Verein zur Förderung der Bodenkunde Hamburg
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Hamburger Bodenkundliche Arbeiten

2019

S. Schaaf-Titel

Band 95

HBA

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Water availability and soil growth conditions of roadside trees in Hamburg

Band 95
2019

ISSN: 0724-6382

Hamburger Bodenkundliche Arbeiten

Dissertation

with the aim of achieving a doctoral degree

at the Faculty of Mathematics, Informatics and Natural Sciences

Department of Earth Sciences

of Universität Hamburg

Water availability and soil growth conditions of roadside trees in Hamburg

Submitted by

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Hamburg

2019

Als Dissertation angenommen am Fachbereich Geowissenschaften

Tag der Disputation: 18. April 2019

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Erschienen als

Hamburger Bodenkundliche Arbeiten, Band 95

Herausgeber: Verein zur Förderung der Bodenkunde Hamburg
Allende-Platz 2, 20146 Hamburg
https://www.geo.uni-hamburg.de/bodenkunde/ueber-das-institut/hba.html
Schriftleitung: Dr. Klaus Berger

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Abbreviations

AWC = available water capacity

BUE = Behörde für Umwelt und Energie

BSU = Behörde für Stadtentwicklung und Umwelt

C = carbon

$CaCO_3$ = calcium carbonate

Cl = chloride

DM = dry matter

DW = dry weight

E = study site with monitoring at an established tree

F = study site at a felled tree

GALK = Deutsche Gartenamtsleiterkonferenz

K_{sat} = saturated hydrologic conductivity

N = nitrogen

SiK = Stadtbäume im Klimawandel (urban trees in times of climate change)

VWC = soil volumetric water content

Y = study site with monitoring at a young tree

Abstract

With increasing urbanization, the importance of preserving and creating green spaces in cities is growing. The roadside vegetation plays an important role here. In this study, growth conditions of established trees and young trees were analyzed at roadside locations in the city of Hamburg. The focus was on analyses of water availability in the crown area of selected trees. For these sites, soil properties and their small-scale variability were quantified. Further, a monitoring of the soil water tension and soil water contents over two vegetation periods (2016, 2017) was conducted and complemented by a modeling of the water tensions, in order to generalize the results of the observation years.

The results of this study show that the water availability can be one of the most important stressors for trees. Most of the other factors examined in this paper, such as pollution by deicing salts, play a minor role, as the pollution was low at all analyzed study sites. However, the CO_2-content in the soils air was higher than 5% at most of the sites for a longer period during summer. This can have negative effects on root growth and can increase the stress of the trees.

The soil moisture monitoring of established trees and young trees reveal clear differences in growing conditions. Established trees are rooting in the urban soil around them, which can be heterogeneous on small-scale. Here, the soil water availability depends on local conditions like soil texture, groundwater depth or the occurrence of low permeable layers. Two of six study sites were the whole year moist. At the other sites, dry phases were observed especially in the topsoil during late summer, which lasts until the begin of winter. The intensity and duration of the dry phases were predominantly controlled by the local weather conditions (precipitation, climatic water balance).

The 60-years modeling of soil water balances based on a constant weather data set and modified with site specific soil hydrologic properties indicates that typical roadside tree sites are experiencing dry phases. In dependence on the weather conditions, these dry phases were strongly varying from year to year during the modelling period. Further, the potential soil droughts showed spatial variability, which was caused by the different soil properties of the studied sites.

In application to standards, young trees are planted in planting pits with special planting substrates. Especially in their first years after planting, the young trees depend on the water availability of these substrates, as the rooting system does not expend in the surrounding soils. These planting substrates have a high skeleton, sand and humus content and therefore different properties compared to the surrounding urban soils. In both soil moisture monitoring years the water tensions increased in late summer and fall. The highest intensities of drought were measured in the root ball substrates and in the topsoil layers, where phases with water tensions ≥2000 hPa were measured at some sites. During dry phases, the planting substrates became dryer than the surrounding urban soils. The precipitation and irrigation events lead to only short-term decreases of the water tensions.

In the second year of the monitoring, the measured water tensions were higher than in the first year, despite of higher precipitation rates in the second year. The high water tensions show that additional irrigations are necessary until the trees have developed a sufficient rooting system. A change of the composition of the planting substrates to a variant with slightly higher silt or clay contents could contribute to a better water retention capacity. However, before the texture of the planting substrates will be modified, it has to be tested, if other necessary properties such as the supply of sufficient air to the roots and thus the prevention of water saturated conditions are still ensured.

The results of this study showed that water deficiencies occur in the soils of roadside trees in the city of Hamburg. This is likely to inhibit the optimal growth of the trees, whereas young trees with their small root system seem to be more at risk. The problem of dry spells may increase in future. Hence, it is important to take early measures to improve the situation, for example by the improvement of planting substrates or an intensified irrigation scheme for young trees.

Zusammenfassung

Mit der zunehmenden Verstädterung wird die Bedeutung des Erhalts und der Erschaffung des Grünbestands in den Städten immer größer. Eine große Rolle spielt dabei das Straßenbegleitgrün. In dieser Studie wurden die Wachstumsbedingungen von etablierten Bäumen und von Jungbäumen an Straßenrandstandorten in der Stadt Hamburg untersucht. Der Fokus lag dabei auf der Analyse der Wasserverfügbarkeit im Kronenbereich ausgewählter Bäume. An diesen Standorten wurden die Bodeneigenschaften des urbanen Bodens und ihre kleinräumige Variabilität analysiert. Weiterhin wurde ein Monitoring der Bodenwasserspannung und Bodenwassergehalte über zwei Vegetationsperioden (2016, 2017) durchgeführt und durch eine Modellierung der Bodenwasserspannungen ergänzt, um die Ergebnisse der Beobachtungsjahre verallgemeinern zu können.

Die Ergebnisse dieser Studie zeigen, dass die Wasserverfügbarkeit einer der wichtigsten Stressfaktoren für Bäume sein kann. Den meisten anderen Faktoren, die in dieser Arbeit untersucht wurden, wie zum Beispiel der Schadstoffbelastung durch Streusalze, kommt nur eine untergeordnete Rolle zu, da die Belastung an allen analysierten Standorten gering war. Allerdings zeigte sich, das die CO_2-Gehalte in den Sommermonaten über längere Zeit an den meisten Standorten 5% überschreiten. Dieses kann sich negativ auf das Wurzelwachstum auswirken und den Stress für die Bäume erhöhen.

Bei dem Monitoring der Bodenfeuchte zeigten sich deutliche Unterschiede der Wachstumsbedingungen von etablierten Bäumen und Jungbäumen. Etablierte Bäume wurzeln in dem sie umgebenden urbanen Boden, der kleinräumig heterogen ausgeprägt ist. Hier hängt die Wasserverfügbarkeit stark von den vor Ort gegebenen Bedingungen wie Bodenart, Grundwassertiefe oder stauenden Schichten ab. Zwei von sechs Monitoringstandorten waren das ganze Jahr hindurch feucht. An den anderen Standorten gab es dagegen besonders in den Oberböden im Spätsommer Phasen mit Austrocknung, die bis zum Winterbeginn angehalten haben. Die Intensität und Dauer der trockenen Phasen war in erster Linie durch das lokale Wetter (Niederschläge, klimatische Wasserbalance) geprägt.

Die Modellierungen des Bodenwasserhaushalts der letzten 60 Jahre, die auf einem konstanten Wetterdatenset und standortspezifischen bodenhydrologischen Eigenschaften basieren, weisen darauf hin, dass an typischen Straßenbaumstandorten Trockenphasen auftreten. In Abhängigkeit von den Witterungsbedingungen schwankten die trocken Phasen in der modellierten Zeit von Jahr zu Jahr stark. Weiterhin wiesen die potentiellen Bodentrockenheiten deutliche räumliche Unterschiede auf, die durch die unterschiedlichen Bodeneigenschaften der untersuchten Standorte hervorgerufen wurden.

Jungbäume werden bei Anwendung von Pflanzempfehlungen in Pflanzgruben mit speziellem Pflanzsubstraten gepflanzt. Gerade in den ersten Jahren nach der Pflanzung sind die Jungbäume auf die Wasserverfügbarkeit in diesen Substraten angewiesen, da sie den

umliegenden Boden mit ihren Wurzeln noch nicht erschlossen haben. Diese Pflanzsubstrate haben einen hohen Skelett- und Sand- und Humusanteil und daher andere Eigenschaften als die sie umgebende urbane Böden. Die Bodenwasserspannung nahm in beiden Untersuchungsjahren im Spätsommer und Herbst deutlich zu. Die größten Austrocknungen haben wir in den Pflanzballen und in den obersten Bodenschichten gemessen, in denen Phasen mit ≥2000 hPa an einigen Standorten gemessen wurden. In den trockenen Phasen trockneten die Pflanzgrubensubstrate meist stärker aus als die umliegenden urbanen Böden. Die Niederschläge und Bewässerungen führten nur zu einer kurzzeitigen Abnahme der Wasserspannungen. Im zweiten Jahr des Monitorings waren die gemessenen Wasserspannungen trotz höheren Niederschlagsraten als im ersten Messjahr größer. Die hohen Wasserspannungen zeigen, dass eine zusätzliche Bewässerung notwendig ist bis sich die Bäume einen ausreichenden Wurzelraum erschlossen haben. Eine Änderung der Substratzusammensetzung zu einer etwas schluff- oder tonreicheren Variante könnte zu einer besseren Wasserhaltekapazität beitragen. Allerdings muss vor einer Änderung der Bodenart der Pflanzsubstrate getestet werden, ob weiterhin andere erforderliche Eigenschaften wie die Versorgung der Wurzeln mit ausreichend Luft und die Verhinderung von Stauwasser gewährleistet sind.

Die Ergebnisse dieser Studie zeigten, dass im Innenstadtbereich von Hamburg Wassermangel in den Böden von Straßenbaumstandorten vorkommen. Dieses kann ein optimales Wachstum der Bäume verhindern, wobei Jungbäume mit ihrem kleinen Wurzelsystem besonders gefährdet erscheinen. Die Problematik der Trockenphasen kann sich in Zukunft verstärken. Daher ist es wichtig, rechtzeitig Maßnahmen zur Verbesserung der Situation zu ergreifen, wie zum Beispiel Verbesserungen der Pflanzgrubensubstrate oder häufigere Bewässerungen der Jungbäume.

1. Introduction

In all cities of Germany are growing trees. These trees are very beneficial for the inhabitants. The trees do not only have an aesthetical and recreational value, because of their appearance, which is changing with the seasons and make the different seasons in the cities better understandable with their color changing leafs and the production of fruits. The trees increase the property value. In addition to that, a very important advantage is their ability to improve the microclimate: They provide shade and reduce the temperatures on the surfaces and in the closer surrounding of them especially in summer, which is pleasant for walking under them and which helps to save heating and cooling energy of the buildings. Additionally, they increase the relative humidity, reduce noise and wind, store carbon dioxide and filtrate the air, which reduces air pollution and can increase human health. The intensity of most of these positive effects variate between the tree species and their age. (e.g. McPherson et al. 1997, Nowak & Crane 2001, Matzarakis & Streiling 2004, Nowak et al. 2006, Nowak & Dwyer 2007, Armsen et al. 2012, Stiftung DIE GRÜNE STADT 2014, Livesley et al. 2016, Salmond et al. 2016, McPherson et al. 2018, Nowak et al. 2018, Sicard et al. 2018)

Therefore, green areas and street trees are very important for people living in cities, but they often forget, that it is not easy for a tree to grow in a city, especially for roadside trees. The difficult growth conditions make their management essential. The protection of trees in urban areas starts with the choice of the location, the tree species and the preparation of the soil. Later it must be irrigated during its first years and needs different kinds of care like pruning.

The living conditions like climate, exposure and soil are very different from the living conditions in a forest (Figure 1). The soil is the basis for the tree, but soils are often influenced by human activities in urban areas and differ from natural soils. Some urban soils contain anthropogenic compounds like rubble. These can affect the urban soils, when they lead to different properties (e.g. pH-value, water retention capacity) than a natural soil in that area would have. Because of the high traffic amount and the allocation of industries, urban soils are more at risk of contamination with pollutants. Especially the de-icing salts are a problem for the road trees in the cities, because they are strewed next to the trees on the roads, where it leads to problems with the nutrient supply and causes damages like leaf necrosis or reduced growth (e.g. Endlicher 2012).

The growing conditions for trees in cities are significantly different from those in forest areas (e.g. Endlicher 2012, Herrmann 2017; Figure 1). The temperatures and the radiation are slightly higher the cities, so that the trees have to cope with it. Another problem is the water supply. Precipitation rates in cities are similar to the rates outside of the city, but in cities, the water do not often reach the roots of the trees. High buildings can block the rain, if the wind blows from the direction from behind of the building. The sealing and the compacted surfaces lead to a fast runoff. In addition to that, cities have a proper working sewage system so that the water can be quickly removed by it. Less water has enough time on an unsealed surface to infiltrate into the soil. This means that urban trees may have to deal with drought stress - even in cities with relatively high precipitation rates, which can lead to reduced growth of the trees (e.g. Clark & Kjelgren 1990, Allen et al. 2010). A side effect of these conditions are increased emissions of some classes of biogenic volatile organic compounds (Kleist et al. 2012, Calapietra et al. 2013, Churkina et al. 2017). These substances decrease the air quality (e.g. Nowak 2002, Calapietra et al. 2013, Churkina et al. 2017). The urban climate and structure conditions intensify the difficulties of living for a tree in urban areas. Therefore, good knowledge of the growing conditions of urban trees is an important prerequisite for the management of these trees.

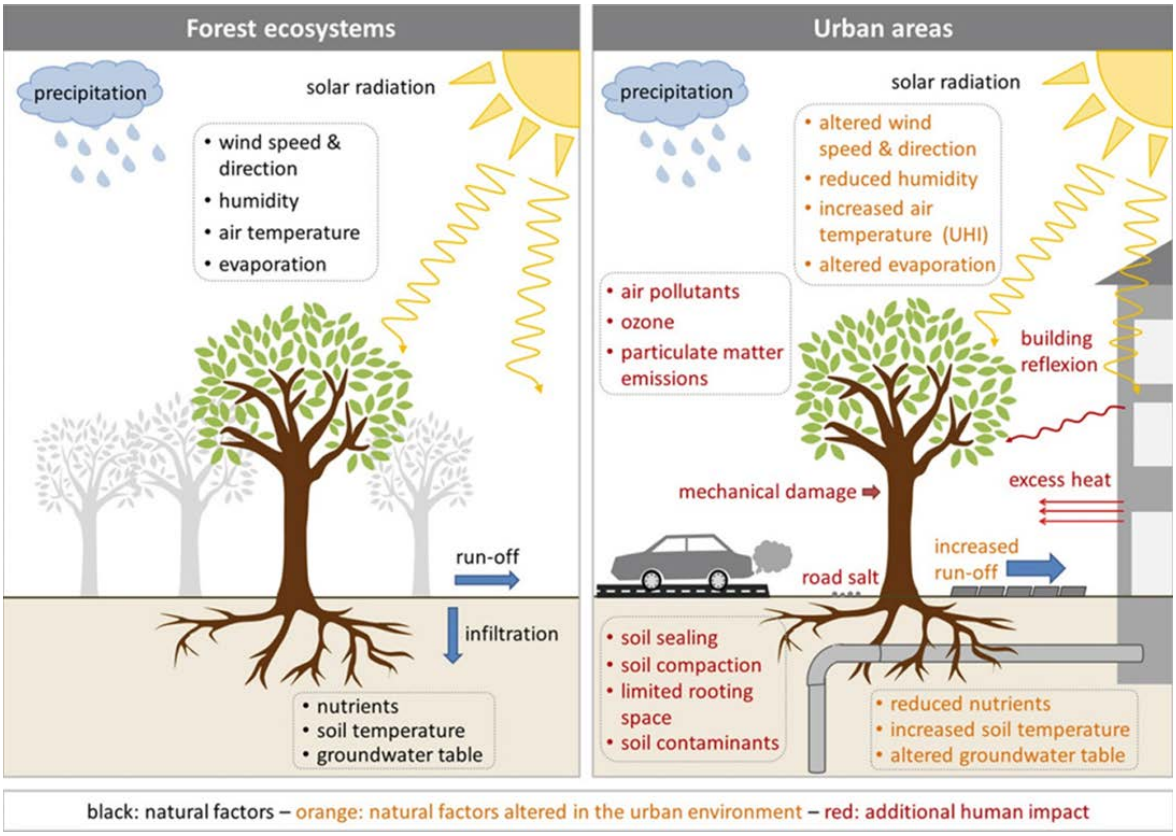

Figure 1: Comparison of climate conditions in forest ecosystems with urban areas. Source: Brune, 2016.

The aim of this study is to determine, to which extent drought occurs at roadside locations of trees in Hamburg. Hamburg is a city in the north of Germany, which is not only famous for its harbor, but also for its rich green. According to this, the city government does a lot to protect the green areas and the trees. Recently, the tree inspectors and experts found indices that the roadside trees may suffer under drought stress (Doobe (BUE, personal communication) 2015), but it is less known about the intensities and length of drought stress as well as about the specific properties of the soil and the surrounding of the trees, which may influence the intensities of drought. That means that there is a high research need to ensure a green and healthy tree population in Hamburg in future. This study will help to broaden the knowledge about soil drought in Hamburg. Therefore, the soil properties, the pollutants in the soil and the soil gas content (O_2, CO_2) were analyzed to determine the general possible stress factors for trees. Possible stress factors are a lack of oxygen, high pH-values or drought. Stressors, which can increase the drought stress, are for example a low water retention capacity or high concentrations of salt as well as the percentages of sealing of the nearer surrounding of the trees. The focus lies on the water availability in the soils near established and recently planted roadside trees. A nearly 2-year-monitoring of soil moisture was conducted at in total 23 tree locations. With this monitoring, the intensity of soil drought stress will be quantified and determined, which time of the year is the most critical. Modeling with the analyzed soil data is done to generalize the monitoring results and to confirm the effects of the soil properties to drought stress.

The leading questions of this thesis are:

(1) Which properties of urban soils increase the stress probability for urban roadside trees in Hamburg?
    a) Which site characteristics and physical soil properties (e.g. texture, compaction) relevant for increasing the potential risk of soil drought?
    b) Are chemical soil properties (e.g. deicing salts, pH) relevant for increasing the potential stress for trees in Hamburg?
    c) Does the aeration of the roadside soils has the potential to reduce tree growth?
(2) Does soil drought occur at roadside tree locations in Hamburg?
    a) When and how long did drought occur in the studied years?
    b) What is the effect of surface sealing on soil drought?
    c) How did the potential soil drought differ between sites from 1959 to 2016?
(3) What are the differences between sites with established trees and young trees according to drought stress?

To answer these questions, chapter 2 gives a rough overview with general information about roadside trees, urban soils and urban climate conditions, before in chapter 3, the study sites and methods used in this study were described. In chapter 4, the constant soil conditions were characterized. In this chapter, the percentage of surface sealing as well as physical and chemical properties of soils at sites with established roadside trees were analyzed. Here, the focus was on the hydrologic properties and potential stress factors like deicing salts, which can lead to similar symptoms at trees as drought stress. With this data, knowledge about the potential for drought stress is gained for urban soils at established roadside trees.

In the next chapter, the water tension, water content and soil gas composition were analyzed at six sites with established trees over two vegetation periods. Times with dry soil as well as periods with high CO_2-contents in the soil gas as well as differences between the two years were identified. With a modeling approach, the time of analyses of the water tension were expended to the past. To validate the model, results of the model were compared with the measurement data before it was used for modeling of past years.

Then, in chapter 6, the problem is widened to young roadside trees, which were planted in planting pits. They do not yet have wide rooting systems like older established trees. Therefore, they are dependent on the water availability in the planting substrates. With analyses of the different soil substrates around the young trees and with the monitoring of the water tension, it is analyzed, if water availability is given over the course of the year.

After that, in chapter 7 a synthesis is given corresponding to the key questions of this thesis and in chapter 8, an outlook to further open research questions is presented.

2. Growing conditions of trees in cities

2.1 Roadside trees

Cities are extreme locations for trees. Buildings and streets mainly dominate the cities, so that the cities have special site characteristics, which lead to special growing conditions for the vegetation, which can be different from the original habitats of the trees.

Three typical locations for trees in the cities can be identified as parks, gardens and roadsides. They differ in particular by the surrounding of the tree and intensity of anthropogenic influence like soil sealing. Parks are in general wide areas with lawn or forest without traffic. The trees can stand separated, in rows, in small groups or in forests, where comparable growing conditions to natural conditions are. Gardens have a wide range of location diversity and as huge range of used species. Some gardens are very small with a high percentage of sealing, so that there is not much space for the trees. Other gardens are huge and have similar growing conditions then parks. All roadside trees have in common, that they are growing close to roads, so that their locations are influenced by them. Normally their space is limited because of the road itself, sidewalks, buildings in the closer surroundings and underground infrastructure like tunnels, wires and pipes. (e.g. Blauermel 1978, Schickhoff & Eschenbach 2018)

In this study, the focus was on roadside trees. Hamburg has about 225,000 roadside trees (BUE 2016). This high amount shows that many trees are planted at roadsides in the cities and that it is important to know more about their situation. Only when we know about stressors of the trees, measures can be taken to prevent them, so that we also have in future green cities. In Hamburg, the most common species of roadside trees are: Common oak (*Quercus robur* L., 40,350 trees, 18.1%), Common linden (*Tilia* x europaea L., 11.3%), Norway maple (*Acer platanoides* L., 5.9%), Small-leafed lime (*Tilia cordata* MILL., 4.9%), London plane (*Platanus* x *hispanica* MÜNCCH., 4.7%), Silver birch (*Betula pendula* ROTH, 4.3%), Common hornbeam (*Carpinus betulus* L., 3.7%) and Sycamore maple (*Acer pseudoplatanus* L., 2.7%) (BUE 2015f).

Based on the special growth conditions, different tree species have a different suitability for being a road tree. Many factors of tree and site properties were especially at roadside locations important, which are listed in Endlicher (2012) or Roloff (2013b). For example, the space is limited, so the tree must have a size, which is suitable for the given space. That includes the space for the tree crown as well as the underground rooting space, which can be limited by underground constructions or which can be disturbed by excavations. They must be tolerant to climate conditions in the city, as well as to tree pruning, which is important for the road safety. Therefore, pruning must be done more often at roadside trees than at trees at locations with greater distance to the roads. Nevertheless, the tree must be have an aesthetical value, which fits to the architecture of the street. Next to streets, the growth of fruits of some species may be a problem, too, when they lead to high waste amounts or unpleasant odor, once they decay. In addition to that, not only the single tree itself must be considered but also the tree species in the surrounding of the location to keep a high biodiversity to prevent high damages by insects, fungi or others. Roloff (2013a and 2013b) also cites immissions, dust pollution, artificial light irradiation, line leakage and the back radiation of buildings as special location factors. Further, the nutrient situation (in urban areas often not to a sufficient amount available) or the soil (e.g. its sealing, compaction, pH value, soil warming, soil air and soil water conditions), road salt and groundwater lowering can lead to impairment of tree growth in cities (e.g. Gregor 1989, Leh 1993, Balder 1998, Day et al. 2010). Kehr (2013) emphasizes that the frequency of diseases and pests in the city differs from that in forests. Additionally, the assessment is different for reasons of aesthetics and traffic safety. The measures are also taken at an early stage.

