")


################################################################
##                  1. CHEMICAL AND PHYSICAL                  ##
##                      PARAMETERS                            ##
################################################################
#cor.test does the pearson test
#assumptions to check for pearson test:
# 1. Samples are random & independant OK
# 2. Both variables are continuous data OK
# 3. Related Pairs (each observation is a related pair) OK
# 4. Normality: # Bivariate normality - for each x, the y are normally distributed
  # check with qqplots or shapiro test  - if not: use spearman test
# 5. no outliers
    #check with boxplot (one for each variable)


################################################################
##                      C and W100                           ##
################################################################
#normality assumption:
```

```
shapiro.test(dt$W100)
shapiro.test(dt$carbon)
#over 0.05 --> ok

#check outliers
boxplot(dt$W100) # no outliers
boxplot(dt$carbon) #outliers but not far?

#pearson correlation
cor.test(dt$W100, dt$carbon)
#p = 0.01043: significant
0.6807216 ^2
#r2 = 0.57314

#plot

C_WV100 <- ggplot(dat=dt, aes(x=WV100, y=carbon))+
  geom_point()+
  geom_smooth(method="lm", se=FALSE, col="darkolivegreen4") + #where se=false takes away th
e standard error lines
  labs(title="Correlation: carbon content and water content", x="Water content at -100hPa \
n [g/g]", y="Carbon Content \n [% by mass]")+
  theme(text = element_text(size = 17))+
  geom_label(aes(x = 0.385, y = 5.7), hjust = 0, size=6,
           label = paste("Pearson Correlation:",
                         "\n     p value =",0.0104,
                         "\n     Rsqu =", 0.46,
                         "\n     n = 13"))
C_WV100


#################################################################
##                       C and BD                              ##
#################################################################

#check normality assumption:
shapiro.test(ldt$BDcorr)
shapiro.test(log(dt$BDcorr))
shapiro.test(dt$carbon)
#BD corr: under 0.05 --> not normally distributed
# log tranformation - still not normally distributed

#spearman correlation:
cor.test(dt$BDcorr, dt$carbon, method = "spearman")
#p=0.3835 --> not significant
#no R2 value

C_BD <- ggplot(dat=dt, aes(x=BDcorr, y=carbon))+
  geom_point()+
  geom_smooth(method="lm", se=FALSE, col="darkolivegreen4")+
  labs(title="Correlation: Carbon content and Bulk density", x="Bulk density \n [g/cm3]", y
="Carbon Content \n [% by mass]")+
  theme(text = element_text(size = 17))+
  geom_label(aes(x = 1.17, y = 6), hjust = 0, size = 6,
             label = paste("Spearman Correlation:",
                           "\n     p value =",0.38,
                           "\n     n = 13"))
C_BD


#################################################################
##                  C and Clay content                         ##
#################################################################
#check normality assumption:
qqnorm(dt$usda_clay)
shapiro.test(dt$usda_clay)
```

```
shapiro.test(dt$carbon)
#over 0.05 --> ok

#chech for outliers:
boxplot(dt$usda_clay)
#ok

#pearson correlation:
cor.test(dt$usda_clay, dt$carbon)
0.5214507^2
#P = 0.06762: not significant
#R2 = 0.2719108

C_clay <- ggplot(dat=dt, aes(x=usda_clay, y=carbon))+
  geom_point()+
  geom_smooth(method="lm", se=FALSE, col= "darkolivegreen4")+
  labs(title="Correlation: Carbon content and Clay content", x="Clay Content \n [% by mass]
", y="Carbon Content \n [% by mass]")+
  theme(text = element_text(size = 17)) +
  geom_label(aes(x = 14, y = 5.8), hjust = 0, size= 6,
             label = paste("Pearson Correlation:",
                           "\n     p value =",0.068,
                           "\n     Rsqu =", 0.27,
                           "\n     n = 13"))
C_clay

#################################################################
##                      C and AV100                            ##
#################################################################
#check normality assumption:
qqnorm(dt$AV100)
shapiro.test(dt$AV100)
shapiro.test(dt$carbon)
#over 0.05 --> ok

#check outliers:
boxplot(dt$AV100)
#ok

#pearson correlation:
cor.test(dt$AV100, dt$carbon)