Urban trees are thus exposed to a variety of different stressors, which impair their growth performance and can lead to stress symptoms. These stress factors can and will usually be present in combination at urban tree locations. The knowledge about the effects of anthropogenic site-related stress factors, thresholds and species-specific reactions of trees as single factors and their combination is still very limited. Nevertheless, it is known, that all these special growth conditions and various stress factors lead to a lower life expectancy of urban and roadside trees in comparison to trees in natural habitats (Blauermel 1978, Roloff 2013a, Roloff 2013b, Clark & Kjelgren 1990). The life expectancy of trees at roads is only about 25% of their potential age range (Roloff 2013a). This can limit the positive functions of urban trees for humans, as stress can result in lower performance, lower growth and premature tree death (e.g. Allen et al. 2010, Clark & Kjelgren 1990, Maurel 2001, Rust 2008).

One of the best-known factor, which affects the growth of trees, are the climate factors temperature and precipitation. Drought and heat stress was observed at forest trees worldwide during the last decades (Allen et al. 2010) and is expected to increase in future (Choat et al. 2012). Pretzsch et al. (2017), said, that trees in urban areas tend to grow faster than in rural areas, where climate change enhances their growth more. In contrast to that, Meineke & Frank (2018) found, that in trees grow less in temperate cities than in rural areas, because of drought stress. David et al. (2015) assumed that one of the most important limiting factors for growth of street trees in Paris is the water availability. Eckstein et al. (1981) have shown that the trees react with their growth on the actual climate as well as on the climate of the year before. They found, that roadside trees (*Tilia, Quercus, Platanus, Aesculus, Fraxinus, Acer* and *Robinia*) in Hamburg reacted with better tree ring growth to high temperatures and high precipitation rates during the vegetation period and in the fall of the year before. Gillner et al. (2014) confirmed that the precipitations and the temperatures of the same year as well as the previous year are effecting the growth of urban tree, whereas the reactions of trees are species depended. Therefore, drought stress seems to be an important stressor. However, from the 1950s to the measurements of Eckstein et al. (1981), no lasting growth increase could be observed by Eckstein et al. (1981), which they explained with the possible stress effects of their urban site factors and especially stress by de-icing salts. Roloff et al. (2009) named the high drought and temperature hardiness as two of the most important characteristics, which are important for trees in urban areas in Germany with a view to the future. Thus, they developed a matrix with drought and temperature tolerance of the trees to classify trees for their possible usage in urban areas. Their classification is derived from literature references, like data from the natural habit of the tree species.

Drought stress is not only caused by climate factors like low precipitations, strong radiations and high temperatures, which lead to higher evaporations. The surrounding of the trees (e.g. shading by buildings or other vegetation), a reduced root zone, soil compaction, sealing, increased runoff, deicing salts and mechanical damages of roots can increase the possibility of drought stress for trees (e.g. Roloff 2013a). The consequence of this is that it is important to consider local conditions – local climate as well as local site conditions – for tree selections in cities. This is supported by the results of the study "Stadtgrün 2021", which showed, that in different cities in south Germany, the growth appearance of the same tree species is different (Böll 2017, Böll 2018).

There exist several methods to measure drought. They can be divided into meteorological measurements, measurements of the soil and measurements of the plant (Jones 2014). The most common measurements in the soil were the soil water content and the soil water potential. For measurements in the plant itself more choices of methods are existing, for example predawn potential, leaf potential, steam potential, turgor pressure, relative water content. For further details of advantages and disadvantages of the methods measured in the soil and in the plant, see the review of Jones (2006) and descriptions of the methods by Kirkham (2014) as well as a compilation of drought indices in Bender and Schaller (2004). Depending on the chosen measurement method, different definitions of drought or drought stress for plants had been made (Jones 2014). Nevertheless, in general no fix thresholds exist because they differ between plant species. Plant species react in various ways to drought stress and have different tolerances to it (e.g. Dickson & Tomlinson 1996, Jones 2006, Moser et al. 2016, Gillner et al. 2017). For instance, *Quercus rubra* or *Quercus robur* react sensitive to water stress, while *Quercus laevis* is tolerant (Dickson & Tomlinson 1996).

In this study, the water tension was used as a measure for drought, because it is well established in agriculture for scheduling irrigation (Shock & Wang 2011). For many crops soil water tensions as irrigation criteria can be found. These thresholds for irrigation vary with the type of crop, the location and soil. For example, the soil water tension varied for irrigation for potatoes between 200 hPa and 600 hPa in different studies compiled by Shock & Wang (2011). Unfortunately, in contrast to crops, it is less known about trees and their needed water tensions for optimal growth. Some studies have shown that trees react very fast to increases of the soil water tension. For instance, Deans (1979) found that roots of Sitka spruce died before soil water tensions reached 100 hPa in very open pored horizons. The critical tension was 200 hPa in peat horizons. Similar were the results of Shock et al.

(2002). They detected that the soil water tension should be above 200 hPa for hybrid poplar (*Populus deltoides*, *P. nigra*) in 20 cm depth on silt loam in a semiarid area during the growing season. They found that an irrigation at 250 hPa was leading to better results of poplar tree growth than irrigation criteria of 500 hPa or 750 hPa, where they measured reduced trunk and total biomass production (Shock et al. 2002). In this study, the 750 hPa (pF≈ 2.9) soil water tension was used as a threshold for moderate drought, because Shock et al. (2002) saw reduced growth at this water tension. In this study, the lower value of the study of Shock et al. (2002) was not used, because at this study sites, oaks and maple were growing, which are known to have better drought resistances than poplar trees. Further, 2000 hPa (pF≈ 3.3) was used as a measure for more intensive drought, which is the maximum value measureable with used water tension sensors of this study.

Therefore, in this study, drought stress means a decreased vitality or growth because of water shortage, which can lead to the death of the plant in extreme cases. Accordingly, soil drought means a reduced water availability, which may affect drought stress for trees. In this study, the threshold is set to a water tension of 750 hPa.

2.2 Urban soils

Categories of urban soils

The soil is the basis for the development of trees. It provides space and anchorage for root growth and supplies the tree with water and nutrients. Therefore, it is a very important factor, which influences the growth of trees.

In urban areas, soils with natural horizon development are uncommon. The long-lasting and intensive human activity in cities have modified the soils, especially during the construction work for industry, houses, roads and other infrastructure. In urban areas, a distinction can be made between semi-natural soils, disturbed soils and soils of sealed sites (e.g. Burghardt 1996, Schickhoff & Eschenbach 2018). Semi-natural soils are soils, which have been created in a more or less long phase of soil genesis, depending on the source material. These semi-natural urban soils may have been former grasslands or forest soil, but also horticultural and agricultural soils belong to this category. So these soils may have been fertilized or lime-treated (Endlicher 2012). These anthropogenic influence is small and do not affect the main natural soil processes, functions and properties. That means that these soils are still morphologically similar to the soils outside the cities, so that existing knowledge about these soils can be transferred to these soils easier than to soils with more anthropogenic influence. In Hamburg, material of the last ice ages and sedimentary deposits of the Elbe estuary characterize the natural soils. Cambisols, Podzols, Gleysols and Luvisols are the most common soil types in Hamburg (Miehlich 2010, BSU 2012b, BUE 2013, BUE 2015c). Semi-natural soils are more frequent in the outer areas of the cities, where the anthropogenic influence is not as strong as in the city center with a lot of construction work.

Disturbed soils have - as the name suggests - not experienced an undisturbed development period; they therefore do not correspond to natural soils. These soils are frequently altered e.g. in the course of construction work due to soil application, soil removal and mixing (Henninger 2011). They often contain technogenic substrates such as building rubble, debris, ash, waste or slag (Burghardt 1996, Endlicher 2012, Henninger 2011, Eschenbach & Pfeiffer 2010). These materials can be contaminated with pollutants or some of their substances contribute to changed physical and chemical conditions. For example, soils at sites with lime containing mortar can have an increased pH value. Filled soils often have different properties than the natural soils of the region, because they are often made from substrates of other regions or are mixtures of special substrates. As a result of the interventions of construction works, sandy soils with a high percentage of skeleton predominate at roadsides (BSU 2012). These soils can be very heterogeneous in small areas (e.g. BSU 2012, Greinert 2015, Wolff 1993).

A special category of these sites with disturbed soils are the substrates of artificial planting pits of street trees. Planting pits are created in order to provide the best possible growing conditions for the trees. Today, they are used for most of the new tree plantings along the roads (Endlicher 2012). The design of these pits is an important factor, which has a high influence on the properties of the plant location. There are differences in the size of the planting pit, planting substrate and, additional measures such as the use of ventilation pipes or drainage pipes, which are used if necessary. In the first few years after planting, the quality of the planting substrate (grain size, pore content, water retention capacity, nutrient content, stratification) is decisive for the establishment and growth performance of the planted trees. Nevertheless, additional measurers like irrigation during summer are used to help the tree surviving the first years. Later on, the trees have developed their root system and can - depending on the environmental conditions - leave the planting pit with their roots and open up surrounding sources of nutrients and water (e.g. Endlicher 2012, FLL 2015). However, the roots of many trees have difficulties to leave the planting pit because, for instance, the soil properties change rapidly with the shift to the surrounding material (Krieter & Malkus 1996). In Germany, recommendations for the construction of planting pits and planting pit substrate mixtures exist, for example FLL (2012) and FLL (2015), which are followed in Hamburg.

Soils at sealed sites are characterized by the sealing of their surface. They have a severely impaired water and gas balance. Other soil functions are also affected. Depending on the used sealing materials, the completeness of the sealant and the age of the sealant, precipitation can penetrate the soil to a much smaller extent than at unsealed and non-compacted sites (Wessolek 2001). The water and nutrient balance as well as the activity of soil organisms can be significantly restricted at these sites.

Properties of urban soils

In general, urban soils can have very different properties because of their history and different natural soils, which are specific for each region. The natural soils are the basic substrates of urban soils. These soils are often influenced by the history of anthropogenic agricultural land use and the later urban land use with construction works and events like burning of houses, which leads to inputs of material into the soils or also to loss of soil material (e.g. Endlicher 2012). A typical characteristic of the urban areas with intensive and long-lasting use is the high small-scale change of soil characteristics. The different soil categories mentioned above can therefore occur side by side at a distance of several meters, so that a high small-scale variability can occur in urban areas (e.g. BSU 2012; Greinert, 2015; Wolff, 1993). Often the urban soils do not have classic soil horizons, but have sharp borders between their individual soil layers. This occurs because of the anthropogenic disturbances and inputs as well as removals of soil material. Because of the relatively short undisturbed time, nearly no soil genesis is visible in these newer layers.

Urban soils are often compacted by construction, driving on and walking on (e.g. Short et al. 1986, Jim 1998c, Wittig 2002, Greinert 2015), where Scharenbroch et al. (2005) found that soils located in areas, which were changed 9 years before into urban landscapes, have a higher bulk density than soils, which are since 64 years in urban landscapes. This means that the soil has fewer medium and coarse pores, which can carry air and water. As a result, the available water capacity of these compacted soils is lower than of uncompacted soils. This causes the effect that less water can be stored in the soils and can used by plants. Therefore, drought stress can occur more quickly. The sealing of the surfaces intensifies this problem, because less precipitation can infiltrate into the soil. In addition, precipitation water is drained off to a large portion into canals so that only a part of the water can infiltrate the ground. Furthermore, the sealing prevents the exchange with the atmosphere so that evaporation is severely restricted. The soil compaction and its sealing reduce the exchange of soil air, too, which can lead to a lack of oxygen (Ruge 1978) or to a critical load of carbon dioxide. This can damage the roots and can stop their growth. In addition, the dense storage of the particles makes the growth of roots more difficult (Endlicher 2012).

In addition to the compaction, other substrate properties have an influence on the soil water balance, too. The technogenic mixtures, which are typical for many urban soils (e.g. Burghardt 1996), have often significantly different textures and properties than the natural soil material. Thus, they significantly change the soil water balance (especially water holding capacity, pore size distribution and water conductivity). For instance, coarse material such as building rubble can lead to an increase of coarse pores, which may have a positive effect on root penetration. In addition to that, some materials like bricks can increase the water retention in soils with poor water storage capability (Wolff 1993) and can in that way enhance soil properties for plants (Nehls et al. 2013). However, the coarse material can have negative effects, too. For example, the reduction of the pore volume of middle pores leads to a lower water storage capability.

Soil temperature, which can be slightly higher in cities because of the urban heat effect, influences microbial activity and thus the degradation rate of the organic substance (Krieter & Malkus, 1996), which is important for the nutrient balance of plants. A sufficient nutrient supply can be another problem in urban areas. By sealing the surfaces, less nutrients infiltrate into the soils. The roads and footpaths are brushed and the green areas are maintained, thereby removing the leaves of trees and bushes with their nutrients from the sites. The reduced humus input reduces the number of soil organisms and their biodiversity. The biodiversity of soil organisms in urban soils differs significantly from more natural habitats such as meadows and forests. Dorendorf et al. (2015) showed that the foliage of city trees can be decomposed faster than that of trees in other areas. Thus, the quality of litter in city trees has changed. The humus content is not always lower in urban soils than in natural soils of the same region. Sometimes soil layers were filled up, including layers with a high percentage of humus. Anthropogenic inputs like rubbish or food particles can cause a higher humus content. Not only a deficiency of the beneficial nutrients can be a problem for the plants. Oversupply or unfavorable concentration ratios also have negative consequences. A surplus of nitrogen and phosphate can also be found in particular in planting pits on the roadside (Kasielske & Buch 2011). In some cases, humus rich soil layers are also in a higher soil depth. This can make problems, because it can lead to water retention and if the aeration is low and the natural degradation process is disturbed (e.g. Höke et al. 2010). Another nutrient problem in urban areas makes uric acid from dog urine, which can damage trees directly (e.g. Leh 1993).

The trees at the roadside are at a risk to be negatively affected by additional salt contamination (e.g. Hootman et al. 1994). Winter services use de-icing salts to keep the roads free of ice. In low concentrations, these salts are needed as essential nutrients by the trees. However, the high exposure to road salt caused severe salt damage to trees in Germany, especially from the 1960s to the 1980s (Petersen & Eckstein 1988). Before external damage such as leaf edge necrosis or premature leaf loss becomes visible, the tree may already be affected by metabolic disorders that lead to loss of growth. The consequences for the tree can be a slower wood growth, a shortened growth period, the decrease of biomass or the development of fewer buds, shoots, leaves and roots. At high salt concentrations, direct tissue damage can also occur (Petersen & Eckstein 1988). Another consequence of the salt stress is that the affected trees react more sensitively to water stress (Petersen & Eckstein 1988). High salt concentrations displace other nutrients in the soil (Rust 2008; Wittig 2008) and change the structure of the soil: The soil can become encrusted and thus it is more difficult for the tree roots to absorb nutrients. Furthermore, the stability of the soil structure can decrease due to the dispersing effect of salt ions (BSU 2012). Since the problem with de-icing salts had become known, the use of them has been reduced or partly banned. Nevertheless, they are still in use today to ensure road safety in winter. In Hamburg, the use of de-icing salts is only allowed on roads, but not on pavements according to section 28 sentence 3 and section 31 sentence 2 Hamburgerisches Wegegesetz[1].

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[1] Hamburgisches Wegegesetz (HWG) in der Fassung vom 22. Januar 1974, letzte berücksichtigte Änderung: §§ 28, 30, 31, 33 geändert, § 32 neu gefasst durch Artikel 1 des Gesetzes vom 28. November 2017, HmbGVBl. S. 361

In the cities and especially at the roadsides, it is known that the pollutant levels are often increased in the soils (e.g. Li et al. 2018). Technogenic inputs in the soils contain pollutants in many cases (e.g. Endlicher 2012). However, not only these direct pollutant inputs lead to an increased pollution of soils near urban trees. The proximity to the pollutant production sites, such as industrial areas, traffic routes and households can cause high level of pollution, too. The pollutants are released directly to trees and urban soils through atmospheric deposition, but also through direct material inputs such as tyre abrasion or washout caused by precipitation, splash water or surface runoff into the soil (e.g. Wittig 2002, Henninger 2011). In Hamburg, there were increased levels of pollutants observed. Especially, elevated amounts of lead, cadmium, zinc and copper had been found (Lux 1986; Dües 1987; Umweltbehörde Hamburg 1994; Vybornova 2012). However, many trace metals at the roadside soils are comparatively immobile due to the high pH of the soils. Organic pollutants such as polycyclic aromatic hydrocarbons can also be a problem in soils next to roadsides; the sources of these pollutants are vehicle exhaust fumes, tire abrasion and oil as well as fuel residues (Gras et al. 2000).

The pH of urban soils has changed in many places due to the anthropogenic admixtures. It can be observed that the variation of the soil reactions in the city is large. Soils in parks are often more acidified by acid rain. On the other hand, roadside soils usually exhibit a comparatively high pH due to the anthropogenic admixtures (see above). Soil reaction is important for nutrient and pollutant binding in the soil. At a pH below 5.5, for instance, many trace metals become increasingly available to plants and can be transferred via soil water (Henninger 2011). In alkaline soil reactions, however, trace metals and nutrients are firmly bound and therefore not available to the plants, so that nutrient deficiency situations can occur. A slightly acidic soil to slightly alkaline is recommended for most of the common tree species in Germany (Goss & Schönfeld 2014).

All these above mentioned soil properties have the potential to cause stress for trees. For a healthy green city, it is important to know, which of the potential stressors make problems at which location, so that measures can be taken, if necessary. That is why this study analyzes the properties of urban soils near tree plantings in the city of Hamburg. Here, the focus is on potential stressors like reduced field capacity or compaction, which can lead to drought stress.

2.3 Climate in cities

The climate in the cities differs from the climate of their surroundings (Figure 2). In particular, the temperature is higher. This phenomenon is known as urban heat island (e.g. Oke 1973, Kim 1992, Arnfield 2003, Eschenbach & Pfeiffer 2010). The increase in temperature in the cities is partly due to the dense construction with a high degree of sealing, which changes the radiation budget and the water balance (e.g. Kim 1992, Henninger 2011, Endlicher 2012, Mohajerani et al. 2017, Wiesner et al. 2018). On the one hand, global radiation is reduced by the urban haze, which is partly due to traffic emissions, so that direct radiation can be lower. On the other hand, there is no closed canopy roof over the roads that prevents direct radiation onto the ground and thus reduces the heat build-up of the ground by throwing shadows (Krieter & Malkus 1996, Kuttler 2009). Due to the reflection, absorption and radiation on artificial surfaces and the increased reflection, the proportions of diffuse radiation and the perceptible heat in the city are higher (Kuttler 2009). Within the city, there are significant differences in air temperature depending on the location and use of the land (e.g. Wiesner et al. 2014). In built-up or sealed urban areas, the processes of exchange between soil, vegetation and atmosphere have changed considerably as a result of sealing and compaction in comparison to extra-urban areas. The evaporation and transpiration of water, in which radiated energy is converted into latent energy and thus not available to the noticeable heat flow, is reduced. As a result, unsealed floors are usually cooler in the upper layers than the floors of the sealed locations. Furthermore, unsealed green spaces - differentiated according to their soil water content - contribute to a lower heating of the air temperature (Wiesner et al. 2015). In addition, the air circulation is reduced at many places due to the building development, location and orientation of the streets, resulting in a lower air exchange rate (Bechtel et al. 2011). The warm air stays in the cities (Kuttler 2009). According to Kuttler (2009), the urban air temperatures are on average about one to two degrees higher than in the surrounding area. In Hamburg's city center, the annual mean air temperature is up to 1.1°C higher (Schlünzen et al. 2010, Wiesner 2013, Bechtel et al. 2014, Wiesner et al. 2014; Figure 3) than in the surrounding rural areas. This overheating is strongly dependent on local and temporal conditions. In the city center, this heating effect is stronger during nighttime and the effect is higher on days with little or no cloud cover as well as low wind speeds (Wiesner 2013, Wiesner et al. 2014). Nevertheless, the surface urban heat island intensity for Hamburg is higher during daytime (Wiesner et al. 2018). Trees can lower the local temperatures (e.g. Coutts et al. 2016). The temperature differences of urban areas are also reflected in the different surface temperatures (Leunzinger et al. 2010). Leunzinger et al. (2010) found, that the surface temperatures of trees on sealed surfaces are warmer than those of park trees. In addition, street trees are sometimes planted at a large distance from other trees on open spaces where they have to cope with strong irradiation that influences the transpiration of the trees. However, tall buildings shade other locations of trees, which receive hardly any direct sunlight. In general, roadside trees are exposed to higher levels of temperature and radiation stress than park trees and trees in forests outside the city.

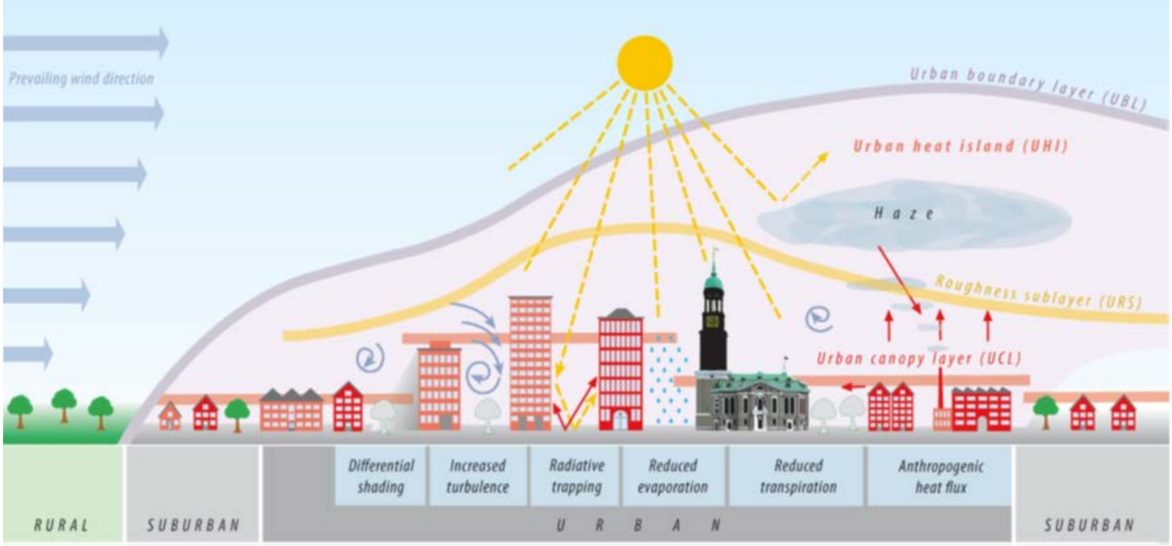

Figure 2: Urban climate is a superposition of various effects and processes. Source: adapted by Bechtel & Schmidt (2011) from Oßenbrügge & Bechtel (2010).

In the cities, the relative humidity in summer is lower during the day than in the surrounding countryside (e.g. Hage 1975, Lee 1990, Wittig 2002, Kuttler 2009). Due to the sealing of the areas and the lack of vegetation, there is less evaporation (Eschenbach and Pfeiffer 2010). In contrast, precipitation in the cities can be slightly higher than in the surrounding area (Wittig 2002). This is due to the increased number of particles in the city air, which act as condensation cores and thus contribute to the formation of clouds and thus precipitation. Despite the possibly higher rainfall, the vegetation in the city often has less water available than in natural locations, because the precipitation water is drained directly into the sewer system (Krieter & Malkus 1996, Henninger 2011). Additionally, sealing and compaction of the soils contribute to a higher surface runoff, so that only a part of the precipitation seeps into the soils (Miess 1978, Henninger 2011, Endlicher 2012) and reaches the roots of the trees. The trees that use the soil water for their transpiration also influence the local climate and contribute to cooling and increasing the air humidity (e.g. Kuttler 2009, Roloff 2013a, FLL 2015, Gillner et al. 2015a, Rahman et al. 2017). Another aspect that affects the water balance is groundwater, which is often lowered in the city for the benefit of urban development (Endlicher 2012) and thus only accessible to a few plants.

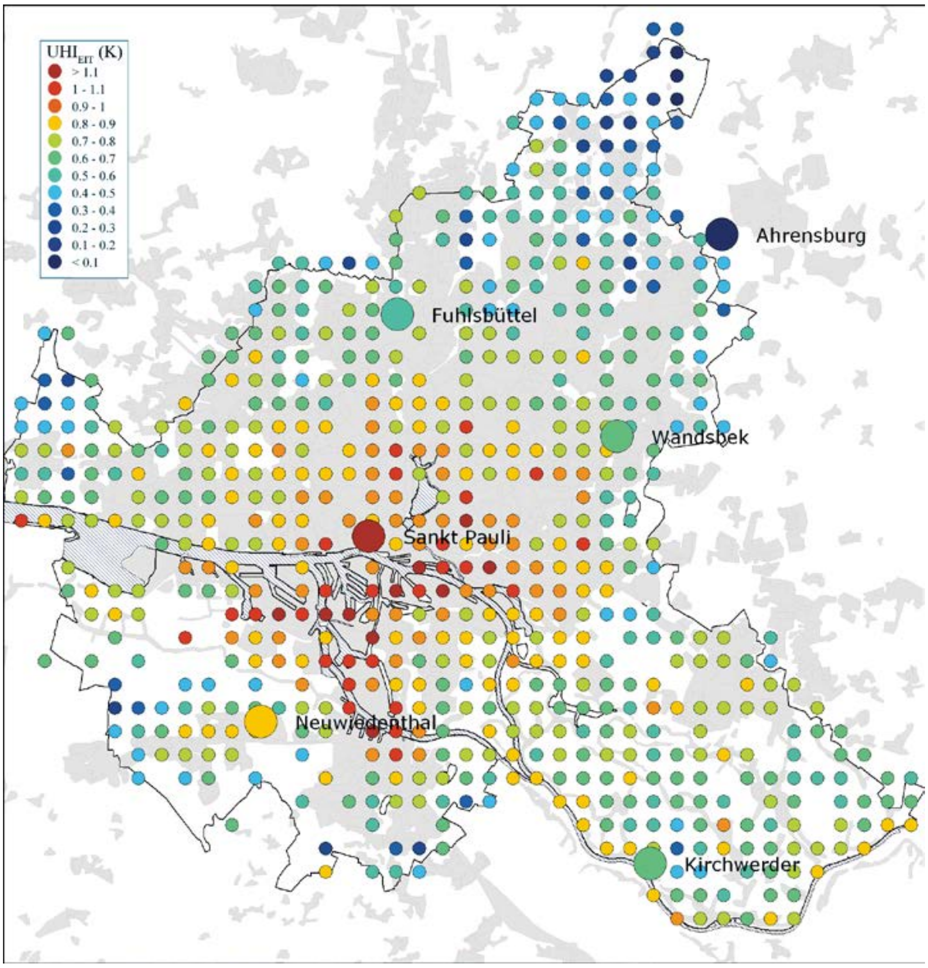

Figure 3: Mean heat island intensity for Hamburg, derived from mean Ellenberg indicator values for temperature (UHI_{EIT}). Large circles: values measured by Schlünzen et al. (2010); small circles: predicted values on a km^2 raster. Source: Bechtel & Schmidt (2011).

Schlünzen et al. (2010) showed that the climate in the metropolitan region of Hamburg has already changed measurably. The daily mean value temperatures have increased by 0.07 K per decade from 1891 to 2007. Precipitation levels have also increased by about 0.8 mm per year in the same period (Schlünzen et al. 2010). However, the change in precipitation in the Hamburg metropolitan region shows significant seasonal differences. According to Schlünzen et al. (2010), there is a general tendency that precipitation decreases in summer month and increases in winter months. As a result of climate change, the air temperature will rise and precipitation events will change in future (Rechid et al. 2014, Schlünzen et al. 2010).

All these climatic aspects affect the growth and the vitality of the trees. Other variables like wind velocity or CO_2 concentrations in the air have additional effects, which are not mentioned here. For instance, higher CO_2 concentrations in the atmosphere can increase the growth rate of trees (e.g. Becker et al. 1994). Many of the climate variables like solar radiation or shading by buildings or wind intensity variate strongly in the cities and affect the tree at different locations to different degrees. For instance, a roadside tree can be planted in a narrow side street with high buildings close to the tree. In contrast to that, a roadside tree can be located next to a main street at a square where no buildings gave shade and where the sealing may be very high. The different locations can affect the ecosystem services of the trees. For example, Duthweiler et al. (2017) had shown that the microclimate and the sealing affects the evaporation performance of trees at urban squares. In the wake of climate change, the site conditions for urban trees will continue to change. Schlünzen et al. (2010) showed that the climate in the metropolitan region of Hamburg has already changed measurably. The daily mean value temperatures have increased by 0.19 K per decade or 0.6 K per decade, depending on the observation period. Precipitation levels have also increased from 1891 to 2007 by about 0.8 mm per year. However, the change in precipitation in the Hamburg metropolitan region shows significant seasonal differences. According to Schlünzen et al. (2010) it there is a general tendency that precipitation decreases in summer month and increases in winter months. These changes are expected to pose a further challenge for the population and the development of urban trees in future. Therefore, it is important to gain more knowledge about the present situation of trees before modeling future conditions. With these data, measures can be taken to improve the situation for trees, so that they will survive now and in future.

3. Study sites and methods

3.1 Overview of the study sites

This study was conducted at 43 different sites in the city of Hamburg. Hamburg is located in the north of Germany (Coordinates: 53°33′55″N 10°00′05″E) and has a warm temperate climate. The average temperature is 9.4°C and the precipitation sum is 793 mm (longtime average of 1981-2010, HH-Fuhlsbüttel, Deutscher Wetterdienst (DWD) 2018). The main wind direction is northwest, so that the climate in the city is influenced by the North Sea, from which the wind often brings low temperatures and moist air. The pristine soils of Hamburg are affected by sediments of the last two glacial periods (Weichsel and Saale glaciation) and of Holocene deposits of the Elbe river, which flows from Southeast to Northwest through the city (BUE 2013, BUE 2015c). Near the Elbe, fertile marsh soils are dominating, whereas in these moraine landscapes, the soils are sandy to loamy and have developed to a variety of types like Cambisols, Podzols, Gleysols and Luvisols. In wide areas of the city, the natural soils are overshaped by human activities (BUE 2013, BUE 2015c).

To prove the hypothesis of this study (see chapter 1.) soils at established road trees (in this study: planted before 1986) were analyzed as well as soils at young road trees (here: trees planted after 2007; profiles Y1-Y11). The sites of established trees can be further differentiated into the group of sites of trees, which were felled in winter 2016 and winter 2017 (profiles F1-F20), and the group with established trees, where the soil monitoring was conducted (profiles E1a-E6c). Most of these sites were located in the city center of Hamburg (see Figure 4).

The following table (Table 1) shows the sites of the analyzed soil profiles, the date of soil sampling as well as the tree species and its year of planting.

Table 1: Location of study sites, tree species and year of planting as well as soil sampling date. “F” in the profile labelling means sampled at sites of felled trees, “E” means sites of established trees with monitoring, where the profiles are marked with a, b and c. “Y” is used for sites of young tree monitoring; a, b, c stand here for different trees in the same street.

Profile no.	Easting (Gauss-Krüger)	Northing (Gauss-Krüger)	Tree species	Year of planting	Date of sampling
F1	3571800	5937636	*Acer pseudoplatanus* L.	1963	10.02.2016
F2	3569459	5940098	*Acer platanoides* L.	1974	10.02.2016
F3.1/ F3.2	3569448	5938665	*Acer pseudoplatanus* L.	1956	12.02.2016
F4	3561089	5935821	*Acer pseudoplatanus* L.	1950	19.02.2016
F5	3563514	5937230	*Quercus robur* L.	1948	01.03.2016
F6	3564786	5938001	*Acer platanoides* L.	1974	21.03.2016
F7	3560727	5935651	*Acer pseudoplatanus* L.	1965	07.04.2016
F8	3568994	5938308	*Acer pseudoplatanus* L.	1950	05.04.2016
F9	3561055	5935607	*Acer pseudoplatanus* L.	1965	07.04.2016
F10	3564193	5938600	*Acer platanoides* L.	1958	21.04.2016
F11	3569744	5933759	*Acer pseudoplatanus* L.	1965	02.03.2017

F12	3569496	5936602	*Quercus robur* L.	1980	07.03.2017
F13	3569440	5936176	*Acer pseudoplatanus* L.	1965	07.03.2017
F14	3566233	5938538	*Acer platanoides* L.	1946	09.03.2017
F15	3569341	5944905	*Acer platanoides* L.	1992	13.03.2017
F16	3563445	5939359	*Quercus robur* L.	1960	16.03.2017
F17	3581286	5929558	*Acer platanoides* L.	1945	24.03.2017
F18	3563217	5925554	*Acer platanoides* L.	1984	27.03.2017
F19	3564829	5925118	*Quercus robur* L.	1970	04.04.2017
F20	3581962	5928608	*Acer pseudoplatanus* L.	1970	06.04.2017
E1a-c	3564757	5936442	*Acer pseudoplatanus* L.	1979	22.02.2016
E2a-c	3563598	5935501	*Acer pseudoplatanus* L.	1981	29.02.2016
E3a-c	3563892	5936667	*Acer pseudoplatanus* L.	1969	07.03.2016
E4a-c	3571985	5947259	*Quercus robur* L.	1984	04.04.2016
E5a-c	3562452	5936424	*Quercus robur* L.	1960	12.04.2016
E6a-c	3567364	5940115	*Quercus robur* L.	1886	2013*
Y1	3565258	5937779	*Carpinus betulus* L.	2016	10.04.2017
Y2a	3575915	5934758	*Quercus cerris* L.	2016	09.08.2016
Y2b	3575806	5934704	*Quercus cerris* L.	2016	09.08.2016
Y2c	3575747	5934663	*Quercus cerris* L.	2016	28.06.2016
Y3a	3576670	5933599	*Acer platanoides 'Fairview'*	2016	09.08.2016
Y3b	3576670	5933715	*Acer platanoides* 'Fairview'	2016	09.08.2016
Y3c	3576671	5933781	*Acer platanoides* 'Fairview'	2016	09.08.2016
Y4a	3575132	5935610	*Quercus cerris* L.	2016	06.06.2016
Y4b	3575098	5935612	*Quercus cerris* L.	2016	06.06.2016
Y4c	3575069	5935613	*Quercus cerris* L.	2016	06.06.2016
Y5	3568137	5935988	*Quercus robur* L.	2015	23.11.2016
Y6	3570727	5935851	*Quercus robur* L.	2014	07.12.2016
Y7	3565958	5934765	*Quercus palustris* Münchh.	2012	07.12.2016
Y8	3566690	5935315	*Quercus palustris* Münchh.	2007	13.12.2016
Y9	3563991	5936130	*Acer pseudoplatanus* L.	2013	13.04.2017
Y10	3568617	5936146	*Acer pseudoplatanus* L.	2011	13.04.2017
Y11	3563901	5934814	*Prunus nigra* Aiton	2017	18.09.2017

* Sampling and analyses of soil data by S. Thomsen (see Thomsen 2018).

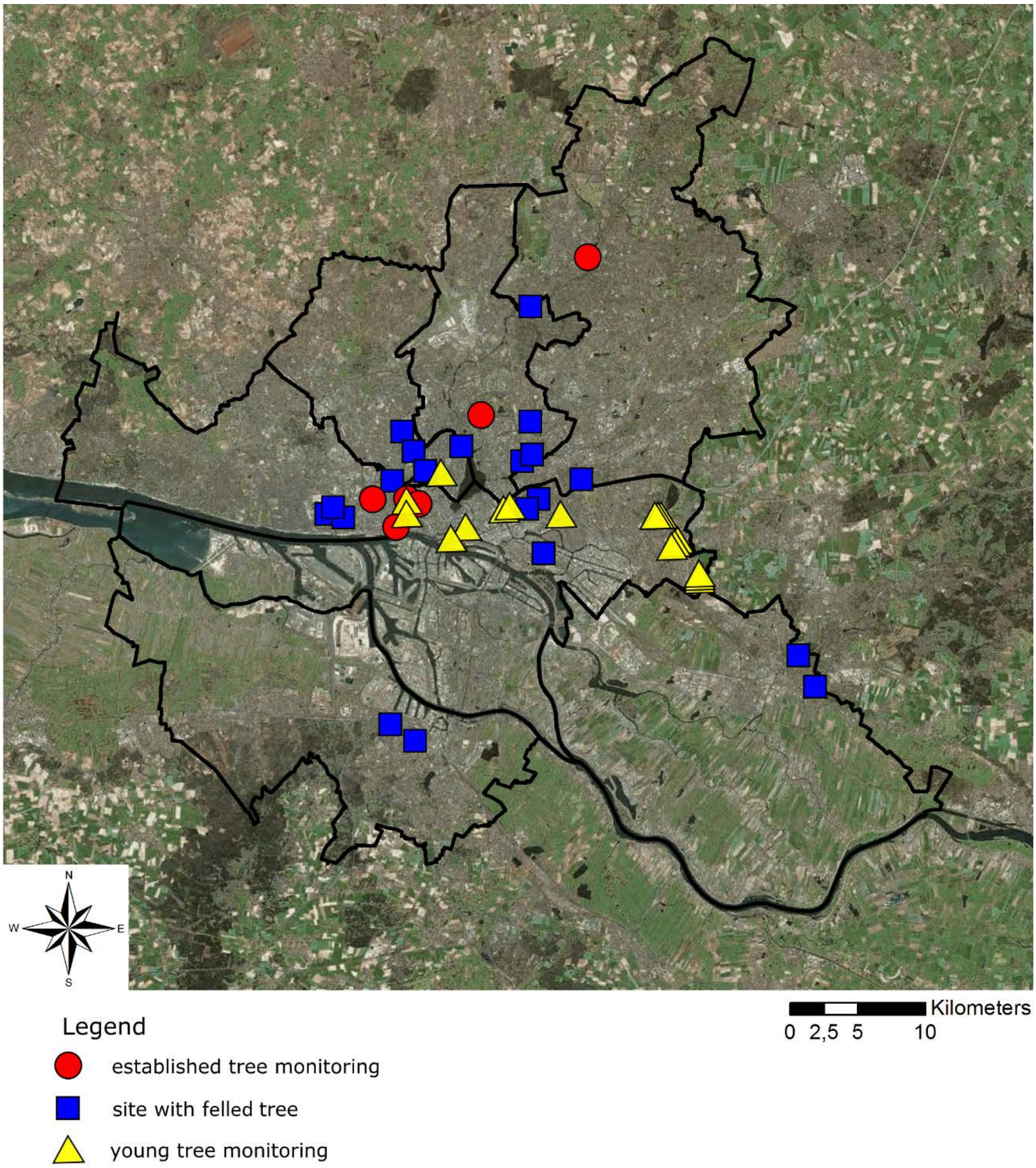

Figure 4: Locations of study sites in Hamburg. Source of base map: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

3.2 Selection of tree species

The selection of tree species had been conducted together with co-workers of the department of Biology (Biozentrum Klein Flottbek, Universität Hamburg) and with consultation of Mr. Gerhard Doobe (Behörde für Umwelt und Energie der Freien und Hansestadt Hamburg, BUE). The most important criteria were their quantity in the city of Hamburg. Species were chosen, which are planted in Hamburg in large numbers, so these species are important to analyze because of their relevance for the city. If these trees do not cope with the future climate, the green of the city will change dramatically. Another aspect for selection was the knowledge about the species concerning their vulnerability to water stress.

The tree species with the highest quantity of roadside trees in the city of Hamburg is the Common oak (*Quercus robur* L.) with 40,351 trees (41,239 inclusive cultivar), which are 18.1% of all roadside trees in Hamburg in the year 2015 (BUE 2015f). *Quercus robur* is named in the GALK-Straßenbaumliste (GALK e.V. 2015) as suitable for planting in urban areas at streets. In addition to that, it is listed in the Klimaartenmatrix (climate species matrix) of Roloff (2013) as drought stress tolerant and by Brune (2016), who compared various drought stress classifications, as moderately stress tolerant. Based on the relevance for the appearance of the streets in Hamburg and its dry stress tolerance, the selection of *Quercus robur* was decided.

As comparison species, maple trees were chosen because of their high number in Hamburg. For this study, Norway maple (*Acer platanoides* L.) and Sycamore maple (*Acer pseudoplatanus* L.) were selected. *Acer platanoides* is after *Quercus robur* and *Tilia x vulgaris* L. the third most common street tree species in Hamburg. Its percentage of all street trees in Hamburg is 5.6% (13,134 trees) (BUE 2015f). Norway maple is concerning to Roloff (2013a) and concerning to the GALK-Straßenbaumliste (GALK e.V. 2015) suitable or with restrictions suitable for planting in urban areas and Brune (2016) classified this species as moderately tolerant. *Acer pseudoplatanus* is with 6,047 trees also one of the more common tree species in Hamburg (2.7% of all street trees in Hamburg; 9th most common species) (BUE 2015f). In contrast to the other two selected species, it is known that this species is not so suitable for urban areas: *Acer pseudoplatanus* is not dry stress tolerant (Roloff 2013a) and this species is also listed in the GALK-Straßenbaumliste (GALK e.V. 2015) under trees, which are not suitable on sites with soil compaction and high degree of sealing, which is often the case in urban areas. Brune (2016) listed it this tree species as a moderately sensitive to drought. During the last few years, this tree species was only seldom planted in Hamburg (Doobe, BUE, personal communication, 2015), because many trees showed problems of low vitality and decreased growth.

Therefore, the study concentrated on three common tree species of Hamburg. Two of them (*Quercus robur* and *Acer platanoides*) are regarded as well suited for present conditions in urban areas. The other one (*Acer pseudoplatanus*) is not that suitable for urban areas and was used for comparison.

For the study of soil moisture reactions at sides of the young trees, mainly the same tree species were chosen, namely *Quercus robur*, *Acer platanoides* and *Acer pseudoplatanus*. Further, measurements at sites with additional tree species were conducted. Therefore, two species, Turkey oak (*Quercus cerris* L.) and Norway maple with variety „Fairview“ (*Acer platanoides* ‘Fairview’), were chosen, which were planted as a part of the GALK test (GALK e.V. 2015). The trees in this test are trees species, which are relatively new species in Hamburg and are not yet frequently planted in this city. They are tested due to their expected suitability for good growth in urban areas. Therefore, they are subjected to a more intensive and more frequent observations by the district office than normal young trees. That makes them suitable for the measurement of this study, because it is expected, that these species can live under urban conditions. The sites with pin oaks (*Quercus palustris* Münchh.) were recommended by the BUE (Doobe, BUE, personal communication, 2015). These trees grow also on dryer soils (GALK e.V. 2015). *Prunus nigra* (Y17) was chosen because it was planted next to the established tree with our measurement at site E3, so that the chance to measure a young tree and an established tree at the same study site was taken.

3.3 Selection of study sites

The criteria for the selection of the study sites were different for the three groups of sites (i) in the canopy of felled trees; ii) below established trees; iii) below recently planted trees), but all selections of study sites had been carried out with use of the street tree cadaster of the City of Hamburg (BUE 2015f).

Study sites next to felled trees:

The notification of trees, which will be felled in the city of Hamburg during the next felling period, is announced by the district offices. With those lists, potential suitable trees were selected. Criteria for the selection were i) tree species (*Quercus robur*, *Acer platanoides*, *Acer pseudoplatanus*, see chapter 3.2), ii) planting year and iii) closeness to city center. The planting year is an important criterion for dendrochronological analyses, which were conducted by colleagues in the department of botany. In the first years after planting annual rings can be anomalous, because of change of location and adaption to it. That is why only trees planted before 1986 were chosen, so that at least twenty years can be dendrochronological analyzed.

The further criterion was the practicability of soil sampling. Main problems are trees with very small unsealed space around them, e.g. „pot trees“ (trees in raised beds), trees surrounded by pavements, roads or parking slots as well as narrow median strips, where a safe digging is not possible. In addition, only "typical" city locations were tried to analyze. That is why no trees were chosen that grow in exceptional locations such as under a bridge. This preselection was done with use of Google Street View (2015, Google LLC, Mountain View, USA), followed by an on-site visit for the final selection. After consultation of the districts and, where appropriate, the companies responsible for felling, the samplings were conducted shortly before or after the tree felling in February/March 2016 and in March/April 2017.

Study sites at established trees:

Like the selection of sites at felled trees, the criterion of planting year (≤1986) and the criterion of closeness to the city center were applied, but the selection of tree species was here reduced to two species: *Quercus robur* and *Acer pseudoplatanus*. The department of Botany needed three trees of the same species and around the same age at each study site for their plant ecological measurements. Therefore, the criterion of closeness (up to 30 meter) to two other trees of the same species and age range was added.

The objective of this approach was to analyze drought stress. Therefore sites were preselected, which were potentially dry or moist. As basis for the preselection, maps of the Behörde für Umwelt und Energie, Freien und Hansestadt Hamburg with topics 'groundwater depth in the wet hydrological year 2008' (BUE 2015a), 'sealing' (BUE 2012) and 'evapotranspiration potential' (BUE 2015b) were used. These maps were combined in ArcGIS 10.1 (Esri Inc., Redlands in California, USA, www.esri.com) to produce a map with potential dry and wet areas in the city of Hamburg. Areas with loamy substrates of low water-conductivity within the upper to two meter depth were excluded, as perched water can occur. That is why it is not sure if that area is dry, when the ground water table is low. Less is known about the artificial fillings at the marshes near the Elbe river, which areas were therefore excluded, too. In this study, a potential dry site has no material of low water conductivity up to two meter depth and the groundwater depth is at least five meter according to the maps. Five of the study sites were in those areas located. For comparison, one site (E2) was located in a potential wet region. As potential wet are named here sites with a groundwater depth less than five meter under surface ground (Figure 5).

The data of groundwater depth of potential suitable sites were justified with data from bore holes (BUE, 2015d). Afterwards the suitability of the sites was checked according to the feasibility criteria. Here the size of the unsealed area around the tree was the main criterion. The placement of the logger box must be possible next to the tree. Again, the preselection is conducted with Google Street View (2015), followed by an on-site visit for the final decision, which resulted in the sites in Table 1.