#p= 0.04207 --> significant
(-0.5697646)^2
#R^2 = 0.3246317

C_AV100 <- ggplot(dat=dt, aes(x=AV100, y=carbon))+
  geom_point()+
  geom_smooth(method="lm", se=FALSE, col= "darkolivegreen4")+
  labs(title="Correlation: Carbon content and pores >15µm", x="Pores >15µm \n [cm3/cm3]", y
="Carbon Content \n [% by mass]")+
  theme(text = element_text(size = 17)) +
  geom_label(aes(x = 13.3, y = 5.8), hjust = 0, size=6,
             label = paste("Pearson Correlation:",
                           "\n     p value =",0.042,
                           "\n     Rsq=", 0.32,
                           "\n     n = 13"))
C_AV100



#################################################################
##                      W100 and BD                            ##
#################################################################

#check normality assumption:
```

```
qqnorm(dt$W100)
shapiro.test(dt$W100)

qqnorm(dt$BDcorr)
shapiro.test(dt$BDcorr)
# p < 0.05 --> not normally distributed

#significant

# as not normally distributed: use spearman:
cor.test(dt$W100, dt$BDcorr, method="spearman")
#p-value < 2.2e-16 --> significant

#plot
BD_W100 <- ggplot(dat=dt, aes(x=BDcorr, y=W100))+
  geom_point()+
  geom_smooth(method="lm", se=FALSE, col= "darkolivegreen4")+
  labs(title="Correlation: Bulk density and Water content at -100hPa", x="Bulk Density [g/c
m3]", y="Water Content at -100hPa \n [g/g]")+
  theme(text = element_text(size = 17)) +
  geom_label(aes(x = 1.16, y = 0.445), hjust = 0, size=6,
             label = paste("Spearman Correlation:",
                           "\n     p value <", 2.2e-16,
                           "\n     n = 13"))
BD_W100

#################################################################
##                COARSE MATERIAL and BD                      ##
#################################################################


#check normality assumption:
qqnorm(dt$Skelett.content)
shapiro.test(dt$Skelett.content)
qqnorm(dt$BDcorr)
shapiro.test(dt$BDcorr)
# p < 0.05 --> not normally distributed


# as not normally distributed: use spearman:
cor.test(dt$Skelett.content, dt$BDcorr, method="spearman")
#p-value = 0.01713 --> significant

#plot
BD_W100 <- ggplot(dat=dt, aes(x=BDcorr, y=Skelett.content))+
  geom_point()+
  geom_smooth(method="lm", se=FALSE, col= "darkolivegreen4")+
  labs(title="Correlation: Bulk density and Coarse Material", x="Bulk Density [g/cm3]", y="
Coarse material \n [% by mass]")+
  theme(text = element_text(size = 17)) +
  geom_label(aes(x = 1.16, y = 22), hjust = 0, size=6,
             label = paste("Spearman Correlation:",
                           "\n     p value =", 0.017,
                           "\n     n = 13"))
BD_W100


#################################################################
##                COARSE MATERIAL and W100                      ##
#################################################################


#check normality assumption:
qqnorm(dt$Skelett.content)
shapiro.test(dt$Skelett.content)
qqnorm(dt$W100)
```

```
shapiro.test(dt$W100)
# p < 0.05 --> not normally distributed


# as not normally distributed: use spearman:
cor.test(dt$Skelett.content, dt$W100, method="spearman")
#p-value = 0.0033981 --> significant

#plot
Coarse_W100 <- ggplot(dat=dt, aes(x=W100, y=Skelett.content))+
  geom_point()+
  geom_smooth(method="lm", se=FALSE, col= "darkolivegreen4")+
  labs(title="Correlation: Water content at -100hPa and Coarse Material", x="Water content
at -100hPa \n [g/g]", y="Coarse material \n [% by mass]")+
  theme(text = element_text(size = 17)) +
  geom_label(aes(x = 0.32, y = 22), hjust = 0, size=6,
             label = paste("Spearman Correlation:",
                           "\n     p value =", 0.0040,
                           "\n     n = 13"))
Coarse_W100


#################################################################
##                  2. NDVIs and SOIL                          ##
##                      PARAMETERS                             ##
#################################################################
### PREPARE DATA###
#take out parc with no NDVI values
dt1 <- dt[-c(5),]


#################################################################
##           NDVI class in Summer and Soil Properties          ##
#################################################################

# only got two groups (good/bad): use t-test
# unpaired t-test, we want to compare means of two groups
# use welch's t-test, as it doesn't assume that the variance of the two groups are equal

#Assumptions of the test:
# 1. Independence of the observations. Each subject should belong to only one group. There
is no relationship between the observations in each group.
# 2. No significant outliers in the two groups
# 3. Normality. the data for each group should be approximately normally distributed.