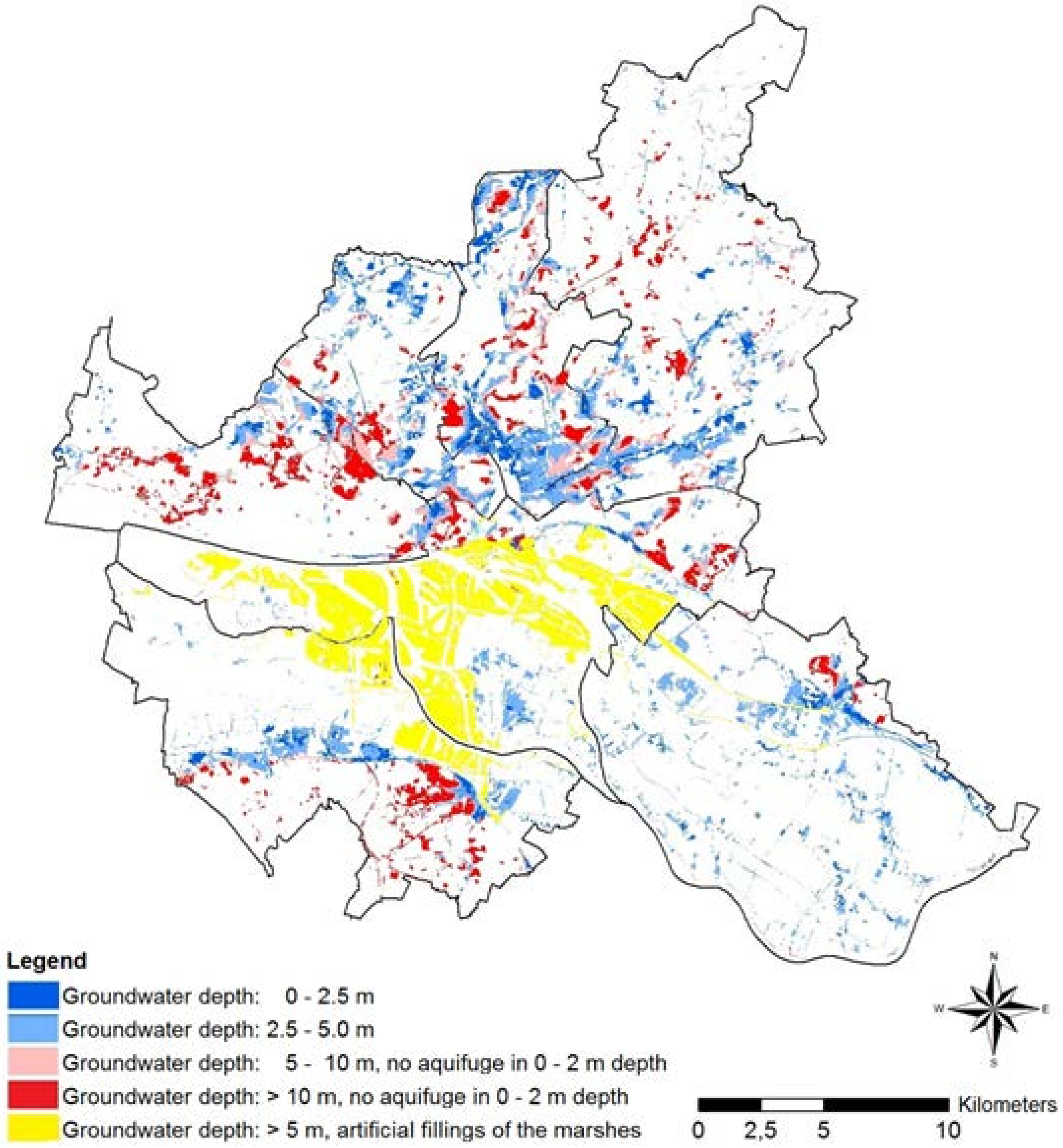

Figure 5: Potential dry (red) and wet (blue) areas in Hamburg with high sealing of the soil. Yellow areas mark artificial fillings and white areas are areas with low soil sealing and areas, which are not definite dry or wet.

Study sites at young trees:

Study sites near young trees were selected with the criterion of distance to city center or other densely populated areas in Hamburg. Other criteria were the plant species (see chapter 3.2), planting year (planted in the last 10 years) and usability of the trees for partner measurements and projects. The district offices and BUE provided lists of possible suitable young trees. Those suggested young trees are mainly trees, which were planted in spring 2016 and spring 2017.

The further tree selection was carried out on site on basis of criteria such as feasibility and representativeness. At three sites, several young trees were planted next to each other in one street. Here, trees from the middle of the plantation as well as from peripheral areas were chosen in order to take into account the possible prevailing heterogeneity along the roads (Y2, Y3 and Y7; Y4, Y5 and Y6; Y8, Y9 and Y10). At two sites (Y13 and Y14), problems with tree growth occurred during the last years before our measurement started. The soils of these trees have been rehabilitated and the trees undergo a more intensive monitoring by the district offices of the city of Hamburg than normal trees. That means, that there is more knowledge about these trees on which measurements of this study can rely on. However, these two trees are older than most of the others. The tree at site Y14 (pin oak, *Quercus palustris* Münchh.) was planted in 2012, the tree at Y13 (*Quercus palustris*) in 2007. As sycamore maple are nowadays rarely planted in the city of Hamburg, trees from earlier plantation had to be used for our monitoring. The two sycamore maples were panted in 2011 and 2013 respectively.

3.4 Study design

The study design was adapted to the research aims and thus at the three different groups of trees - felled established trees, living established trees and young trees – different sets of soil properties were analyzed.

Study sites at felled trees

At study sites at felled trees, soil analyses were conducted to gain knowledge about the different urban soils, in which the roots of road trees grow in Hamburg.

In winter 2015/2016, sampling was done at ten soil profiles at sites of felled trees in the unsealed area of the roadside vegetation (tree pit surfaces, grass strips, green areas and medial strips). The study sites were in the following streets (see Table 1): Ahornstraße 6 (F1), Drosselstraße 15 (F2), Holsteinischer Kamp 101 (because of horizontal small-scale heterogeneity in the dug profile, two directly adjacent profiles (F3.1, F3.2) were analyzed), Bleickenallee 16 (medial strip; F4), Langenfelder Straße 4 (F5), Monetastraße 1 (address: Sedanstraße 24; F6), Bernadottestraße 43 (adress: Bei der Rolandsmühle 1a; F7), Gluckstraße 6a (F8), Bernadottestraße 32 (F9) and Bismarckstraße 83 (F10). In the following winter, soil profiles were sampled in Hanseatenstieg (F11), Hirtenstraße 19 (F12), Eiffestraße 440 (F13), Pöseldorfer Straße (Harvestehuder Weg 24; F14), Stübeheide 89-95 (F15), Stresemannallee (Troplowitzstraße 17; F16), Reinbeker Weg 53 (F17), Denickestraße 151 (F18), Baererstraße 82 (F19) and in August-Bebel-Straße 253 (F20).

At each study site, one soil profile was dug in the area of the former crown region of the felled trees. Depending on the local conditions, the distances of the profiles were about 0.4 to 3.5 meter away from the tree trunk. Because of different local conditions, it was not possible to choose at all study sites exactly the same distance.

The soil profiles were analyzed up to a depth of one meter, if it was possible to open the profiles up that depth. In the field, the soils were described according to Ad-hoc-

Arbeitsgruppe Boden (2005). Samples (mixed samples and undisturbed samples with steel cylinders where possible) were taken from each soil layer for laboratory analytics.

Laboratory analytics (see chapter 3.6): particle size distribution, color, pH value, electrical conductivity, total C and N content, inorganic C content, bulk density, particle density, pore volume, effective field moisture capacity, water retention curve with pressure plate method and with HYPROP (2015, UMS GmbH, München, Germany). Water-soluble ions were analyzed at the topsoil samples.

Study sites of established trees with monitoring

At study sites with monitoring at established roadside trees, the trees were living during the study period. At these sites, soil analyses were also conducted, but additionally a soil monitoring from spring 2016 to December 2017.

The study sites at established trees were in Glacischaussee 1 (E1), Silbersacktwiete 9 (E2), Bei der Schilleroper 3 (E3), Poppenbüttler Landstraße (intersection with Kritenbarg) (E4), Gerichtstraße 9-11 (E5) and Borgweg 2 (E6) (see Figure 4). Whereas E3 is located in a potential wet area, while the other sites were potential dry.

At each site, three soil profiles were analyzed and instrumented with soil water content, soil water tension and temperature sensors as well as gas lances. The profiles were located within the crown region of the respective trees, with 1m-2.5m distance from the trunk and a depth of one meter, whereas two profiles were close to the stem with about one meter distance, while the other had a higher distance of about 2.5 m from the stem. To reduce the possibility of damaging roots a vacuum truck was used to suck profile holes at four sites and used compressed air to loosen the soil and a vacuum pump create the hole for the soil profile at other site. Arborists of the district offices accompanied these excavations to ensure that the tree roots were not damaged. In March and April 2016, the monitoring devices were installed in 20 cm, 40 cm, 70 cm and 100 cm beneath the surface (see Figure 6). In the profiles E1b, E1c, E2b, E2c, E3b, E3c, E4b, E3c, E5b, and E5c the temperature was measured only in depths of 20 cm and 100 cm.

The installations at E6a-E6c were differing, as the devices were taken over from a former measurement program (see Thomsen 2018 for details). The water tension devices were in 10 cm, 20 cm, 40 cm, 80 cm, and in E6a additionally in 160 cm. Water content sensors were in 5 cm, 10 cm, 20 cm, 40 cm, 80 cm, and in profile E6a additionally in 160 cm. Temperature sensors were located in E6a in 5 cm, 40 cm and 160 cm under the surface. Gas lances were added near the monitored profiles in July 2016. At profile E6a, the gas lances were in 15 cm, 30 cm, 40 cm and 80 cm depth. In profile E6b, they were in 15 cm, 30 cm, 50 cm and in profile E6c in 30 cm, 50 cm and 80 cm depth.

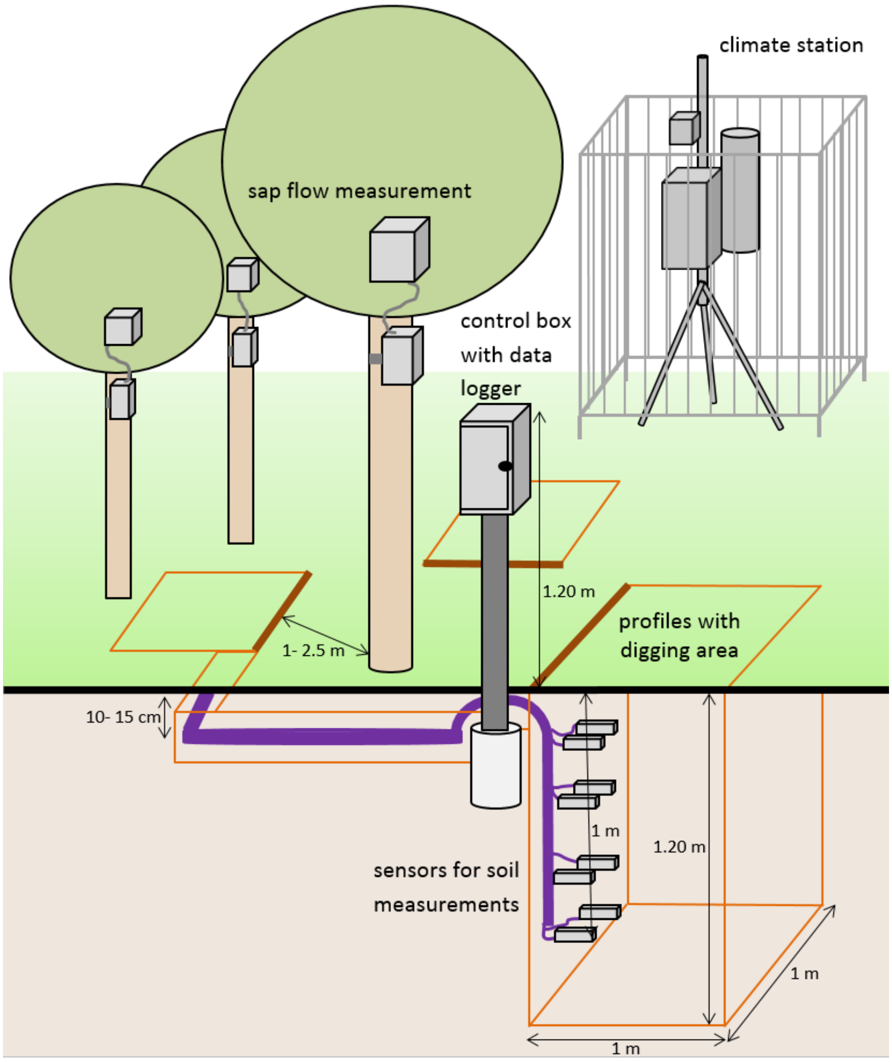

Figure 6: Scheme of the location of the profiles and sensors for soil water tension, soil water content, soil temperature and gas lances around established trees.

The water content, water tension and soil temperature were logged every ten minutes (at some profiles every 15 minutes or hourly). The data were converted in hourly and daily values for further analyses. Soil gas (CO_2 and O_2) was manually measured every two weeks with a gas analyzer. In summer/fall 2017 the measurement frequency has been increased up to weekly measurements until the end of all field monitoring measurements of this study at the end of December 2017.

The soil profiles E1a-E5c were analyzed up to a depth of one meter. In the field, the soils were characterized according to Ad-hoc-Arbeitsgruppe Boden (2005). Mixed samples and undisturbed samples with soil sampling rings where possible were taken from each soil layer if possible for laboratory analytics.

Measurements of the infiltration rates (double-ring infiltrometer, 300 mm inner ring diameter) were done at the unsealed surfaces of the sites E1-E6 by Kuqi (2017).

The following laboratory analyses were performed on samples of each layer (see chapter 3.6): particle size distribution, color, pH value, electrical conductivity, total C and N content, inorganic C content, bulk density, particle density, pore volume, effective field moisture capacity, water retention curve with pressure plate method and with HYPROP. Water soluble ions (chloride, fluoride, nitrite, bromide, nitrate, sulfate, calcium, sodium, magnesium, potassium) were analyzed in the topsoil samples. Additionally, these and other pollutants (lead, cadmium, zinc, copper, nickel, arsenic and polycyclic aromatic hydrocarbons) were analyzed in all substrate layers of one profile of each site by Zander (2016). In this study, the laboratory analyses of E6a-c, which Thomsen (2018) had published, were used. In those profiles, the samples were from fixed soil depths.

At the sites E3, E4, and E6, climate stations with measurement sensors for precipitation, air temperature, solar radiation and soil heat flux were installed within the "Stadtbäume im Klimawandel" (SiK)-project.

Study sites at young urban trees

A monitoring of the soil water tension and soil temperature was conducted at 17 young trees (see Table 1). At three sites (Y2, Y3, Y4), the measuring were done at three different trees of the same species to determine the variation within one street. At the other sites, measuring was conducted always at one tree.

The measuring devices were installed from the soil surface at the study sites after all planting activities were completed and aimed to register the soil water tension in the root ball, the planting pit and the "natural" substrate around them in different depth (see Figure 7). At each tree, two water tension sensors were in the root ball substrate in about 30 cm depth. In the planting pit, two water tension sensors were in 20-30 cm depth, two in 60 cm depth and one in 70 cm depth at the bottom of the planting pit. In the surrounding urban soils, two water tension sensors were placed in 20-30 cm, 60 cm and in 100 cm depth. Temperature sensors were in 30 cm, 70 cm and in 100 cm depth installed (see Figure 7). The water tensions and the temperatures were logged every 30 minutes during the measurement period, starting after installation of the sensors (see sampling date in Table 1).

During the installation of the sensors, soil samples of the respective substrates could be taken from the drill. The following laboratory analytics (see chapter 3.6) were conducted at these samples: particle size distribution, color, pH value, electrical conductivity, total C and N content and particle density. P and K content were measured in the uppermost layers.

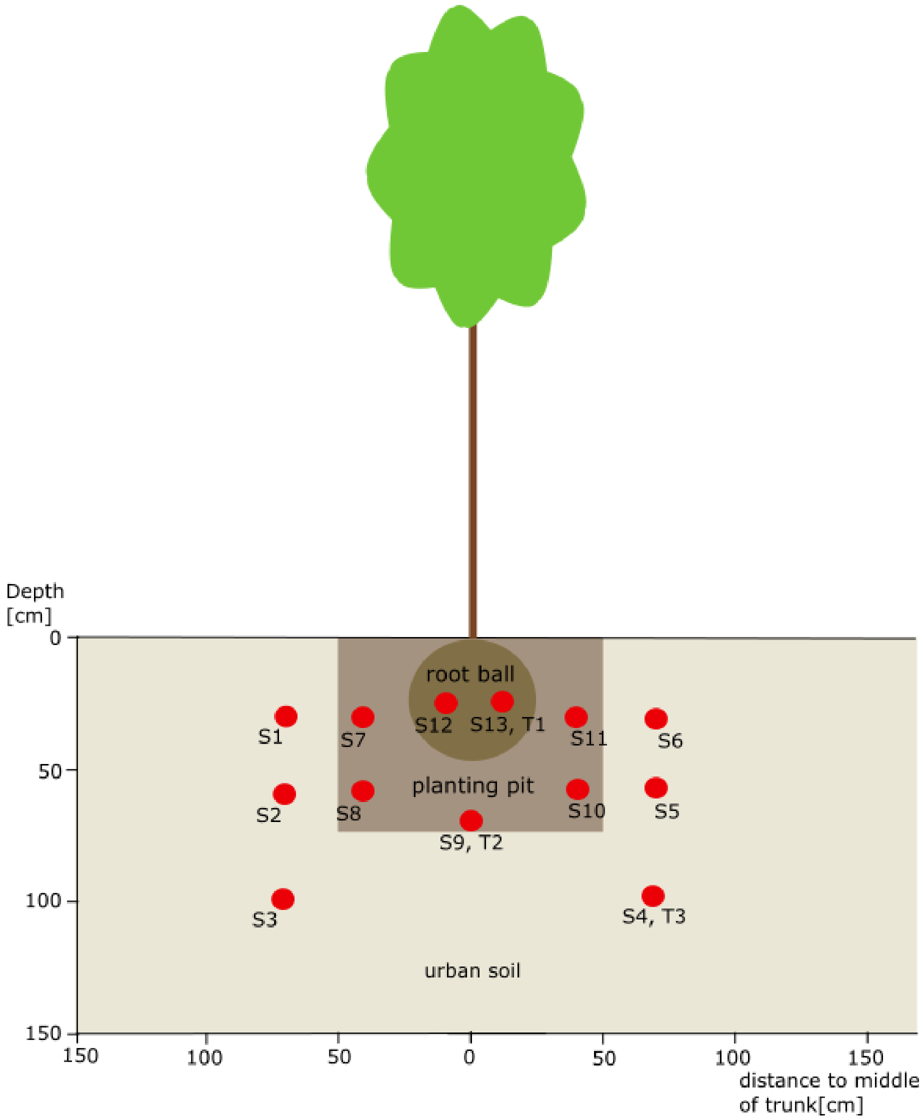

Figure 7: Scheme of the distribution of water tension sensors (S1-S13) and temperature sensors (T1-T3) in the different substrates at young trees.

3.5 Site survey, field measurements and climate data

3.5.1 Site survey and soil profile characterization

The surrounding area of all studied trees were characterized by a detailed survey of the surface features. Therefore sketches of the surrounding of the trees (20 x 20 m) and digging spots were drawn, showing the distance to the roads, buildings and green areas and so the soil sealing. A site and soil profile survey was conducted according to Ad-hoc-Arbeitsgruppe Boden (2005), for which the geographic coordinates and the elevation above sea level were identified by GPS. The measured GPS data were compared and verified with data of the Freie und Hansestadt Hamburg, Landesbetrieb Geoinformation und Vermessung (2014), because the GPS-measurements of the elevation were often very inaccurate. On the site, inclination, relief characteristics, types of use (e.g. green area, sidewalk), surface cover, weather and orientation of the dug profile were identified. The horizon and layer boundaries of the soil profile were identified, the soil texture was determined with finger test and the colors were marked without use of color tables according to Ad-hoc-Arbeitsgruppe Boden (2005). Further soil properties such as special characteristics of layer boundaries or hydro-morphologic characteristics (e.g. rust spots) were noted, as well as humus content, soil moisture, structure and size, the bulk density, cavities, the density of roots, number of soil organisms and skeleton content. The determination of the carbonate content was carried out with hydrochloric acid. The corresponding horizon symbols were assigned to the horizons and the soil systematical unit as well as the soil types were noted. The soils were classified according to the Ad-hoc-Arbeitsgruppe Boden (2005). Additionally, more detailed surface characterizations with analyses of the height at the monitoring sites (run off direction) were done by Kuqi (2017), Strachwitz (2017) and Ruprecht (2018). They measured the relative surface heights in relation to the surface heights at the trees with a surveyor's optical level (Pentax AL 320) in the 20 x 20 m areas. At each site, the degree of surface sealing was determined on basis of the 20 x 20 m drawings (partly done by Kuqi (2017) and Ruprecht (2018)). Whereas sealing means in this study full sealed surfaces as well as partly sealed surfaces like paving stones, where only very few water inflow into the soils were expected. Kuqi (2017) did measurements of the infiltration rates of the unsealed surfaces with a double ring infiltrometer according to DIN 19682-7:2015-08 at the sites E1-E6. The infiltration rates were classified according to Wolff (1993).

3.5.2 Soil sampling

At study sites of established trees excavations of soil profiles were done. During these excavations, up to five small 100 cm³ sampling rings and up to three large sampling rings with a volume of 250 cm³ were taken at each layer of the soil profiles. In addition to that, mixed samples from each horizon were taken.

At study sites of young trees, only mixed samples were taken with a soil driller. The planting pit substrates and the urban soil next to the planting pits were sampled, if possible. Thin layers could not be sampled due to methodical reasons. Sampling of the root ball substrate was not feasible due to the strong root penetration.

3.5.3 Soil gas and moisture monitoring devices and data corrections

For soil O_2 and CO_2 measurements, soil gas concentrations were analyzed with the gas-analyzer BIOGAS BM 2000 (Geotechnical Instruments (UK) Ltd., Leamington, UK). This measurement was conducted biweekly, except for the vegetation period of 2017, when weekly measurements were done.

The soil volumetric water content (VWC) was measured with CS650 probes (Campbell Scientific Ltd., Bremen, Germany), which have a water content accuracy of ± 3% (if the factory VWC model is applied) at E1a, E2a, E3a, E4a and E5a. These probes measure in addition to VWC the soil temperature. At E6a-c, CS615 probes (Campbell Scientific Inc., Shepshed, UK; same accuracy) are used. At all other soil profiles, CS616 probes (Campbell Scientific Ltd., Bremen, Germany) were used, which have a measurement range of 0-50% VWC with a slightly improved accuracy of ± 2.5%. The water content was logged with the data logger CR1000 (Campbell Scientific Ltd., Bremen, Germany).

For measurements of the soil water tension at the young trees and at established trees, the WATERMARK soil moisture sensors - 200SS were used, which measure the soil water tension in the range of 0-200 kPa, and WATERMARK temperature sensors together with the WATERMARK M900 Monitor as data logger (Irrometer Inc., Riverside, CA, USA). All soil water and soil temperature data were logged in regular intervals (10 min, 15 min, 30 min or 1 hour) and were converted in hourly and daily values for the analyses.

The following temperature correction functions according to Allen (2000) were used for all water tension data:

(1) For R = 0 kΩ:

$$P = 0$$

(2) For 0 kΩ < R < 1 kΩ:

$$\mathrm{P} = -20 * \left(\mathrm{R} * \left(1 + 0.018 * (\mathrm{T} - 24)\right) - 0.55\right)$$

(3) For 1 kΩ < R < 8 kΩ (by Shock et al. 1998):

$$\mathrm{P} = \frac{(-3.213 * \mathrm{R} - 4.093)}{(1 - 0.009733 * \mathrm{R} - 0.01205 * \mathrm{T})}$$

(4) For 8 kΩ < R:

$$\mathrm{P}=-2.246-5.239 * \mathrm{R} * \left(1+0.018 * (\mathrm{T}-24)\right)-0.06756 * \mathrm{R}^2 * \left(1+0.018 * (\mathrm{T}-24)\right)^2$$

with:

P = water potential [kPa],
R = measured resistance [kΩ],
T = soil temperature [°C].