#If data not normally distirbutes: use wilcoxon test


#######################################
##   SOIL DEPTH AND NDVI in SUMMER   ##
#######################################

### t.test/ wilcoxon test ####
#prepare data
depth_highNDVI_summer <- subset(dt1$soil_depth, dt1$NDVI_class_summer=="high")
depth_lowNDVI_summer <- subset(dt1$soil_depth, dt1$NDVI_class_summer=="low")

# check normality assumption
shapiro.test(depth_highNDVI_summer)
shapiro.test(depth_lowNDVI_summer)
#p<0.5 --> not normally distributed

##QQpot
qqnorm(depth_highNDVI_summer)
qqnorm(depth_lowNDVI_summer)
#also visible in QQplot that data is not normally distributed
```

```
#as data not normally distributed: Wilcoxon test
wilcox.test(depth_highNDVI_summer,depth_lowNDVI_summer, paired=FALSE)
#p=0.04331: significant difference in means

#prepare plot data
mean_soil_depth <- c(mean(depth_highNDVI_summer),mean(depth_lowNDVI_summer))
NDVI_class <- c("high", "low")
sd_soil_depth <- c(sd(depth_highNDVI_summer),sd(depth_lowNDVI_summer))
signi <- c("a", "b")
df <- data.frame(mean_soil_depth, NDVI_class, sd_soil_depth, signi)

#plot
plot_depth_summer <- ggplot(df, aes(x=NDVI_class, y=mean_soil_depth))+
  geom_col(fill=c("darkolivegreen4", "darkorange")) +
  labs(title="", x="NDVI class in Summer", y="Mean Soil Depth \n [cm]")+
  coord_cartesian(, ylim = c(0, 140)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_soil_depth-sd_soil_depth, ymax=mean_soil_depth+sd_soil_depth)
, width=0.5)+
  geom_text(aes(label=signi, y=mean_soil_depth+sd_soil_depth), vjust = -2, size=5)
plot_depth_summer



#######################################
##   COARSE FRACTION AND NDVI SUMMER ##
#######################################
# t.test/wilcoxon test ####
coarse_highNDVI_summer <- subset(dt1$Skelett.content, dt1$NDVI_class_summer=="high")
coarse_lowNDVI_summer <- subset(dt1$Skelett.content, dt1$NDVI_class_summer=="low")
boxplot(coarse_lowNDVI_summer, coarse_highNDVI_summer)

#check assumptions:
#without log: not normally distrbuted: so transformed to log
#normality:
qqnorm(coarse_highNDVI_summer) #nope
qqnorm(coarse_lowNDVI_summer) #nope

shapiro.test(coarse_highNDVI_summer)
#normally distributed
shapiro.test(coarse_lowNDVI_summer)
#not normally distributed

#not normally distributed data --> use wilcoxon test
wilcox.test(coarse_highNDVI_summer, coarse_lowNDVI_summer)
# p value = 0.0101 --> significant


#prepare plot data
mean_coarse <- c(mean(coarse_highNDVI_summer),mean(coarse_lowNDVI_summer))
NDVI_class <- c("high", "low")
sd_coarse <- c(sd(coarse_highNDVI_summer),sd(coarse_lowNDVI_summer))
signi <- c("a", "b")
dfcoarse <- data.frame(mean_coarse, NDVI_class, sd_coarse, signi)
dfcoarse

#actual plot
plot_coarse_summer <- ggplot(dfcoarse, aes(x=NDVI_class, y=mean_coarse))+
  geom_col(fill=c("darkolivegreen4", "darkorange")) +
  labs(x="NDVI class in Summer", y="Mean Coarse Material \n [% by mass]")+
  coord_cartesian(, ylim = c(-2, 30)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_coarse-sd_coarse, ymax=mean_coarse+sd_coarse), width=0.5)+
  geom_text(aes(label=signi, y=mean_coarse+sd_coarse), vjust = -2, size=5)
```