3.5.4 Climate data

Actual climate data

Climate data (precipitation rates, wind velocity, sunshine duration, radiation) from the climate station in Hamburg-Fuhlsbüttel (latitude/ longitude: 53°38’24”N /9°58’58”E) of the Deutscher Wetterdienst (DWD) and from the three SiK climate stations are used. They are located close to the study sites E3, E4 and E5. Missing data of these three stations were filled with the weather dates of the climate station in Hamburg-Fuhlsbüttel of the Deutscher Wetterdienst (DWD 2018). For this study, hourly and daily values were used.

Past climate data

Daily climate data (precipitation rates, wind velocity, sunshine duration, radiation) of the past from 1950 to 2016 were used from the climate station in Hamburg-Fuhlsbüttel (latitude/ longitude: 53°38’24”N /9°58’58”E) of the Deutscher Wetterdienst (DWD). The measurement of solar radiation started later at this station, so that these data were given since 1981. Missing data were estimated by average data from earlier and later days.

3.6 Methods of analyses

3.6.1 Sample preparation, skeleton content and color determination

Samples taken in the field were stored in a cool (4°C) storage room until usage. The mixed samples were homogenized. Half of each sample were dried and sieved (<2 mm) to determine the skeleton content. Small part of the sieved samples were grinded. The color of the homogenized samples were determined in dry and in wet condition according to the Munsell Color Notation.

3.6.2 pH-value, pore volume, particle size distribution, ions

The following laboratory analyses were conducted:

- pH value is taken after DIN-ISO10390 (2005). The pH value in H_2O and in 0.01 M $CaCl_2$ were measured.
- Electrical conductivity: according to DIN-ISO 11265 (1994) with WTW Cond 330i (WTW GmbH, Weilheim, Germany).
- Particle density of the dried mixed samples are measured with a gas pycnometer (AccuPyc II 1340 Pycnometer, Micromeritics Instrument Corporation, Norcross, GA, USA).
- Particle size distribution according to DIN-ISO 11277 (2002): sieving and sedimentation method in accordance with the Köhn analysis method with the Sedimat 4-12 (UGT GmbH, Müncheberg, Germany) and a mechanical shaker used for sieve analyses (Retsch, Typ Vibro, Haan, Germany).
- Soil texture class according to Ad-hoc-Arbeitsgruppe Boden (2005).
- Water retention characteristics (water capacity and available water capacity (volume of water bound in soil with a soil moisture tension between pF 1.8 and 4.2)) according to DIN EN ISO 11274 and pore volumes (pore volume and air capacity) with ceramic plates in extractors (undisturbed samples (100 cm^3 samples): -3 hPa, -20 hPa, -60 hPa, -130 hPa, and -300 hPa; mixed samples: -3000 hPa, -15000 hPa).
- Water retention characteristics of 250 m^3 samples and calculating of water tension curves (with use of the traditional constrained van Genuchten-Mualem model

(m=1-1/n, original and bimodal)) with HYPROP-FIT version 3.5.1.13951 (2015, UMS GmbH, München, Germany).

- Bulk density of dried (104°C, one day) undisturbed samples by volume and weight measurements (bulk density = dry weight/ volume); effective bulk density = dry soil bulk density + 0.009*clay[%]
- Total C content is measured with Vario MAX cube (Elementar Analysensysteme GmbH, Langenselbold, Germany) according to DIN-ISO 10694 (1996). Organic matter content was calculated by multiplying the organic carbon content by the factor 1.724 (Blume et al. 2010).
- Total nitrogen and total carbon content as well as content of water soluble ions with the atomic Absorption spectrometer (AAS) Varian AA280Z (Varian Inc. Palo Alto, California, USA). Water soluble ions were extracted with an 1:1 water: solid ratio, thus concentrations in mg/l are equal to mg/kg.

3.6.3 Modeling of water tension

The water tension of selected soil profiles is modeled with Hydrus 1D version 4.16.0110 (PC Progress s.r.o., Prague, Czech Republic). For detailed information about the model, see the technical manual written by Simunek et al. (2013).

Input data are the measured soil properties (depth of soil layers, van Genuchten parameters (Appendix II: Table 20)), daily climate data of 2016 and 2017 (see chapter 3.5.5) and biological data like the leaf area index (LAI; 3 for maple and 4.5 for oak trees in summer and 1.1 in winter season according to Breuer et al. (2003), Thomsen (2018), and Reisdorff (personal communication, 2018)) and the distribution of roots. Here, the biological input data were assumed to be constant, which means that the growth of the trees were not considered. The model can use only constant interceptions. All profiles are below tree canopies, so that the influence of interception is important und the rates are changing in the course of the year. That is why it was decided to reduce the precipitation rates by a calculated interception rate according to the following formula described by Berger (Institute of soil science, Universität Hamburg, 2012) with small changes by personal recommendations by the author (2018):

$$\mathrm{Int}_{\mathrm{Max}_i} = 12 * (1 - \exp(-\mathrm{LAI}_i \;/\; 14.2))$$

$$\mathrm{Int}_i = \mathrm{Int}_{\mathrm{Max}_i} * \left(1 \quad - \exp(-\mathrm{N_i}/\left(\mathrm{Int}_{\mathrm{Max}_i} * 1.5\right))\right)$$

with:

$\mathrm{Int}_{\mathrm{Max}_i}$ = capacity of interception storage [mm] of the day i,

LAI_i = leaf area index of the day i,

Int_i = interception of the day i,

N_i = precipitation (only rain, no snow) [mm] on the day i.

For evaluation of the quality of the model for this specific study sites, at first the period from the 3rd of June 2016 to the 3st of December 2017 was modeled with the climate data of the nearest station and the soil parameters of the profile. Then the results were compared with the measured water tensions of the profile. For comparison, the Pearson correlation coefficient (r) was used on the data from January to December 2017:

$$\mathrm{r}_{\mathrm{X,Y}} = \frac{\mathrm{cov}(\mathrm{X},\mathrm{Y})}{\sigma_{\mathrm{X}}\sigma_{\mathrm{Y}}}$$

with:

X and Y = data of measurement and data generated by the model,

$\mathrm{cov}\ (\mathrm{X},\mathrm{Y})$ = covariance of X and Y,

σ_{X} = standard deviation of X,

σ_{Y} = standard deviation of Y.

Then the inverse function of the Hydrus 1D model was used to optimize the van Genuchten soil parameters for the period from 3rd of June 2016 to the end of that year by using the water tension measurement data as data for the inverse solution.

With the resulting optimized soil parameters, the same period as with the not optimized soil parameters was modeled again, were compared with the measured data using the Pearson correlation coefficient and the root-mean-square error (RMSE) of the data of 2017 were calculated for each of the two modeled runs:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\mathrm{t}=1}^{\mathrm{T}}(\hat{\mathrm{y}}_{\mathrm{t}} - \mathrm{y}_{\mathrm{t}})^2}{\mathrm{T}}}$$

with:

t = time

$\hat{\mathrm{y}}_{\mathrm{t}}$ = modeled value to the time t

y_{t} = measured value to the time t

T = number of t.

For modeling at sites with felled trees (n=7: F1, F3, F6, F8, F12, F19, and F20), the same model with the measured soil data of each site was used. However, for all sites the same climate input data from the DWD station in Fuhlsbüttel was used. Here, site selection was based on the possibly cooperation with the department of Biology (Biozentrum Klein Flottbek, Universität Hamburg), who did dendrochronological and isotope ($^{13}CO_2$) analyses at the tree discs of these felled trees. The results of this study will be compared with the measurements of the department of Biology and together evaluated in further studies.

For each of the sites, the whole time from planting (but with the earliest year 1951 based on data quality) to 2017 was simulated. From 1951 to 1981 modeling with potential radiation was done, later years with the measured solar radiation of the station. The modeling was done with 10-years-runs, with around one year lead time. For each modeled year the amount of days with dry soil were counted (for ≥750 hPa and ≥2000 hPa in different depths up to 1 m depth; for the whole year and vegetation period). The trend of the number of dry years was calculated with a linear regression model.

3.6.4 Statistical analyses and graphical display

Statistical analyses, writing and graphical display were conducted with Microsoft Word and Microsoft Excel (Microsoft Office Professional Plus 2016), IBM SPSS Statistics version 21.0.0.0 (2012, International Business Machines (IBM) Corporation, Armonk, New York, USA), and R version 3.1.2 (2014, The R Foundation for Statistical Computing, Vienna, Austria). In this study, the one-way analysis of variance (ANOVA), and (2-sided) Pearson correlation coefficient (r), Spearman's rank correlation coefficient (r_S) for categorized data, and the Mann-Kendall test for trends of time series were used. Results of the correlation with a probability p value of less than 0.05 according to the t-test were considered significant.

Inkscape™ 0.91 (2015, Free Software Foundation, Inc., Boston, Massachusetts, USA) was used for graphics. Spatial analysis of the potential soil moisture of Hamburg was done with Esri ArcMAP 10.1 (Esri Inc., Redlands, California, USA , 2012). Schemes of the sites were drawn with TurboCAD 2D version V.19 (GK-Planungssoftware GmbH, Grabenstätt-Marwang, Germany).

4. Constant conditions at sites of established roadside trees

In this chapter, constant conditions of sites of established roadside trees in Hamburg were characterized. The focus of the analyses were location and soil properties, which have the potential to cause stress for the trees. At first, the surface sealing of the surrounding of the trees were analyzed and the infiltration rates of the unsealed parts of the soils were analyzed. This is followed by analyses of the physical and chemical soil properties. Here, the focus was on the hydrologic properties and potential stress factors like deicing salts. With this data, the potential risk for stress of established roadside trees can be determined for different urban sites next to streets.

4.1 Results

4.1.1 Surface sealing and infiltration rates

The mean surface sealing in an area of 20 m x 20 m with the tree in the middle of the 26 study sites (E1-6, F1-20) was 66%. This proportion includes completely sealed surfaces as well as surface covers with high fraction of sealing like paved sidewalks. The lowest surface sealing was found with about 16% at F13 and the three highest sealing rates with ≥90% were observed at F3 (92%), E1 (91%) and F2 (90%). The proportion of unsealed surfaces thus varied between 8% and 84% (see Figure 8).

At E1, the percentage of unsealed surface of the 400 m^2-area was 45% and at E4 40%. At E3, the unsealed area was 25% and at E6 20%. At the other two monitoring sites, the unsealed areas were with 13% (E5) and 9% (E2) much smaller. Here, the trees were located at a narrow (1.8 and 2.3 m) green area between the street and the sidewalk, where no or nearly no other vegetation were growing, except the trees. At F2, F3, F6, F9, F10 and F17, the soil directly around the trees had similar low vegetation cover during the sampling. At all other monitoring sites, the unsealed soils were vegetated by grass.

Low sealing were especially at sites, where the trees were planted in larger green areas (E1, F13 and F15). At all monitoring sites besides F13, the trees were located close to partly sealed areas like the sidewalks or totally sealed areas like streets and buildings. At most of the sites, sidewalks or streets disconnected the unsealed areas. Therefore, the unsealed areas, which were directly connected to the tree (the tree pit, green stripes or green area), were at 69% of the sites smaller; they cover on average 18.6% of the 20 x 20 m areas (standard deviation: 21.6%) (Figure 8). These areas were very small, when the tree was planted as a single tree in a planting area only for this tree (F3, F5, F7, F16 and F18) and not in a green stripe or lawn. At the site E5, the tree had the closest distance of about 3.7 m to a building. At other sites like E1, E4 and F13, the next building was more than 10 m away from the tree. For more details of E1-6, see the site plans of these sites (Appendix I: Figure 52 to Figure 57, Kuqi 2017, Ruprecht 2018).

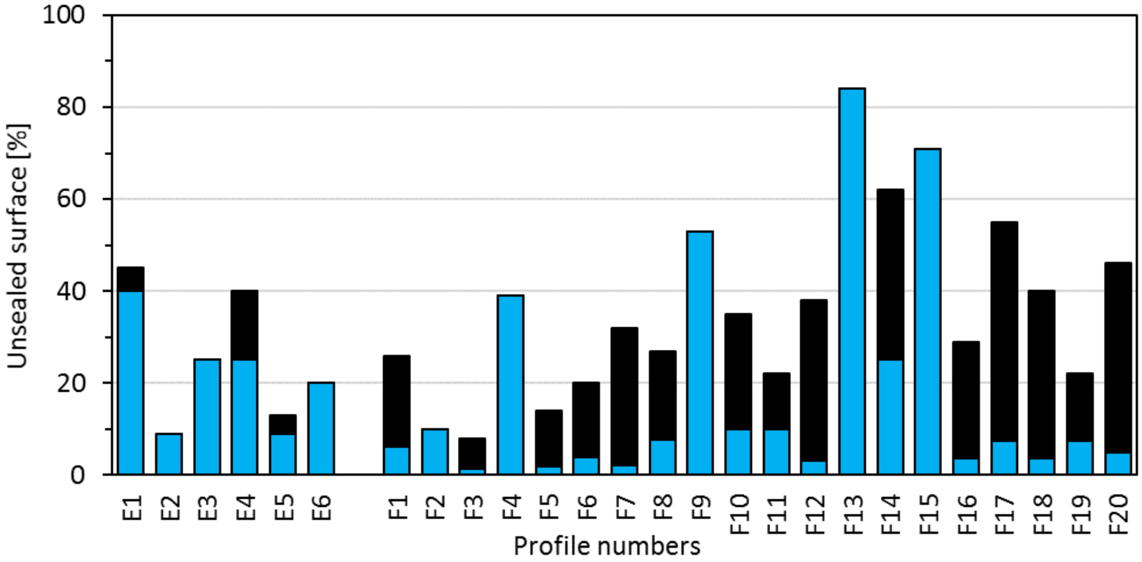

Figure 8: Proportion of the unsealed surfaces around the trees of the sites E1-6 and F1-20 in an area of 20 m x 20 m (black). Fractions of unsealed surface, which were directly connected to the tree, are marked in blue.

The mean infiltration rates of the unsealed surfaces at the sites E1-6 were varying from 2.7 cm/h (E3) to 100.2 cm/h (E1). According to the classification of Wolff (1993), the lowest value is a "low" infiltration rate, while the infiltration rate of E1 is "very high". At E6, the infiltration rate was with 34.0 cm/h high according to the classification of Wolff (1993). The infiltration rates of the other sites were close together with 7.2 cm/h (E2), 8.8 cm/h (E4) and 11.2 cm/h (E5) (Figure 9) and ranged in the category "low to medium".

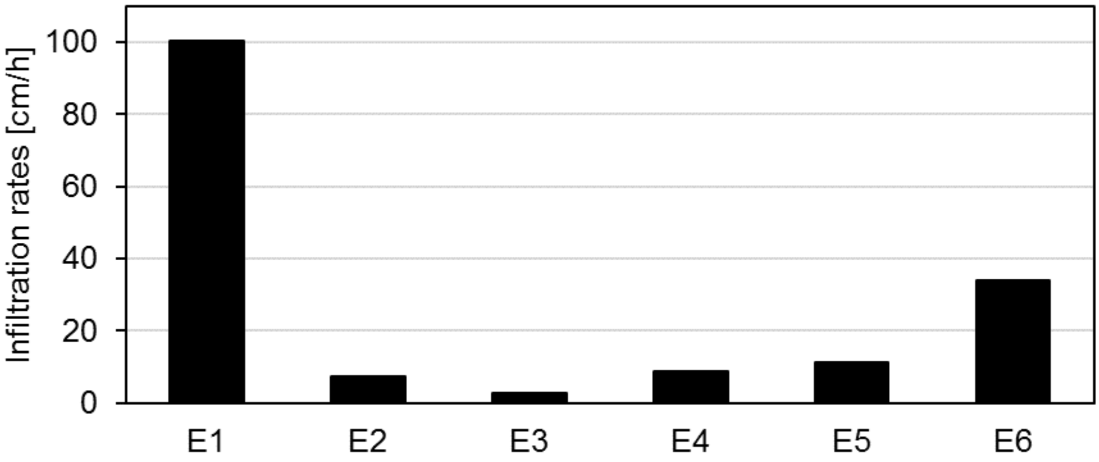

Figure 9: Mean infiltration rates of the unsealed areas at the sites E1 to E6.

4.1.2 Morphological and textural soil parameters

The majority of the analyzed soils at established roadside trees were strongly anthropogenic influenced (see chapter 2.2). Within the studied depth of one meter, the soils contained different layers with sharp layer boundaries. The different layers could be easily optical separated by their color, texture and skeleton content. Only at two sites (F1 and E1), the deeper layers were most likely of natural origin. These soils were classified as Arenosols according to the World Reference Base (IUSS Working Group WRB, 2015). The others were Terric Anthrosols or Transportic Arenosols, where no aggregation or soil genesis processes were visible. They had mainly an anthropogenic Ah-horizon (humous topsoil horizon) followed by one to six ylC-horizons (anthropogenically rearranged loose subsoil horizon). At some sites, the Ah-horizon was missing (e.g. E5a-c). In those cases, there were only C-horizons. In this study, no sites with organic topsoil layers (O or L) were found. The coloring of the layers reached from nearly white over yellow and brown to dark brown. The colors were mostly influenced by the humus content. The soils with a higher humus content had a darker brown color. White and yellow colors were found only in sandy layers with a very low clay, silt and humus content. Typically, adjacent layers had clearly different colors.

The majority of the analyzed layers consisted of anthropogenic soil substrates with a high content of sand. Very common were sandy fill materials, which were sometimes used as protection for wires or pipes. The mean of the sand content of the analyzed soil layers (n=168) from profiles E1a-E6c and F1-20 was 86.2%. The lowest sand content of the soils with 56.6% occurred in a depth of 70 to 82 cm at the profile E6c. The highest sand content with 98.7% was found in 60 to 100 cm depth at E1c. Table 18 (Appendix II) contains the grain sizes of all examined sites at established trees. Furthermore, the texture classes according to Ad-hoc-Arbeitsgruppe Boden (2005) are given. According to this systematic, 54.3% of the analyzed soil layers were pure sands (German: Reinsande) and 42.1% were loamy sands (German: Lehmsande). The few others were sandy loams (German: Sandlehme; 2.4%), normal loams (German: Normallehme; 0.6%) and silty sands (German: Schluffsande; 0.6%).

Within the layers, the percentage of coarse particles was very divers. It varied between 69.8% dry weight (DW) (F3.1, 7-15 cm depth) and 0.1% (E5c, 3-100 cm depth). The median stone content was 11.1% DW (n=150; mean: 14.1%). Ten layers had a high or very high skeleton content with more than 40% DW (see Figure 10). These layers were thin layers (thickness ≤ 22 cm), which were all located above 35 cm soil depth. 80 percent of these layers were loamy sands, and the other 20% were pure sands. In contrast to these layers with high percentage of skeleton, 20 layers had a very low skeleton content with less than 3% DW. 60% of these layers were in the deepest layers up to 100 cm of the analyzed soils. 20% were above these deepest layers. Twelve of these layers were pure sands and contained more than 90% sand particles; three layers had a sand content less than 75% DW. The coarse particles consisted of natural boulders, building debris, bricks and only to a very low percentage of waste. Red bricks were found in at least one layer at 15 of the 26 sites. In 50 cm depth of profile F13, a dense debris layer made a further excavation impossible.

Typically, layers next to power lines and pipes (F5, F12, F20, E2a-c, E3c) had a very high percentage of sand combined with a very low skeleton content. Sometimes bricks or big natural stones (diameter >15 cm) were placed over the cables to protect them. Those stones were too big for our laboratory analyses, so their influence is in this study neglected.

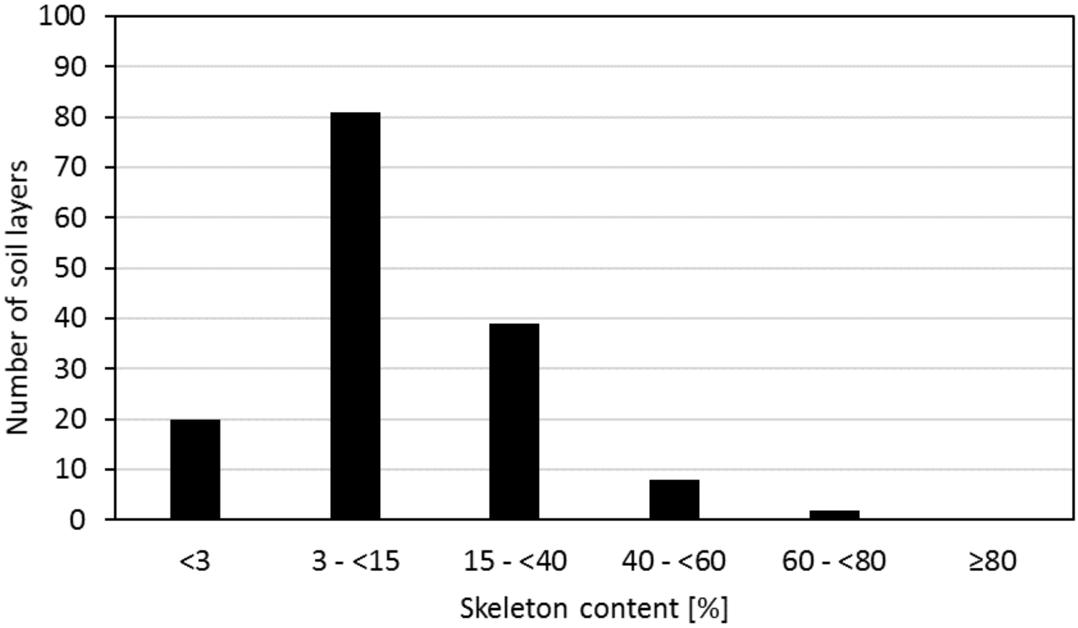

Figure 10: Skeleton content of the layers of profiles at established roadside trees (F1-20, E1a-E5c, and M6b; n=150). Categories of the skeleton content are classified according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005).

4.1.3 Density, pore volume, field capacity, air capacity and hydrologic conductivity

The mean particle density of all layers was 2.59 g/cm³. 66.7% of the layers had a density higher than 2.60 g/cm³ (Figure 11), which is similar to the density of quartz (2.65 g/cm³). 6.5% of the layers had a density lower than 2.40 g/cm³. Most of these layers were humus rich topsoils (Appendix II: Table 17).

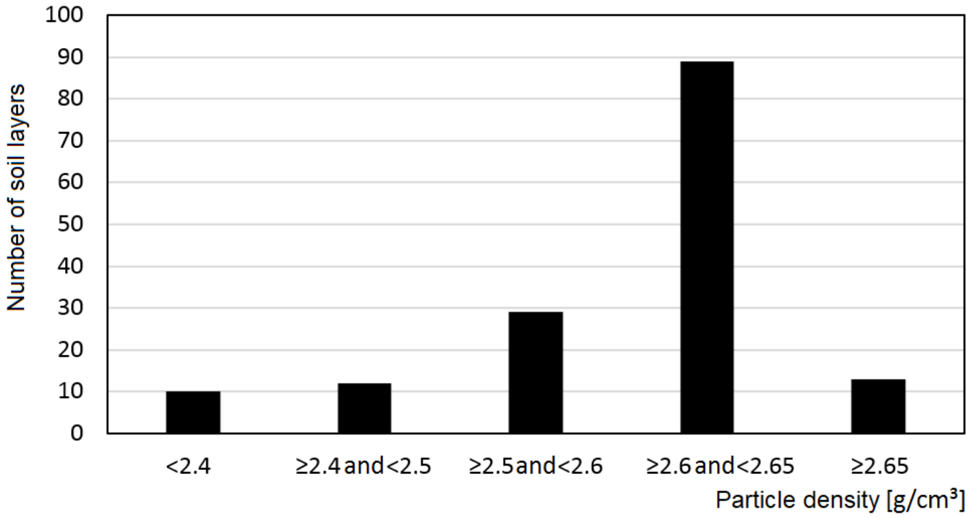

Figure 11: Distribution of the particle density of all layers (n=153).

The average effective bulk density was 1.53 g/cm³, which is classified as "low" according to Ad-hoc-Arbeitsgruppe Boden (2005). 36 layers had a "very low" effective bulk density, 36 layers a "low", 53 a "medium" and 8 layers a "high" effective bulk density (Figure 12). At most of the profiles, the bulk density was increasing with the depth (see examples in Figure 13). Only for F1, F8, F10, F11, E2a, E2c, E3b and E3c, it was found that the topsoil was denser than the second layer, which was not significant correlated with the occurrence of vegetation or the possibility of car parking on the soil surface. F14 was the only profile, for which the deepest layer (50-100 cm) was the layer with the lowest density (1.31 g/cm³) of the profile (higher layers: 1.56 and 1.60 g/cm³). The vegetated soil profiles had a slightly lower average effective bulk density of 1.27 g/cm³ in the uppermost analyzed layer than profiles with bare soils (1.39 g/cm³) (Figure 14).

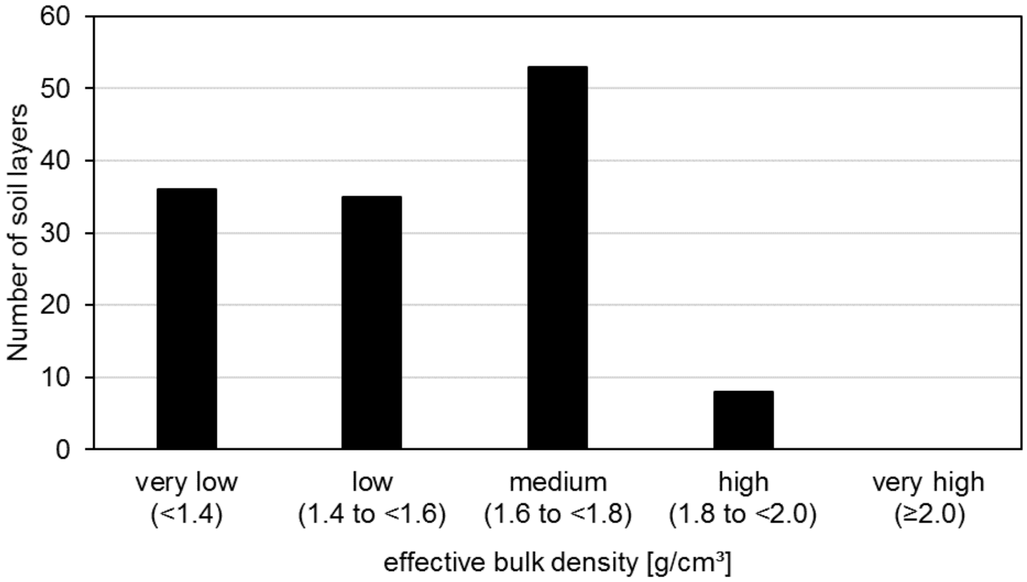

Figure 12: Distribution of the effective bulk density of the soil layers (n=132). Categories are classified according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005).

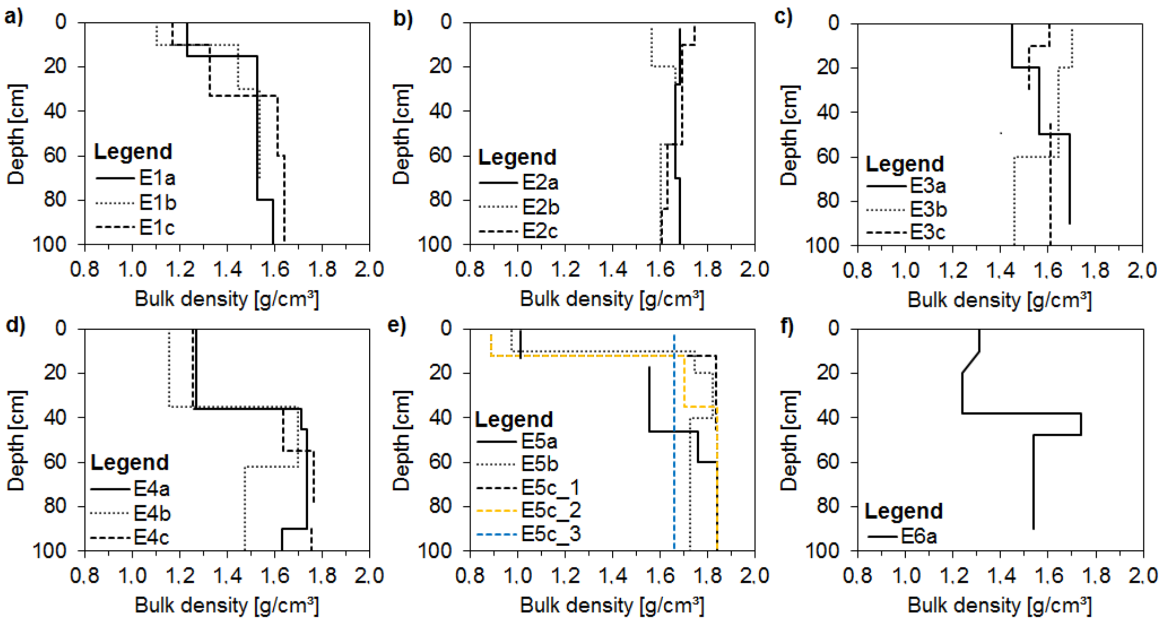

Figure 13: Examples of the bulk density profiles at the sites a) E1, b) E2, c) E3, d) E4, e) E5 and f) E6a. Data source of E6a: Thomsen (2018).

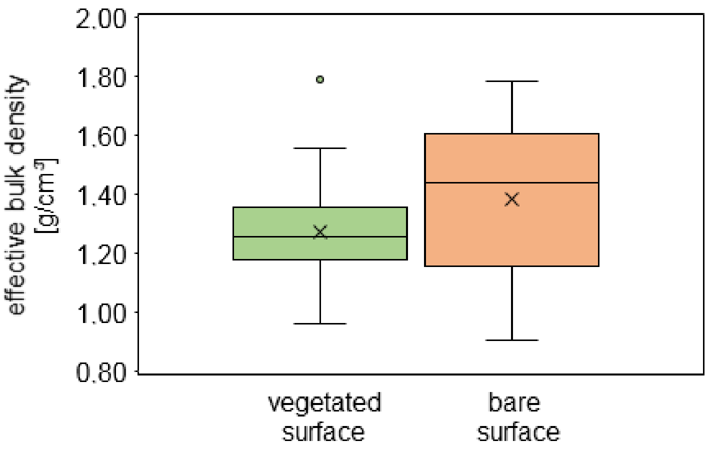

Figure 14: Effective bulk densities of the uppermost analyzed layers of profiles with vegetation on the soil surface (n=19) and of profiles with bare surfaces (n=18). The bars show the quartiles. The lines in the bars mark the medians, the outer lines the range without outliers, the crosses mark the average values, and the points the outliers.

The lowest bulk densities were 0.83 g/cm³ at F11 (10-20 cm), 0.91 g/cm³ at E5c (3-12 cm), 0.93 g/cm³ at F3.1 (0-7 cm), 0.96 g/cm³ at F4 (0-22) and 0.99 g/cm³ at E5b (1-10 cm). The highest bulk density was found with 1.96 g/cm³ in profile E5c in a depth of 45 to 100 cm. Other "high" bulk densities (>1.80 g/cm³) according to Ad-hoc-Arbeitsgruppe Boden (2005) were measured in the same profile in 12 to 45 cm depth (1.89 g/cm³) and in the two other profiles of that site (E5b: 20-100 cm, 1.90 and 1.81 g/cm³; E5a: 46-100 cm, 1.82 and 1.95 g/cm³). Only one other layer of another site had a similar high bulk density: F17 (70-100 cm, 1.81 g/cm³). The bulk density had a high significant correlation of r=0.824 (p<0.001) with the particle density.

The distribution of the pore volume was almost inverse to the bulk densities. The highest pore volume (66.7 vol.-%) was found at F11 (10-20 cm) and was classified as "very high" according to Ad-hoc Arbeitsgruppe Boden (2005). "Very high" pore volumes (≥54 vol.-%) were measured only at the top layers above 20 cm (F3.1, F4, F5, F8, F11, F13, F16, F19, E1b, E5a, E5b, and E5c). Sometimes under these high-porosity topsoil layers, a change of material with a sharp decrease in pore volume was observed. For example, the top layer of profile E5c had a high pore volume with 61.6 vol.-%, but the layers below exhibited a pore volume of only 30.1 vol.-% to 37.5 vol.-% (see Appendix II: Table 19). In this profile, the lowest pore volume of all layers was measured in 45-100 cm depth. Other layers with "low" pore volumes (<38 vol.-%) were E6a (20 cm), F1 (4-10 cm, 15-100 cm), E2a (3-100 cm), E2b (20-55 cm), E2c (2-84 cm), E3a (50-90 cm), E3b (3-60 cm), E3c (0-10 cm), E4a (36-100 cm), E4b (35-62 cm), E4c (55-80 cm, 90-100 cm), E5a (46-100 cm), E5b (10-100 cm), E5c (12-100 cm), F10 (0-7 cm), F15 (18-62 cm), F17 (8-100 cm) and F19 (9-20 cm, 24-39 cm). 30% of all measured layers had a small pore volume. The average was 42.7 vol.-% and is according to the classification of Ad-hoc Arbeitsgruppe Boden (2005) a "medium" pore volume.

The average air capacity of all soil layers was 19.8 vol.-%. This is a "high" value according to Ad-hoc Arbeitsgruppe Boden (2005). The lowest air capacity was 3.1 vol.-% in profile E5b in a depth of 20-40 cm. Other sites with "low" air capacities (<5 vol.-%) according to Ad-hoc Arbeitsgruppe Boden (2005) were found in F1 (15-22 cm), E5a (60-100 cm) and E5c (12-100 cm). "Very high" air capacities (≥26 vol.-%) were measured in the profiles F2, F5, F6, F7, F8, F9, F11, F12, F14, F18, F19, F20, E1a, E2c, E3a, E3c, E5a, E5b and E5c. This means that nearly half of the measured profiles had at least one layer with a "very high" air capacity. These layers were mostly near to the surface, but were also often the lowest layers. They contained a high sand content or they had a small bulk density. Therefore, profiles with decreasing air capacities with the depth, as well as profiles with increasing air capacities were found (see examples in Figure 15). The mean air capacities of the profiles were at 19.4% of the profiles "medium" (5 to <13 vol.-%), at 52.8% "high" (13 to <26 vol.-%) and at 25% "very high" (≥26 vol.-%) according to Ad-hoc Arbeitsgruppe Boden (2005) (Figure 16). The mean air capacity of the profiles was 19.6 vol.-% with a standard deviation of 6.4 vol.-%. The correlation between air capacity and sand content was $r=0.591$ ($p<0.001$) and between air capacity and bulk density $r=-0.243$ ($p<0.001$).

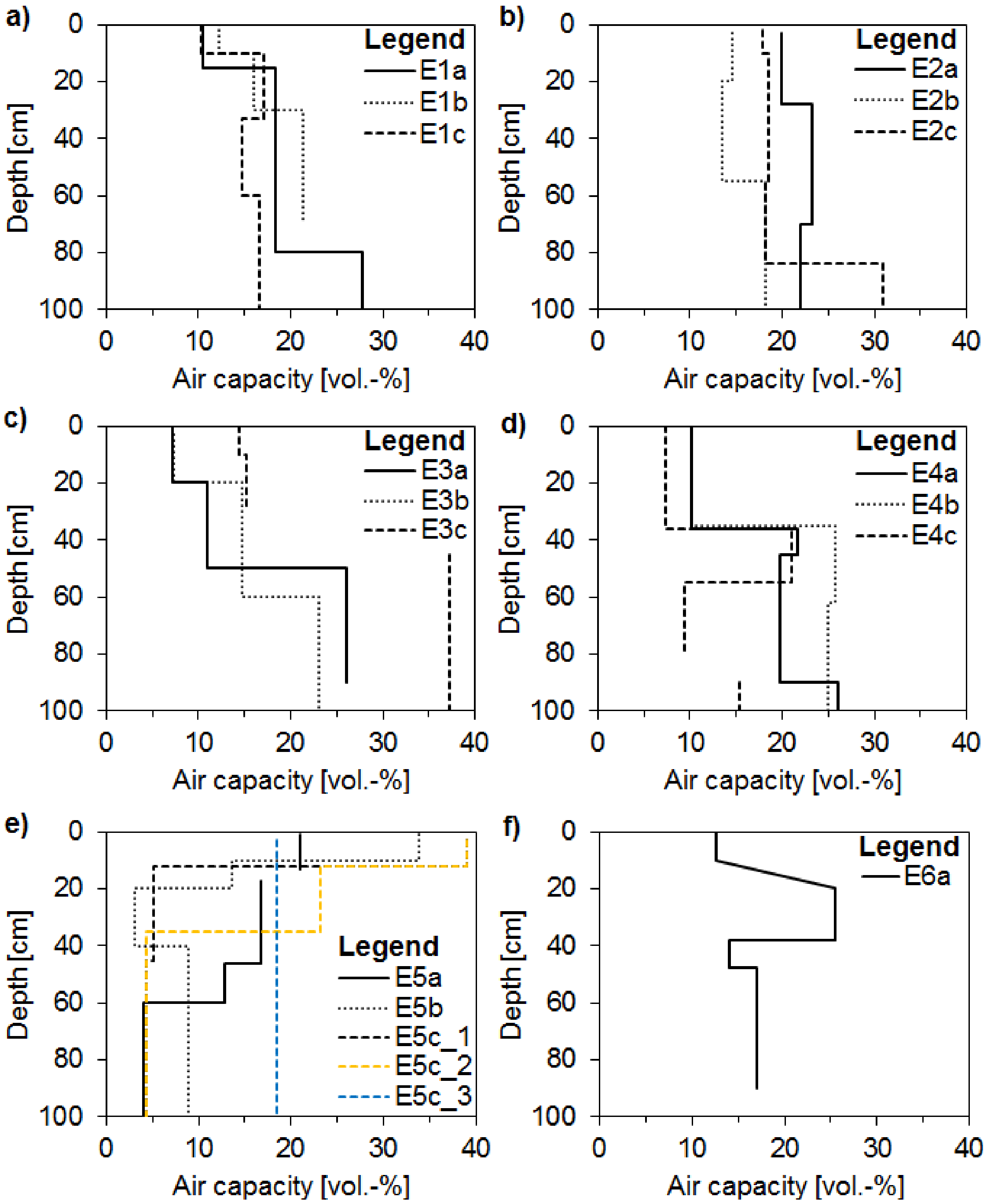

Figure 15: Examples of air capacity profiles at the sites a) E1, b) E2, c) E3, d) E4, e) E5 and e) E6a. Data source of E6a: Thomsen (2016 unpublished data).

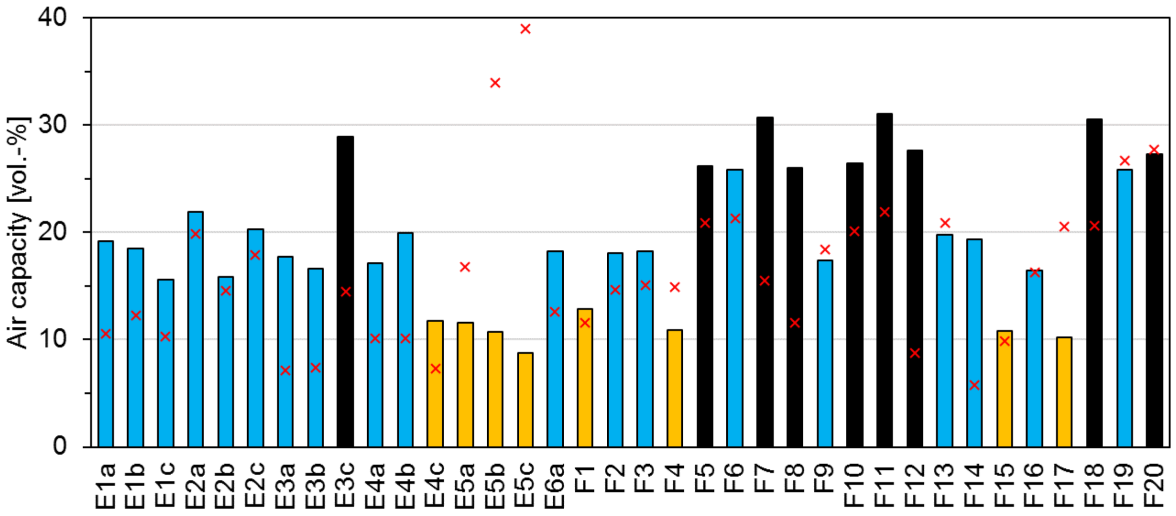

Figure 16: Mean air capacities of the uppermost 100 cm of the profiles E1a-E6a and F1-F20. At the following profiles, the mean air capacities were calculated to a lower depth: E6a (90 cm), F8 (70 cm), F9 (80 cm), F12 (90 cm), F13 (50 cm), F15 (62 cm) and F20 (58 cm). Orange bars mark "medium" (5 to <13 vol.-%), blue "high" (13 to <26 vol.-%) and black "very high" mean air capacities (≥26 vol.-%) according to Ad-hoc Arbeitsgruppe Boden (2005). Red crosses mark the air capacities of the uppermost measured layer of each profile.

The available water capacity (AWC; volume of water bound in soil with a soil moisture tension between pF 1.8 and 4.2) of the analyzed layers (n=131) was on average 15.5 vol.-%, which is a medium AWC according to the classification of Ad-hoc Arbeitsgruppe Boden (2005). The AWC was decreasing with the depth in most of the profiles (see examples in Figure 17). Only eight profiles had no layer, which had a low or very low AWC (<14 vol.-%) (see Appendix I: Table 19). 7.6% of the measured layers had a very low AWC of less than 6 vol.-%. Eighty percent of them were the lowest measured layers of their profiles. Only three profiles (F3.1, F4, E4b) had layers with a very high AWC with more than 30 vol.-%. It were always the topmost analyzed layers of the profiles. 11.5% of the measured profiles had a high AWC with values between 22 and 30 vol.-% (see Appendix II: Table 19). The AWC correlates significantly with the bulk density (r=-0.656, p<0.001), the humus content (r=0.615, p<0.001), the air capacity (r=-0.480, p<0.001) and the sand content (r=-0.330, p<0.001).

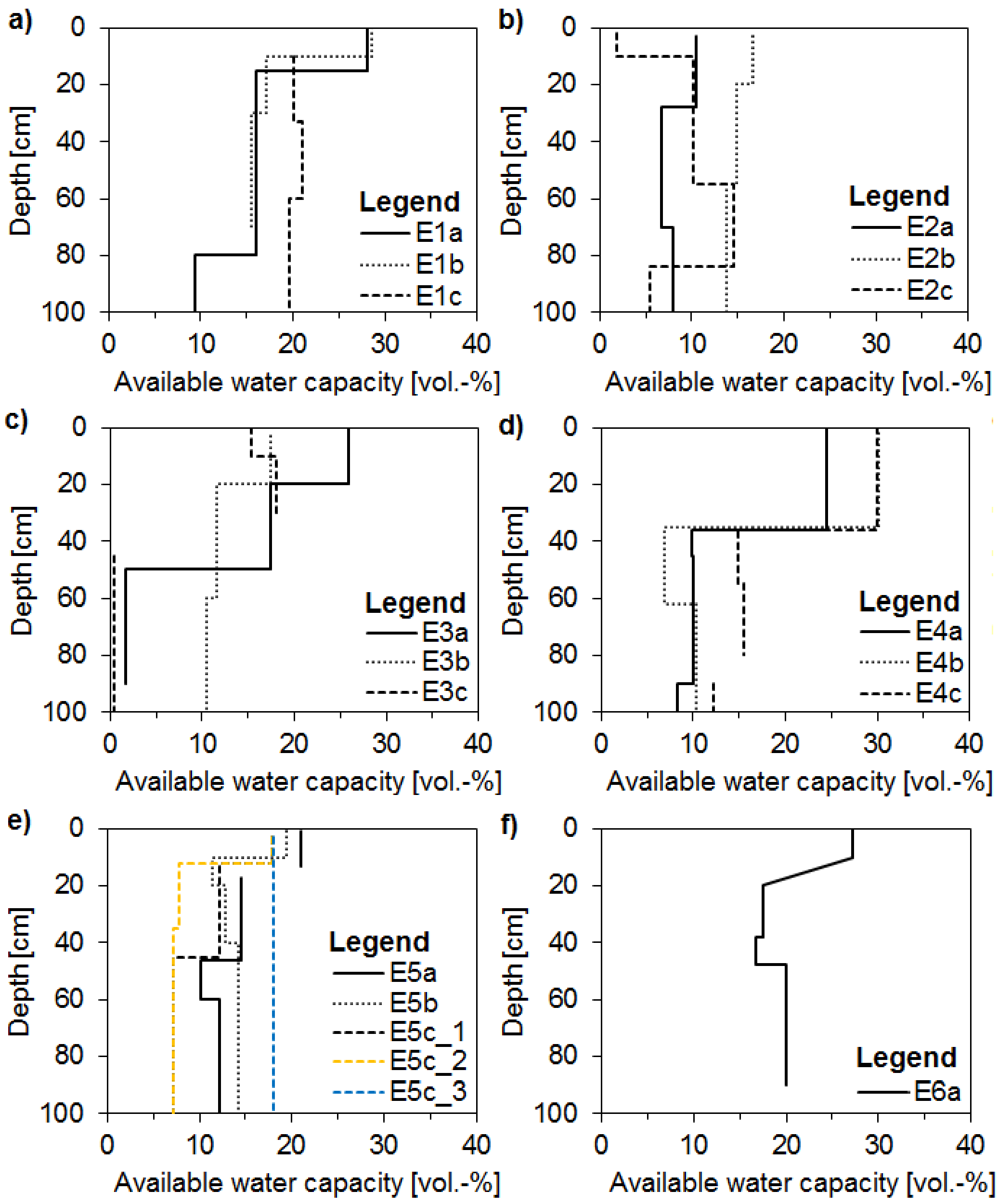

Figure 17: Examples of available water capacity profiles of the profiles at the sites a) E1, b) E2, c) E3, d) E4, e) E5 and f) E6a. Data source of E6a: Thomsen (2018).

Therefore, the AWC variated between the different layers of each profile and influenced the AWC of the whole profiles. The average available water capacity of the profiles E1a to E5c was 141.7 mm, measured from the surface to one meter depth. This is according to the classification of Ad-hoc Arbeitsgruppe Boden (2005) a “medium” AWC. Profiles E2a, E2c, E3a-c, and E5c had “low” field capacities with values below 140 mm (Figure 18). The site with the profiles E2a-c had the highest variations between the three profiles. The mean AWC of the profiles F1 to F20 is 145.9 mm and ranges from 78.0 mm (F18) to 223.6 mm (F16), whereas F16 is the only profile with a “high” value according to Ad-hoc Arbeitsgruppe Boden (2005). “Low” AWCs occurred in nearly half of the profiles (47% of the profiles: E2a, E2c, E3a-c, E5c, F5-12, F18-20) (Figure 18), no profiles were classified as “very low” (<60 mm) or “very high” (≥300 mm).