```
plot_coarse_summer


#######################################
##      BD  AND NDVI SUMMER          ##
#######################################
# t.test/wilcoxon test ####
BD_highNDVI_summer <- subset(dt1$BDcorr, dt1$NDVI_class_summer=="high")
BD_lowNDVI_summer <- subset(dt1$BDcorr, dt1$NDVI_class_summer=="low")

#check assumptions:
#normality:
qqnorm(BD_highNDVI_summer)
qqnorm(BD_lowNDVI_summer)

shapiro.test(BD_highNDVI_summer)
#p: 0.02 --> not normally distributed
shapiro.test(BD_lowNDVI_summer)
#normally distributed


#not normally distributed data --> use wilcoxon test
wilcox.test(BD_highNDVI_summer, BD_lowNDVI_summer)
# p value = 0.34 --> not significant

#prepare plot data
mean_BD <- c(mean(BD_highNDVI_summer),mean(BD_lowNDVI_summer))
NDVI_class <- c("high", "low")
sd_BD<- c(sd(BD_highNDVI_summer),sd(BD_lowNDVI_summer))
signi <- c("a", "a")
dfBD <- data.frame(mean_BD, NDVI_class, sd_BD, signi)
dfBD

#plot
plot_BD_summer <- ggplot(dfBD, aes(x=NDVI_class, y=mean_BD))+
  geom_col(fill=c("darkolivegreen4", "darkorange")) +
  labs(title="", x="NDVI class in Summer", y="Bulk Density \n [g/cm3]")+
  coord_cartesian(, ylim = c(0, 1.75)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_BD-sd_BD, ymax=mean_BD+sd_BD), width=0.5)+
  geom_text(aes(label=signi, y=mean_BD+sd_BD), vjust = -2, size=5)
plot_BD_summer


#######################################
##         CARBON AND SUMMER         ##
#######################################

#t.test / wilcoxon test:####

c_highNDVI_summer <- subset(dt1$carbon, dt1$NDVI_class_summer=="high")
c_lowNDVI_summer <- subset(dt1$carbon, dt1$NDVI_class_summer=="low")

#check normality:
shapiro.test(c_lowNDVI_summer)
shapiro.test(c_highNDVI_summer)
#both normally distributed as p> 0.5
qqnorm(c_lowNDVI_summer)
qqnorm(c_highNDVI_summer)

#t.test
t.test(c_highNDVI_summer,c_lowNDVI_summer, paired=FALSE)
#not significant

#plot preparation
mean_c <- c(mean(c_highNDVI_summer),mean(c_lowNDVI_summer))
```

```
NDVI_class <- c("high", "low")
sd_c <- c(sd(c_highNDVI_summer),sd(c_lowNDVI_summer))
signi <- c("a", "a")
dfc <- data.frame(mean_c, NDVI_class, sd_c, signi)
dfc

#plot
plot_c_summer <- ggplot(dfc, aes(x=NDVI_class, y=mean_c))+
  geom_col(fill=c("darkolivegreen4", "darkorange")) +
  labs(x="NDVI class in Summer", y="Mean Carbon Content \n [% by mass]")+
  coord_cartesian(, ylim = c(0, 7)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_c-sd_c, ymax=mean_c+sd_c), width=0.5)+
  geom_text(aes(label=signi, y=mean_c+sd_c), vjust = -2, size=5)

plot_c_summer

#######################################
##          W100 AND SUMMER         ##
#######################################
# t.test/wilcoxon test ####
W100_highNDVI_summer <- subset(dt1$W100, dt1$NDVI_class_summer=="high")
W100_lowNDVI_summer <- subset(dt1$W100, dt1$NDVI_class_summer=="low")


#check assumptions:
#normality:
qqnorm(W100_highNDVI_summer)
qqnorm(W100_lowNDVI_summer)

shapiro.test(W100_highNDVI_summer)
shapiro.test(W100_lowNDVI_summer)
#p>0.05 --> normally distributed

#t.test
t.test(W100_highNDVI_summer, W100_lowNDVI_summer, paired =FALSE)
# p value = 0.1301 --> not significant

#plot praparation
mean_W100 <- c(mean(W100_highNDVI_summer),mean(W100_lowNDVI_summer))
NDVI_class <- c("high", "low")
sd_W100 <- c(sd(W100_highNDVI_summer),sd(W100_lowNDVI_summer))
signi <- c("a", "a")
dfw100 <- data.frame(mean_W100, NDVI_class, sd_W100, signi)
dfw100

#plot
plot_W100_summer <- ggplot(dfw100, aes(x=NDVI_class, y=mean_W100))+
  geom_col(fill=c("darkolivegreen4", "darkorange")) +
  labs(title="", x="NDVI class in Summer", y="Gravimetric Water Content at -100hPa \n [g/g]
")+
  coord_cartesian(, ylim = c(0, 0.55)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_W100-sd_W100, ymax=mean_W100+sd_W100), width=0.5)+
  geom_text(aes(label=signi, y=mean_W100+sd_W100), vjust = -2, size=5)

plot_W100_summer


#######################################
##          AV100 AND SUMMER         ##
#######################################
# t.test/wilcoxon test ####
AV100_highNDVI_summer <- subset(dt1$Av100, dt1$NDVI_class_summer=="high")
AV100_lowNDVI_summer <- subset(dt1$AV100, dt1$NDVI_class_summer=="low")
```

```
#check assumptions:
#normality:
qqnorm(AV100_highNDVI_summer)
qqnorm(AV100_lowNDVI_summer)

shapiro.test(AV100_highNDVI_summer)
shapiro.test(AV100_lowNDVI_summer)
#p>0.05 --> normally distributed

#t.test
t.test(AV100_highNDVI_summer, AV100_lowNDVI_summer, paired =FALSE)
# p value = 0.39 --> not significant (with A100 instead of AV00: p=0.83)


#################################################################
##           NDVI class in Spring and Soil Properties          ##
#################################################################
#tests: same logic as NDVI class in summer

####################################
####   SOIL DEPTH AND SPRING    ####
####################################

## t.test/ wilcoxon test ####

depth_highNDVI_spring <- subset(dt1$soil_depth, dt1$NDVI_class_spring=="high")
depth_lowNDVI_spring <- subset(dt1$soil_depth, dt1$NDVI_class_spring=="low")

#check normality:
shapiro.test(depth_highNDVI_spring)
shapiro.test(depth_lowNDVI_spring)
#both not normally distributed as p < 0.5
qqnorm(depth_highNDVI_spring)
qqnorm(depth_lowNDVI_spring)


#not normal distribution: wilcoxon test
wilcox.test(depth_highNDVI_spring, depth_lowNDVI_spring, paired = FALSE)
#p = 0.61 -> not significant


#plot preparation
mean_depth <- c(mean(depth_highNDVI_spring),mean(depth_lowNDVI_spring))
NDVI_class <- c("high", "low")
sd_depth <- c(sd(depth_highNDVI_spring),sd(depth_lowNDVI_spring))
signi <- c("a", "a")
dfdepth <- data.frame(mean_depth, NDVI_class, sd_depth, signi)
dfdepth

#plot with texture
plot_depth_spring <- ggplot(dfdepth, aes(x=NDVI_class, y=mean_depth, fill=NDVI_class))+
  geom_col_pattern(aes(pattern = NDVI_class),
                   colour  = 'black',
                   pattern_fill = "black",
                   pattern_density= 0.2,
                   pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "white"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  theme(legend.position = "none")+
  labs(title="", x="NDVI class in Spring", y="Mean Soil Depth \n [m]")+
  coord_cartesian(, ylim = c(0, 140)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_depth-sd_depth, ymax=mean_depth+sd_depth), width=0.5)+
  geom_text(aes(label=signi, y=mean_depth+sd_depth), vjust = -2, size=5)
```

```
plot_depth_spring



####################################
#### COARSE MATERIAL AND SPRING ####
####################################

## t.test/ wilcoxon test ####

coarse_highNDVI_spring <- subset(dt1$Skelett.content, dt1$NDVI_class_spring=="high")
coarse_lowNDVI_spring <- subset(dt1$Skelett.content, dt1$NDVI_class_spring=="low")

#check normality:
shapiro.test(coarse_highNDVI_spring) #p=0.004 --> not normally distributed
shapiro.test(coarse_lowNDVI_spring)
#both normally distributed as p> 0.5
qqnorm(coarse_highNDVI_spring)
qqnorm(coarse_lowNDVI_spring)