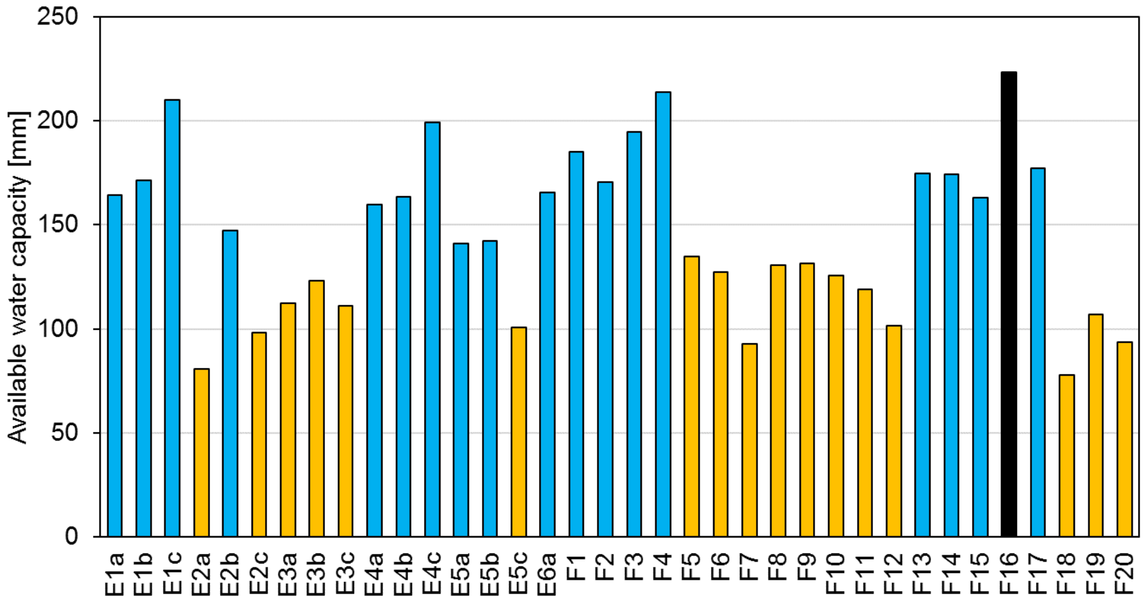

Figure 18: Available water capacities of the profiles E1a to E6a and F1 to F20 from the surface to 1 m depth. Orange bars mark "low" (60 to <140 mm), blue "medium" (14 to <22 mm) and black "high" mean air capacities (20 to <300 mm) according to Ad-hoc Arbeitsgruppe Boden (2005).

The saturated hydraulic conductivity (normalized to 10°C; K_{sat}), which describes the water permeability in a saturated soil, was ranging between 0.25 cm/day (E5a, 60-100 cm) and 4000 cm/day (F7, 85-100 cm) (see Appendix II: Table 19), the median of the 49 measured soil layers was 325 cm/day. The highest values were measured in soil layers with high sand content, while low values were found in layers with higher silt and clay content. The correlations of K_{sat} with sand content (Pearson: r=0.-469, p<0.001), silt content (r=-0.481, p<0.001), clay content (r=0.388, p=0.006), and air capacity (r=0.398, p=0.005) were significant. There was no significant correlation between K_{sat} and bulk density or humus content. The profiles E5a-c, which were the silt and clay richest profiles in this study, had below the uppermost surfaces the lowest conductivities ranging from 0.25 to 3.33 cm/day. Only the top layers up to a depth of around 15 cm had a higher saturated conductivity with 521 and 573 cm/day.

4.1.4 pH-value und electrical conductivity

The pH-value measured in $CaCl_2$ ranged between 4.2 and 7.5 (n=159) with a median of 6.2. In most of the profiles, the topsoil had the lowest pH-value. Normally, the pH-value was slightly increasing with the depth (see Figure 19). Exceptions were profiles F9, F10, F17 and F19. For instance, in profile 19, the uppermost layer had a pH of 7. The pH is slightly lower in the depth (100 cm) with a pH 6.6. The difference between the highest and the lowest measured pH values in each soil was mostly <1. Only in three profiles (F6, E3a, E3b), the difference of the pH values was >2 within a profile of one meter depth. Such a high difference was found for example in F6. Here the pH was 5.1 in the topsoil and 7.5 in the lowest layer (see Appendix II: Table 17).

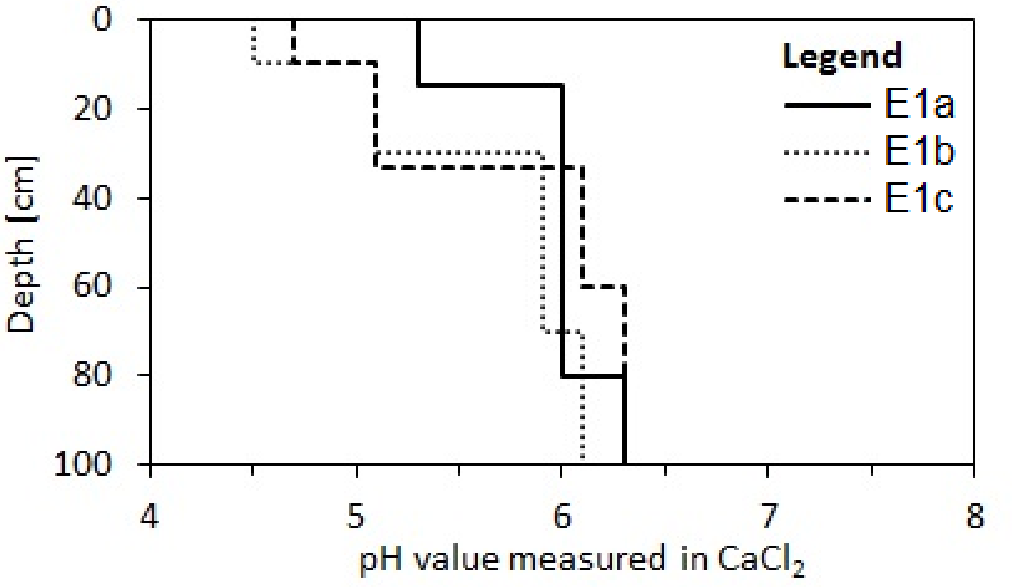

Figure 19: Example of increasing pH values with the depth at the profiles E1a, E1b and E1c.

The electrical conductivity varied from 12 to 152 µS/cm with a median of 37 µS/cm (see Appendix II: Table 17). Typically, the highest values were found in the substrates of the topsoils, but in some profiles the electrical conductivity was increasing with the depth, e.g. in profiles E3a-c from around 30 µS/cm to 100 µS/cm. Ten of 38 profiles exhibited at least one layer with an electrical conductivity higher than 100 µS/cm. The profile F10 was the only profile with higher values than 100 µS/cm in all layers from the topsoil to 100 cm depth.

There was only a very low significant correlation between pH value and electrical conductivity (r^2=0.2), pH value and skeleton content (r^2=0.1) or between electrical conductivity and skeleton content (r^2=0.3).

4.1.5 Carbon and nitrogen content

The total carbon (C) content reached from < 0.1% to 9.0% with a median of 0.8%.

In most of the profiles, the content of calcium carbonate ($CaCO_3$, calculated from inorganic C) content was very low. Only in four profiles, layers with concentrations > 1% were detected (E3a 50-100cm, E3b 60-100cm, F10 0-7cm, F15 18-62 cm), corresponding to the highest pH values. Nevertheless, the correlation of $CaCO_3$ with the pH value is not significant at the 5% level (r=0.349, p=0.059).

The humus content decreased in all soil profiles (E1-6 and F1-20) with depth. The highest value was 15.5% (E5c, 3-12 cm) and the lowest was zero (E5c_3 in 3-100 cm depth and F1 in 68-110 cm). The arithmetic mean was 2.9%, the median 1.4% (n=168). 41.1% of the layers (n=168) had a humus content of <1%, which are “very low” humus contents according to Ad-hoc Arbeitsgruppe Boden (2005). 18.4% of the soil layers had a “low” humus content (1% to <2%), while 7.7% of the soils had a “very high2 or an “extreme high” humus content.

The topmost layer or the layer below it contained normally the highest amount of humus (Figure 20). This thickness of the higher humus containing topsoil layers varied between 2 cm (E2c) and 40 cm (F2), the median is 19 cm (n=39). Only five profiles had a humus content higher than 2.0% below a depth of 50 cm and in only one profile, it is higher than 3.0% (F4: 2.4% up to 58 cm; F9: 2.7% in 22-80cm; F14: 3.4% in 50 to 100 cm; E3b: 2.2% in 60-100 cm; E4b: 2.2% in 62-100 cm, see Appendix II: Table 17).

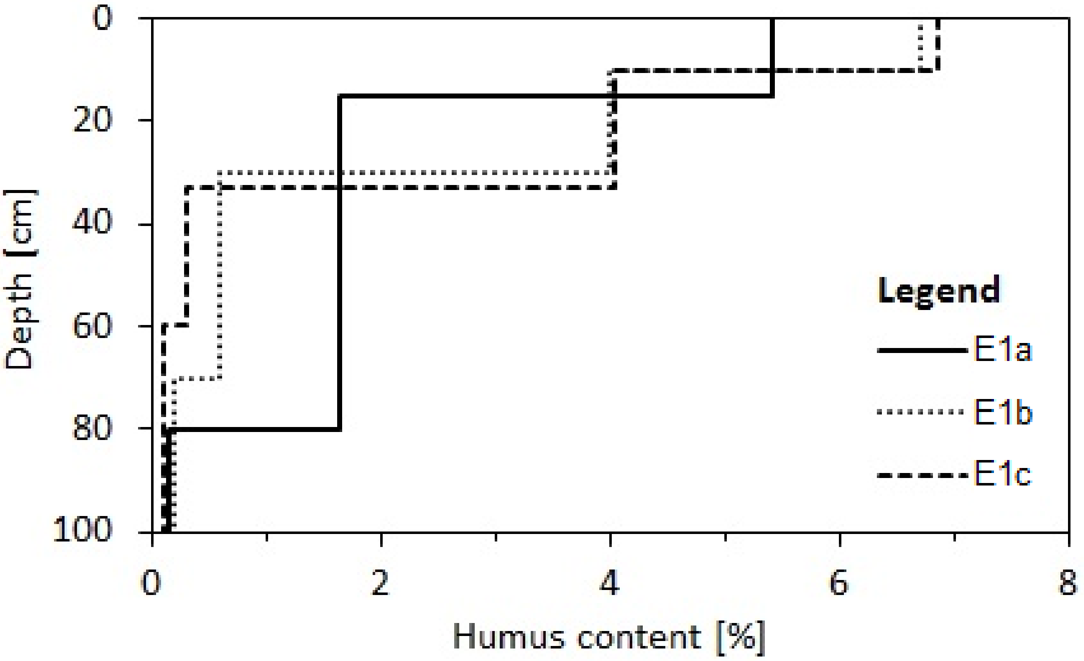

Figure 20: Example of decreasing humus content with depth at the profiles E1a, E1b and E1c.

In samples with a high particle density, lower humus contents were present (Pearson: r=-0.864, p<0.01). The correlation between the bulk density and the humus content was significant (r=-0.817, p<0.01), but this correlation was smaller in deeper layers with middle of their layer below 50 cm depth (r=-0.535, p<0.01). In addition to that, humus content and field capacity as well as available water capacity were significantly positive correlated (r=0.639, p<0.01; r=0.615, p<0.01).

The total nitrogen (N) content varied from 0.01% to 0.63%. The median was 0.06%. The median of the C/N ratio was 14.05 (average: 14.57) and varied from 1.63 to 53.19 (Appendix II: Table 17).

4.1.6 Water soluble ions and pollutants

The nutrient and pollutant contents are shown in Appendix II: Table 15 and Table 16.

The median of chloride content of the analyzed layers was 4.1 mg/kg dry matter (DM). The highest value was 25.6 mg/kg dry matter at E6b in 0-5 cm and 0.6 mg/kg DM at E5a in 1-13 cm. The sodium concentration was in average with 8.5 mg/kg DM higher than the chloride concentration. Here the highest value was 82.5 mg/kg DM at E2a in 0-3 cm and the lowest value was 2.0 mg/kg DM at E3c in 45-100 cm.

The sodium (Na) and chloride (Cl) concentrations of the topsoil vary from site to site. The median Cl-concentration of all measured layers of E1-5 and F1-20 was 4.1 mg/kg DM (minimum: 0.6; maximum: 25.6 mg/kg DM). Only in seven from 35 measured topsoils the Cl-concentration was higher than 10 mg/kg DM (F4, F5, F6, F10, F16, E2a, E6b), and in four of them higher than 20 mg/kg DM (F5, F10, E2a, E6b).

The Na-content varied from 2.0 mg/kg DM (E3c 45-100 cm) to 82.5 mg/kg DM (E2a 0-3 cm), the median was 8.5 mg/kg DM (n=52). Na-contents higher than 30 mg/kg DM were measured in five profiles (E2a, F3.2, F4, F5, F10).

In the six full-analyzed profiles, the concentration of Na and Cl were in most of the profiles decreasing with the depth (see Zander, 2016).

The median calcium (Ca) content was 15.7 mg/kg DM. The lowest value was 3.4 mg/kg DM at E2a in 28-70 cm depth. The highest value was 385.8 mg/kg DM at E2b in 0-3 cm. This site (with profiles E2a-c) showed a high variability of calcium concentrations at the topsoil of the three profiles: While E2a had a lower value with 19.5 mg/kg DM, the concentrations were much higher in the topsoils of E2b with 385.8 mg/kg DM and E2c with 78.1 mg/kg DM.

There was a strong correlation between the Cl-content and the Na-content ($r=0.753$, $p<0.001$). However, there was no significant correlation between Ca and Cl or Ca and Na (data not shown). The Cl, Ca and Na concentrations were significantly correlated with the electrical conductivity (Cl: $r=0.485$, $p<0.001$; Ca: $r= 0.430$, $p=0.001$; Na: $r=0.354$, $p=0.013$), but not with the pH value.

The concentration of bromide was in all measured layers small. Only in the topsoil of E3a and in 20 to 40 cm depth at E6b values higher than the detection limit were measured with 0.1 and 1.0 mg/kg DM.

The nitrite concentration was in 24 of the 52 analyzed layers lower than the detection limit. In the other layers, it did not exceed 20 mg/kg DM. The median was 0.1 mg/kg DM.

The median of nitrate was 7.0 mg/kg DM, the values varied from <0.1 to 347.1 mg/kg DM. The nitrate content was decreasing with the depth. Values higher than 25 mg/kg DM were only found in the topsoil layers. At the site E2, the values were variating on a high level between the three profiles (from 169.3 to 257.3 mg/kg DM). At this site, many pedestrians with dogs were present and dog mess was often lying on the green space. The maximum value of 347.1 mg/kg DM was measured at profile F3.2, but the adjacent profile F3.1 (less than 40 cm away from F3.2) had a much lower nitrate content of 25.6 mg/kg DM, which demonstrated the high variability on small-scales.

The other analyzed ions were in the soils in low concentrations (see Appendix II: Table 16): the median of fluorite was 0.3 mg/kg DM, the median of sulfate was 6.1 mg/kg DM, the median of magnesium was 2.2 mg/kg DM and potassium had a median of 10.5 mg/kg DM.

4.1.7 Small-scale heterogeneity

Here, the small-scale heterogeneity is regarded as the difference in soil properties within three soil profiles analyzed in the canopy range of established road trees (E1-E6), thus within a distance of less than 7 m. For the analysis of the heterogeneity, data of six sites were existing (E1-E6). In relation to the anthropogenic substrate layering, the differences between the three profiles were varying to different degrees at the six sites. Quite similar substrate layering was found at the three profiles E4a-c (Figure 21), as well as at E5a-c and E1a-c, respectively. Nevertheless, next to our main profile E5c, different substrates were detected: These additional substrates had been analyzed as well. Substrates of those additional layers are marked in this study with E5c_2 and E5c_3 (Figure 22).

Figure 21: Relatively low small-scale heterogeneity of the site E4 with the profiles E4a (left), E4b (middle) and E4c (right).

Figure 22: High small-scale within-profile heterogeneity at profile E5c with the subprofiles E5c_1 (left), E5c_2 (middle) and E5c_3 (right).

At these three sites (E1, E4, E5), the substrate layers were similar to each other in all three profiles and so the soil texture distribution. Nevertheless, differences between the profiles occurred. The depths of the layers varied up to 20 cm. In some profiles additional layers were identified, because of different amount of constituents; e.g. a higher content of brick in E5a in comparison to E5b and E5c. In comparison to the other three sites, the differences between the substrates were small at the sites E1, E4 and E5.

At the other three sites (profiles E2a-c, E3a-c and E6a-c), the differences between the three adjacent profiles were higher, because of different substrate layering. At two profiles of these sites (E2c, E3c), additional layers with fill sand over pipes or cables were present. These fill sand layers were composed of pure sands (>98% DW sand content). Therefore, the clay, silt and humus content was smaller than their content in the same depth of the other two profiles of each site.

The three profiles at E3 were optical very different in substrate layering (Figure 23). E3a had different layers: at the top to 50 cm depth were two layers with around 10% silt and 85% sand content. The humus content was 4.0% and 3.2%, while deeper layer contained less humus with 0.7 and 1.7%. The layer from 50 to 90 cm had a high skeleton content (15.6%) and contained up to 95% sand. In comparison to that, the deepest layer was a sandy loam with 64.7% sand, 20.0% silt and 15.3% clay content. The whole profile under three centimeter depth of E3b was mottled in yellow and brown colors. The percentage of brown and yellow parts varied over the depth: highest percentages of yellow sand content was in 20 to 60 cm depth. The sand content varied from 76.9% to 89.7% with highest values in the more yellowish layer and the humus content ranged from 2.6 to 1.5%. The topsoil layer was very similar to the topsoil of E3a as well as of E3c. In these three layers, the pH value varied from 4.9 to 5.2, and was lower than the other layers. The layer in 20-30 cm of E3c had nearly the same grain size distribution than its topsoil and so it was very similar to the layers of E3a down to 50 cm and E3b down to 60 cm. This profile had a fill sand with 98.4% sand content and only 0.1% humus content below 45 cm. The highest pH values were 7.3 in E3a in 90-100 cm and 7.4 in E3b below 20 cm.

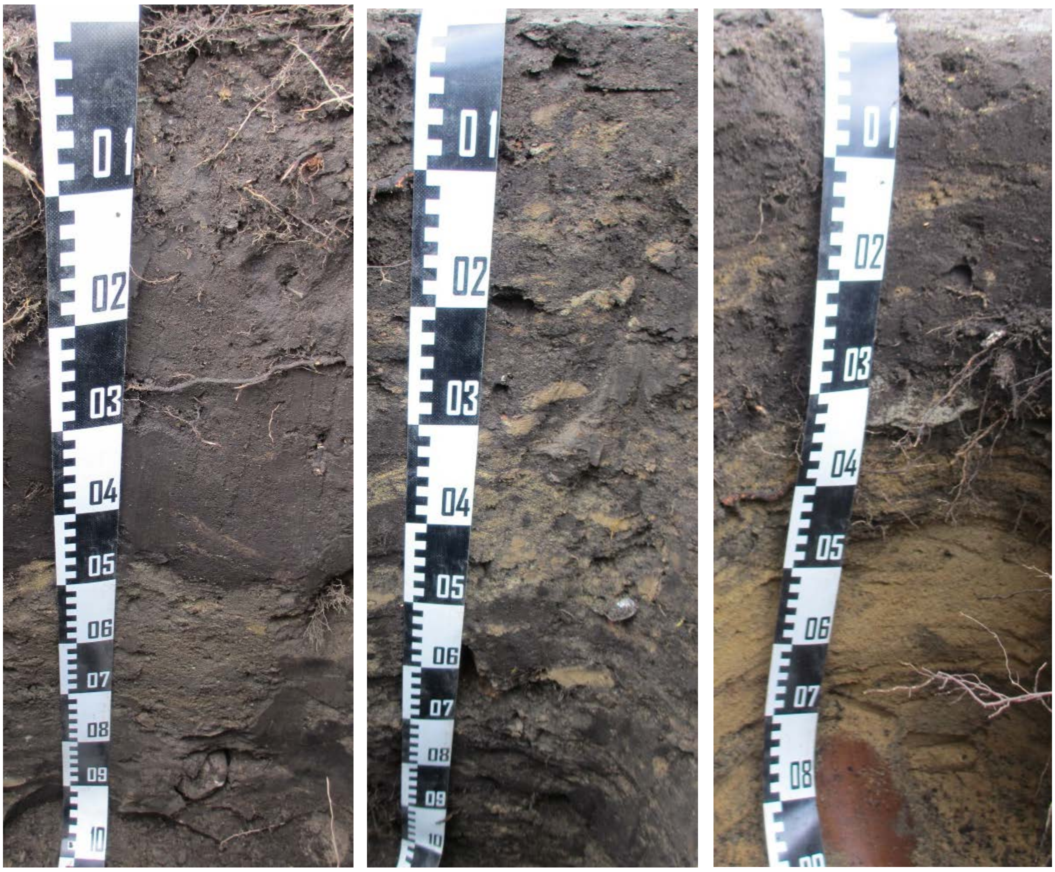

Figure 23: Strong small-scale heterogeneity at the site E3 (left: E3a, middle: E3b, right: E3c).

E6a was a sand-rich profile: the sand content varied from 89.2% in the top layer to 95.1% in the depth of 100 cm. In comparison to that, the highest measured sand content of E6b was with 88.5% lower than the lowest value of E6a. In 40-80 cm depth, the sand content was with 64.4% relatively low. In 70-90 cm depth of E6c, there were similar low sand contents with 56.6% respectively 73%, while the deeper and lower layers were sand-rich with 83.9 to 95.2% sand content. Nevertheless, the humus content of these profiles was similar: only in the uppermost layers (up to 38cm in E6a, 20cm in E6b and 38cm in E6c) the humus content was higher than 5%. Here the highest contents were in E6b around 6%, while the other profiles had lower values with 5.5% (E6a) and 5.3% (E6c). In all other layers of this site, the humus content was low or very low (between 0.2% and 1.9%).

The comparison of the properties in the same depth of adjacent profiles (or same layers, if the depth is very different) showed a much smaller variation than the variation between all analyzed profiles. For instance, the standard deviation of the sand content in 10 cm depth was on average on the adjacent profiles 2.9% (with the smallest standard deviation of sand content at profiles E5a-c with 1.6%), while the standard deviation of sand content in 10 cm depth of all profiles was with 5.6% nearly two times higher (see Table 2). The difference between standard deviations of stone content in 10 cm depth of adjacent profiles and the mean variance of all profiles was even higher with a standard deviation of 2.4% at adjacent profiles and 15.3% at all profiles. Similar were the differences of standard deviations with the humus content, which was for example with a mean of 1.8% at 10 cm depth at adjacent profiles much smaller than at all profiles with 3.5%. The standard deviation between the profiles E4a-c2 was with 3.9% higher than the standard deviation between all profiles, because of the very high humus content in E4a and E4c with around 15%, while the humus content in E4b was with 8.6% nearly the half.