#not normal distribution: wilcoxon test
wilcox.test(coarse_highNDVI_spring, coarse_lowNDVI_spring, paired = FALSE)
#p = 0.048  --> significant


#plot preparation
mean_coarse <- c(mean(coarse_highNDVI_spring),mean(coarse_lowNDVI_spring))
NDVI_class <- c("high", "low")
sd_coarse <- c(sd(coarse_highNDVI_spring),sd(coarse_lowNDVI_spring))
signi <- c("a", "b")
dfcoarse <- data.frame(mean_coarse, NDVI_class, sd_coarse, signi)
dfcoarse

#plot with texture
plot_coarse_spring <- ggplot(dfcoarse, aes(x=NDVI_class, y=mean_coarse, fill=NDVI_class))+
  geom_col_pattern(aes(pattern = NDVI_class),
                   colour  = 'black',
                   pattern_fill = "black",
                   pattern_density= 0.2,
                   pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "white"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  theme(legend.position = "none")+
  labs(x="NDVI class in Spring", y="Mean Coarse Material \n [% by mass]")+
  coord_cartesian(, ylim = c(-2, 30)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_coarse-sd_coarse, ymax=mean_coarse+sd_coarse), width=0.5)+
  geom_text(aes(label=signi, y=mean_coarse+sd_coarse), vjust = -2, size=5)

plot_coarse_spring


####################################
####       BD and spring       ####
####################################
## t.test/ wilcoxon test ####

BD_highNDVI_spring <- subset(dt1$BDcorr, dt1$NDVI_class_spring=="high")
BD_lowNDVI_spring <- subset(dt1$BDcorr, dt1$NDVI_class_spring=="low")

#check normality:
shapiro.test(BD_highNDVI_spring)
```

```
shapiro.test(BD_lowNDVI_spring)
#both normally distributed as p> 0.5
qqnorm(BD_highNDVI_spring)
qqnorm(BD_lowNDVI_spring)

#t.test
t.test(BD_highNDVI_spring, BD_lowNDVI_spring, paired = FALSE)
#p= 0.02736 significant

#as not sure about normal distribution: try also wilcoxon test
wilcox.test(BD_highNDVI_spring, BD_lowNDVI_spring, paired = FALSE)
#p = 0.048 --> also significant


#plot
mean_BD <- c(mean(BD_highNDVI_spring),mean(BD_lowNDVI_spring))
NDVI_class <- c("high", "low")
sd_BD <- c(sd(BD_highNDVI_spring),sd(BD_lowNDVI_spring))
signi <- c("a", "b")
dfBD <- data.frame(mean_BD, NDVI_class, sd_BD, signi)
dfBD


#plot with texture
plot_BD_spring <- ggplot(dfBD, aes(x=NDVI_class, y=mean_BD, fill=NDVI_class))+
  geom_col_pattern(aes(pattern = NDVI_class),
                   colour  = 'black',
                   pattern_fill = "black",
                   pattern_density= 0.2,
                   pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "white"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  theme(legend.position = "none")+
  labs(title="", x="NDVI class in Spring", y="Bulk Density \n [g/cm3]")+
  coord_cartesian(, ylim = c(0, 1.75)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_BD-sd_BD, ymax=mean_BD+sd_BD), width=0.5)+
  geom_text(aes(label=signi, y=mean_BD+sd_BD), vjust = -2, size=5)

plot_BD_spring


####################################
####      W100 and spring       ####
####################################
# t. test or wilcoxon test: ####
W100_highNDVI_spring <- subset(dt$W100, dt$NDVI_class_spring=="high")
W100_lowNDVI_spring <- subset(dt$W100, dt$NDVI_class_spring=="low")

#check normality:
shapiro.test(W100_highNDVI_spring)
shapiro.test(W100_lowNDVI_spring)
#both normally distributed as p> 0.5
qqnorm(W100_highNDVI_spring)
qqnorm(W100_lowNDVI_spring)

#t.test
t.test(W100_highNDVI_spring, W100_lowNDVI_spring, paired = FALSE)
#p= 0.03385 --> not significant



#plot with texture to go with other graphs
```

```
mean_W100 <- c(mean(W100_highNDVI_spring),mean(W100_lowNDVI_spring))
NDVI_class <- c("high", "low")
sd_W100 <- c(sd(W100_highNDVI_spring),sd(W100_lowNDVI_spring))
signi <- c("a", "b")
dfW100 <- data.frame(mean_W100, NDVI_class, sd_W100, signi)
dfW100

plot_W100_spring_texture <- ggplot(dfW100, aes(x=NDVI_class, y=mean_W100, fill=NDVI_class))
+
  geom_col_pattern(aes(pattern = NDVI_class),
                   colour  = 'black',
                   pattern_fill = "black",
                   pattern_density= 0.2,
                   pattern_spacing = 0.01) +
  scale_pattern_manual(
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "white"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  theme(legend.position = "none")+
  labs(title="", x="NDVI class in Spring", y="Gravimetric Water Content at -100hPa \n [g/g]
")+
  coord_cartesian(, ylim = c(0, 0.55)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_W100-sd_W100, ymax=mean_W100+sd_W100), width=0.5)+
  geom_text(aes(label=signi, y=mean_W100+sd_W100), vjust = -2, size=5)

plot_W100_spring_texture


####################################
####        C and spring        ####
####################################

# t. test or wilcoxon test: ####

C_highNDVI_spring <- subset(dt$carbon, dt$NDVI_class_spring=="high")
C_lowNDVI_spring <- subset(dt$carbon, dt$NDVI_class_spring=="low")
boxplot(C_lowNDVI_spring, C_highNDVI_spring)

#check normality:
shapiro.test(C_highNDVI_spring)
shapiro.test(C_lowNDVI_spring)
#both normally distributed as p> 0.5
qqnorm(C_highNDVI_spring)
qqnorm(C_lowNDVI_spring)

#t.test
t.test(C_highNDVI_spring, C_lowNDVI_spring, paired = FALSE)
# not significant

#plot praparation
mean_C <- c(mean(C_highNDVI_spring),mean(C_lowNDVI_spring))
NDVI_class <- c("high", "low")
sd_C <- c(sd(C_highNDVI_spring),sd(C_lowNDVI_spring))
signi <- c("a", "a")
dfC2 <- data.frame(mean_C, NDVI_class, sd_C, signi)
dfC2

#plot with texture
plot_c_spring_texture <- ggplot(dfC2, aes(x=NDVI_class, y=mean_C, fill=NDVI_class))+
  geom_col_pattern(aes(pattern = NDVI_class),
                   colour  = 'black',
                   pattern_fill = "black",
                   pattern_density= 0.2,
                   pattern_spacing = 0.01) +
  scale_pattern_manual(
```

```
    values = c("none", "stripe")) +
  scale_fill_manual(values=c("darkolivegreen4", "white"),
                    guide = guide_legend(override.aes = list(pattern = "none")))+
  theme(legend.position = "none")+
  labs(x="NDVI class in Spring", y="Mean Carbon content \n [% by mass]")+
  coord_cartesian(, ylim = c(0, 7)) +
  theme(text = element_text(size = 17)) +
  geom_errorbar(aes(ymin=mean_C-sd_C, ymax=mean_C+sd_C), width=0.5)+
  geom_text(aes(label=signi, y=mean_C+sd_C), vjust = -2, size=5)

plot_c_spring_texture


####################################
####   AV100 and spring        ####
####################################


AV100_highNDVI_summer <- subset(dt1$AV100, dt1$NDVI_class_spring=="high")
AV100_lowNDVI_summer <- subset(dt1$AV100, dt1$NDVI_class_spring=="low")

#check assumptions:
#normality:
qqnorm(AV100_highNDVI_summer)
qqnorm(AV100_lowNDVI_summer)

shapiro.test(AV100_highNDVI_summer)
shapiro.test(AV100_lowNDVI_summer)
#p>0.05 --> normally distributed

#t.test
t.test(AV100_highNDVI_summer, AV100_lowNDVI_summer, paired =FALSE)
# p value = 0.6 --> not significant (with A100 instead of AV00: p=0.091)
```

Appendix 6 Declaration of Originality

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

PHYSICAL SOIL PROPERTIES AND URBAN LAWN HEALTH - A CASE STUDY IN GENEVA

Authored by (in block letters):
For papers written by groups the names of all authors are required.

Name(s):	**First name(s):**
DAVIES	MANON

With my signature I confirm that
- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date	**Signature(s)**
Zurich, 01.07.2022	MDavies

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.