The small-scale variation of soil substrates can have a strong effect on the water balance in the soil. This was especially the case when the profiles contain different substrates like at the site E3. In E3a and in E3c occurred layers with a sand content higher than 95%. In these layers, the air capacity was very high, but the available water capacity was very small. In addition to that, less roots were found than in the adjacent profile E3b in the same depth, where the sand content was lower and so the usable field was capacity higher.

Variations of the available water capacities were small in adjacent profiles with similar substrates and similar depth of layers, e.g. the standard deviations in 10 cm depth of E5a-c was 1.6% and in E1a-c 0.16%. At more heterogeneous sites like E2 or E3, the standard deviations were similar to the standard deviation between all sites with 7.3%. At E2a-c the standard deviation was 7.4% and at E3a-c 5.6%. In E3a, the available water capacity was decreasing with the depth from high values at the uppermost layer to a very low value in 50-90 cm. In E3b the variation was not as high as in E3a. Here it decreased from medium to low values. E3c had medium values according to Ad-hoc-Arbeitsgruppe Boden (2005) in its topsoils, but a very low value below 45 cm.

The standard deviations of air capacities in 10 cm depth was in average at adjacent profiles 4.0% and between all profiles 9.4%. This variable was always more similar at adjacent profiles than at the average. Nevertheless, there are differences at some sites. The highest standard deviation of adjacent profiles was with 4.1% the site with E3a to E3c. The air capacity of profile E3b was medium according to Ad-hoc-Arbeitsgruppe Boden (2005). In E3a it was medium in 0-50 cm, but in 50-90 cm very high. In E3c the air capacity was very high below 45 cm and in the other layers high. That led to a high standard deviation in 100 cm depth with 10.0%, while the standard deviations in the other adjacent profiles varied from 2.7% to 7.9% (Table 4). In four of the five sites with adjacent profiles, where the air capacity was measured, the standard deviation was increasing with the depth (see Table 2, Table 3 and Table 4).

Table 2: Standard deviations of stone content, sand content, pH, el. conductivity, air capacity, field capacity and available water capacity in 10 cm depth.

Profile numbers	Standard deviation in 10 cm depth							
	Stone content [%]	Sand content [%]	Humus content [%]	pH in $CaCl_2$	el. conduc. [µS/cm]	Air capacity [%]	Field capacity [%]	AWC [%]
E1a-c	0.5	3.7	0.79	0.41	15.9	1.0	2.0	0.7
E2a-c	4.9	3.4	0.66	0.76	18.1	2.6	5.4	7.4
E3a-c	1.6	2.2	1.24	1.00	24.9	4.1	6.5	5.6
E4a-c	1.0	2.7	0.87	0.00	6.6	1.6	0.6	3.2
E5a-c	0.4	1.6	3.88	0.35	7.1	4.0	1.8	1.6
E6a-c	-	3.4	0.47	0.31	2.1	-	-	-
E1a-E6c*, F1-20	15.2	5.6	3.53	0.77	32.3	8.2	9.4	7.3

* E6a-c only sand content, pH humus content and el. conductivity

Table 3: Standard deviations of stone content, sand content, pH, el. conductivity, air capacity, field capacity and available water capacity in 50 cm depth.

Profile numbers	Standard deviations in 50 cm depth							
	Stone content [%]	Sand content [%]	Humus content [%]	pH in $CaCl_2$	el. conduc. [µS/cm]	Air capacity [%]	Field capacity [%]	AWC [%]
E1a-c	4.9	2.2	0.70	0.10	5.0	3.3	2.2	3.1
E2a-c	5.4	1.4	0.48	0.26	11.2	4.8	4.6	4.2
E3a-c	5.4	5.9	0.91	0.50	41.7	11.2	10.3	5.0
E4a-c	1.5	1.2	0.25	0.06	1.8	3.2	3.8	4.1
E5a-c	7.9	5.0	0.17	0.66	18.6	4.2	3.0	3.6
E6a-c	-	14.6	0.40	0.43	7.8	-	-	-
E1a-E6c*, F1-20	7.2	10.0	0.90	0.48	25.4	8.2	7.0	4.8

* E6a-c only sand content, pH humus content and el. conductivity

Table 4: Standard deviations of stone content, sand content, pH, el. conductivity, air capacity, field capacity and available water capacity in 100 cm depth.

Profile numbers	Standard deviations in 100 cm depth							
	Stone content [%]	Sand content [%]	Humus content [%]	pH in $CaCl_2$	el. conduc. [µS/cm]	Air capacity [%]	Field capacity [%]	AWC. [%]
E1a-c	0.7	0.7	0.05	0.12	3.0	7.9	6.8	7.2
E2a-c	0.7	4.5	0.67	0.23	21.7	6.5	6.1	4.2
E3a-c	5.3	17.1	1.11	0.61	49.2	10.0	13.5	3.2
E4a-c	8.0	2.8	0.92	0.20	5.8	5.9	2.8	2.0
E5a-c	0.8	1.1	0.08	0.29	5.8	2.7	0.5	3.7
E6a-c	-	14.7	1.03	-	-	-	-	-
E1a-E6c*, F1-20	6.0	11.4	0.82	0.47	27.3	9.2	7.0	4.9

* E6a-c only sand content, pH humus content and el. conductivity

The variation at the three different profiles at each of the five sites with E1a-E5c at established trees showed different high variations of the ion concentrations in the topsoils, too. In E1a-c and E3a-E4c the values of chloride (Cl) and sodium (Na) were on a similar low level with small variations. In E5a-E5c, they were in the same range: the average of them is 1.9 mg Cl/kg DM, but they had a higher standard derivation with 1.5 mg Cl/kg, because in E5b the value of 3.6 mg Cl/kg DM was six times higher than in E5a with 0.6 mg Cl/kg DM.

The top layers of E2a, E2b and E2c were heterogeneous: E2b and E2c had very similar chloride concentrations with 5.0 and 5.4 mg/kg DM. In contrast to them, E2a had more than four times higher values with 21.4 mg/kg DM, so that the standard deviation was with 9.6 mg/kg DM much higher than the standard deviation of 6.5 mg/kg DM between all sites (E1a-E5c, E6b and F1-20). The variation of sodium was even higher: E2a had 82.5 mg Na/kg DM. The sodium contents were with 8.5 (E2b) and 18.4 mg/kg DM (E2c) much lower in the other two profiles of this site. Therefore, the standard deviation was with 40.2 mg/kg DM very high in comparison to the average variance of the other adjacent sites with 0.9 mg/kg DM or to the average of all measured top layers with 15.5 mg/kg DM.

At M4-6, the other ion concentrations like nitrate, magnesium or calcium varied very strong in the top layer, too, while the other sites were much more homogeneous (see Table 5).

Table 5: Standard deviations of ion concentrations in the top soils.

Profile	Standard deviations [mg/kg dry matter]*								
numbers	Cl	Fluoride	Nitrite	Nitrate	Sulfate	Calcium	Sodium	Mg	K
E1a-c	1.4	0.1	7.2	5.2	1.3	6.7	1.6	0.6	2.0
E2a-c	9.6	0.1	3.8	44.6	11.0	196.8	40.2	3.0	5.6
E3a-c	0.8	0.1	0.3	4.2	0.5	68.9	0.2	0.3	0.8
E4a-c	1.6	0.3	0.0	1.5	1.1	4.0	0.2	0.5	2.6
E5a-c	1.6	0.1	0.1	1.3	1.5	8.0	0.9	4.6	5.7
E1-E5, E6b, F1-20	6.5	0.3	5.1	80.3	11.5	63.1	15.5	3.3	16.2

*values smaller than detection limits were set to 0 for calculation of variances

4.1.8 Relation between soil properties and root distribution

The fine and coarse roots of the trees were not distributed in all different layers of each profile with the same density (see Appendix II: Table 19). At some profiles like F11, layers without any roots were found but also layers with dense root mats. Root mats were found in six profiles of three sites (F11, E1a, E1b, E1c, E2b and E2c). In general, the root density in the upper soil layers was higher than in deeper layers and decreased with the depth (see examples in Figure 25).

The highest correlation between the root density (fine and coarse roots; categorized according to Ad-hoc-Arbeitsgruppe Boden (2005)) and the soil properties were given with the available water capacity (AWC). Here the Pearson correlation coefficient was $r=0.658$ ($p<0.001$; Figure 24, Figure 25). In some profiles like E1a and E3a, a clear positive relationship between the root density and the AWC (Figure 25) as well as a negative correlation to the bulk density was found. Therefore, more roots were found in layers with high AWC and low bulk densities. Nevertheless, this relationship was not that clear or not found in some other profiles (e.g. E2b, E2c).

In addition to that, there were significant correlations between root density (fine and coarse roots) and effective bulk density ($r=-0.521$, $p<0.001$), pore volume ($r=0.499$, p<0.001), humus content (r=0.486, p<0.001), pH-value (r=-0.445, p<0.001), depth (middle of the layers) (r=-0.377, p<0.001) and air capacity (r=-0.352, p<0.001). The correlation with sand content, silt content and clay content were smaller (r=-0.180, r=0.176 and r=0.168), but also significant (p<0.05). There was no significant correlation between the skeleton content and root density.

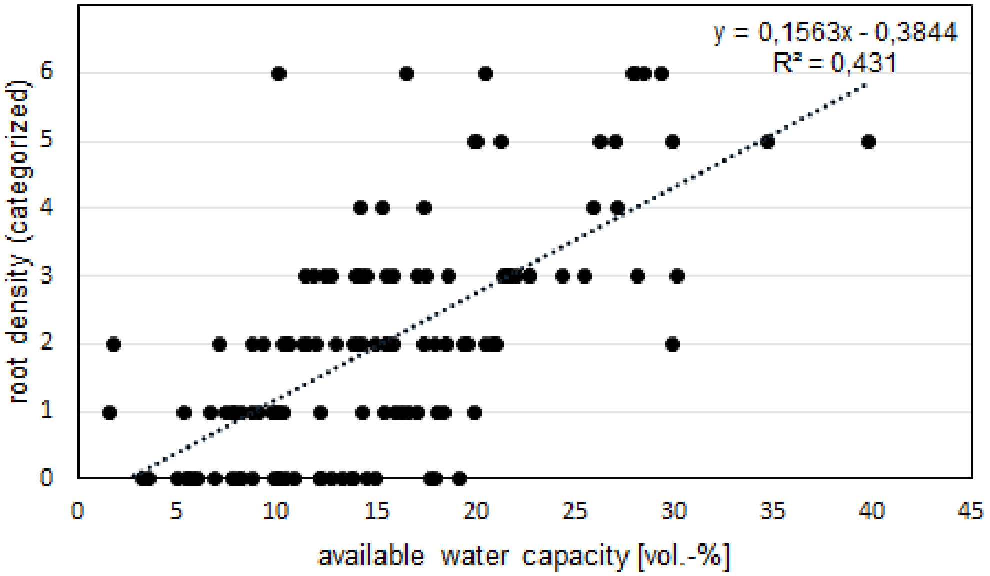

Figure 24: Relation between available water capacity (vol.-%) and root density. The root density is divided into seven categories according to Ad-hoc-Arbeitsgruppe Boden (2005): 0= no roots, 1= 1-2 roots/dm², 2= 3-5 roots/dm², 3= 6-10 roots/dm², 4= 11-20 roots/dm², 5= 21-50 roots/dm² and 6= >50 roots/dm². The dotted line is the trend line.

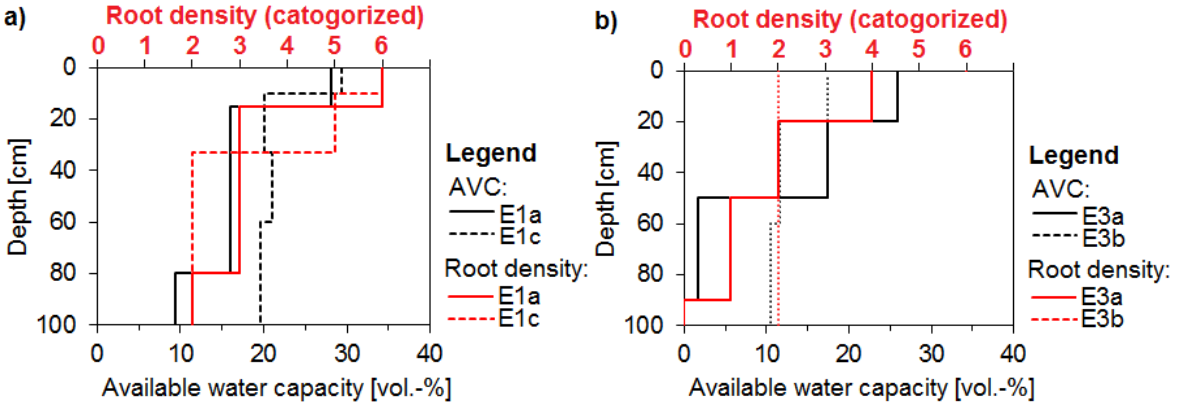

Figure 25: Examples of root distribution (red) and available water capacity (black) from the surface to 100 cm depth in the profiles a) E1a and E1b and b) E3a and E3b. The root density is categorized according to Ad-hoc-Arbeitsgruppe Boden (2005).

4.2 Discussion

4.2.1 Properties and heterogeneity of urban soils

Soils and soil development

The heterogeneity of the natural soils in the area of Hamburg is in general high because of the different geological sources of soil material from the last glacial periods and the material transported by the Elbe (BUE 2015e), so that there are for example areas, where sand soils occur, and in other areas clay soils (BUE 2015c). That leads to the most common soil types in Hamburg: They are brown earths, podsols, gleys, pseudogleys and river clay marshes (Miehlich 2010, BSU 2012b). In addition to the different source materials, the human land use effects the soils genesis. Especially in urban areas, the natural soil horizons can be removed, mixed and/or filled with other materials by human activities (e.g. Pouyat et al. 2010, BSU 2012, Greinert 2015). As described in chapter 2.2, soils can be categorized in semi-natural soils, disturbed soils and soils of sealed sites (e.g. Burghardt 1996, Schickhoff & Eschenbach 2018). In this study, only soils of the second category were analyzed.

The analyses of the profile data, which were very close to each other, show that the small-scale heterogeneity has a different degree of intensity in different study sites. In E1a-c, the small-scale heterogeneity is small. No parameters – physical as well as chemical parameters - varied over a wide range (see chapter 4.1). That shows that these soils are homogenous with only small varying soil properties. E1 was located in a lawn close to a huge crossroads and on the other sites to a building and a parking area. The similarity of the layering of all three profiles indicates that after creating the lawn and planting the tree, no small-scale excavations were performed on that spot. Although power lines were found in the lawn near the sidewalk. There were no visible disturbances above them, which indicates that they were installed without excavations of the lawn, which would have led to changes of the soil materials.

In other areas like E2 or E3, the soils were more heterogeneous. The stratification in adjacent profiles was different, and so the soil properties. In the profiles E2a-c and E3c, power lines or tubes were found in or below the profiles. They were enclosed by fill sands. The excavations and following refilling caused a horizontal heterogeneity of substrates.

This observation, that areas with high and areas with low heterogeneity in cities are existent, is consistent with the results of other urban soil studies like Craul (1985), who analyzed streetside soils in Syracuse (New York), and Greinert (2015). Whereas Greinert (2015) recognized that areas with uniform urban construction projects have more homogenous soils. The different degree of heterogeneity can be caused by the location and the amount of extinctions and construction works in the past (e.g. Greinert 2015). E3 was located near a huge crossroad and close to a serving area interface. Several excavations during the last hundred years for laying power lines and wires have changed the layering of the soil. Those excavations are mainly only along the route of the power lines, so the changes in the soil are along narrow lines, but because of the crossroad, many cables came from different directions. They were not installed all to the same time, so over time a mixture of soils was created. A pipe lies in profile E3c, but not in the adjacent E3a and E3b. Therefore, in E3c layers with filling sands are present, which are not in the other profiles. These filling sands had other properties than the surrounding urban soil. Other areas like F5, F12, F20, E1 and E2 were influenced by different kinds of line and pipe excavations, too.

Another reason for special soils in Hamburg are the demolition of old houses and burying debris and bricks in the soil. The debris and bricks can be caused by normal rebuilding of areas or could be caused by incidents like house burning or destruction for example during the world wars. That kind of soils are more often in the center of the city or in urban areas with long settlement history. The high amount of profiles with bricks (nearly 60%) is in accordance with the findings of other studies, which were conducted in Hamburg: BSU (2012) found anthropogenic constituents (e.g. building waste, slag, glass) in 41.9% of their study sites (n=62) and Wolff (1993) found technogenic particles bigger than 2 mm in 55% of his analyzed layers. Those high percentages are typical for urban areas, which is confirmed by other studies. For instance, Greinert (2015) has found bricks in around 70% of his analyzed profiles in roadside areas in Zielona Góra, Poland.

In comparison to the findings of Greinert (2015), the soils in our study were mostly Terric Anthrosols or Transportic Arenosols. Therefore, in this study, the range of soil groups was not as wide as he had found. That can be caused by the location of the profiles. Greinert (2015) selected profiles in the whole area of the town Zielona Góra (Poland) with different intensities of human impact. Therefore, he analyzed profiles in the city center as well as profiles in parks and forests. In contrast to that, this study was concentrated on roadsides of the city center and of dense populated areas of Hamburg. Greinert (2015) identified the land use form and the technology used for construction of buildings and land development as important factors, which influences the heterogeneity on a small-scale. Nevertheless, he observed in 82.4% of his analyzed profiles anthropogenic soil transformations, which lead for example to clear horizon boundaries. Similar percentages were also found in other studies like Short et al. (1986), who had anthropogenic transformations in 95% of his profiles in Washington. In this study all of the profiles were effected, which can be influenced by the choice of roadside locations in the inner city of Hamburg for the soil analyses.

Most of the analyzed soils in this study were anthropogenic soils with a high sand content and often with technogenic constituents. The soil profiles lay close to roads, so that such an anthropogenic influence and a high sand content was expected. That is consistent with former studies conducted in Hamburg (Wolff 1993, BSU 2012). In the study conducted by BSU (2012), 83.8% of the topsoils were pure sands, while the others have low loam contents (ls, us, sl, l). In the study of Wolff (1993), ¾ of the analyzed layers were sands or slightly cohesive sands.

The relative high skeleton content is a typical sign for urban areas (e.g. Day & Bassuk 1994). Other studies conducted in cities found a high skeleton content, too. For instance, Kahle & Coburger (1996) measured a mean of 13% skeleton content in the topsoils in the city center of Rostock and Jim (1998b) measured a mean of 41.71% stone content in urban soil samples of Hong Kong. In our profiles, the median of the skeleton content of the layers is with 11.1% similar to the results of Kahle & Coburger (1996). In this study, many layers with anthropogenic sand layers with a very small skeleton content were found, which is consistent with the analyses of Wolff (1993), too. These kind of anthropogenic soils lowered the median in our study. In general, the variation of skeleton content from nearly zero percent to 70% in my analyzed soil profiles is high and reflects the heterogeneity of soils and substrates in the city. That is also recognized in the soils of Berlin in the study of Nehls et al. (2013), where they found skeleton contents up to 50%, or in a urban park in Hong Kong with the range from 5.85% to 65.51% (Jim, 1998c) or in Zielona Góra in Poland with the range from 0.0 to 79.9% (Greinert 2015).

Bulk density and compaction

A problem of urban areas are compacted soils (e.g. Patterson 1976, Craul 1985, Jim 1993, Jim 1998a). Contrary to my expectations, only seven of the 131 analyzed layers had a high bulk density of more than 1.80 g/cm³ (categories according to Ad-hoc-Arbeitsgruppe Boden (2005)). One reason for the relatively low densities of the other layers is the high percentage of sand content, which prevents a high compaction. In addition to that, the studied urban soils were relatively young, because of excavations for constructions and repairs of wires and tubes, so that they were loosen up. These observations were also made by Jim (1998c) in Hong Kong, where he measured in soil layers with high sand content lower bulk densities than in other layers, or by Greinert (2015), who recognized, that 50.3% of his analyzed urban soil horizons in Zielona Góra (Poland) have no compaction because of sandy textures. Nevertheless, in other cities, higher bulk densities were measured: The mean bulk density in planting pits in Hong Kong is for example with 1.67 g/cm³ (Jim 1998a) or 1.65 g/cm³ (Jim 1998b) higher than in our study with 1.53 g/cm³. In a park in Honk Kong the bulk density is in five of six profiles exceeding 1.75 g/cm³ and in two profiles higher than 2.00 g/cm³ in at least one layer (Jim, 1998c). In Washington Short et al. (1986) measured bulk densities with a mean of 1.61 g/cm³ and a maximum of 1.85 g/cm³ in the surface horizon. In 30 cm depth, the situation was worse: here the mean bulk density was 1.74 g/cm³ and values up to 2.03 g/cm³ were reached. These examples show the problem of compacted soils in urban areas. The range from 1.14 to 2.63 g/cm³ (Jim 1998a), measured in these studies as well as the mean of 1.74 g/cm³ in 30 cm depth (Short et al. 1986) are much higher than the values in this study about soils at roadside trees in Hamburg. In contrast to our measurements, Jim (1998a) had a light significant correlation between sand content and bulk density (-0.318, $p<0.001$) and between clay content and bulk density (0.235, $p<0.001$).

A natural soil normally has higher bulk densities, lower pore volumes and lower air capacities in the subsoil compared to the upper layers, because of the higher mechanical load. That was also the case at most of the analyzed soils in this study, which correlates with findings of other studies like Short et al. (1986) and Greinert (2015), who had measured higher compactions mostly in the deeper horizons of urban soils. In addition to that, the lowest measured effective bulk densities of this study with less than 1.00 g/cm³ (see Appendix II: Table 21) were all in the topsoils or in the layers below them. Some of the analyzed profiles had higher effective bulk densities in the uppermost layer than in the following layer. This could be caused by the use of the areas, too. For example by people walking on the soil (e.g. E2, E3 and F10) or car parking (F1). Nevertheless, at two other sites (F2 and F17), car parking was observed, but their top layer was not more compacted than deeper layers. The relatively low amount of litter, soil microorganisms and soil animals like earth worms led to more dense structure of soils (Meyer 1978). In addition, the different materials of the layers with different particle sizes can be a reason, that each layer has a different effective bulk density. All of these soils are anthropogenic soils. So it is likely that they were compacted after they were placed, to make it even and firm, which is needed to ensure a save surface in the city.

Air capacity and available water capacities

The air capacity is important for the aeration of the roots. It is known, that especially the soils with a high bulk density have a small pore volume and a small air capacity, because a dense compaction of particles leads less space for pores and so for coarse pore, which are important for the air capacity (e.g. Blume et al. 2010). In the soils analyzed in this study, the mean air capacity was classified as “high”, which is a consequence of the particle size distribution. Most of the soils are sandy soils. Those soils tend to have high pore volumes and high air capacities, which can be confirmed with this study.

Not only is the air capacity dependent on the bulk density. The available water capacity showed a significant correlation ($r = 0.656$, $p<0.001$) to the effective bulk density, too. This correlation is higher than the correlation to the sand or clay content ($r_{sand} = 0.330$, $r_{clay} = 0.303$, $p<0.001$). It shows that the normal sand layers have a low available water capacity, which increases, when the effective bulk density is higher. The available water capacities of single layers of each profile varied at some profile to a high degree. Overall, only one profile (F16) had at average a high available water capacity from 0-100 cm depth, while the others had low or medium values. The profile F16 had a thick layer of silty sand and in comparison to the other profiles only with thin layers of silty sand and thicker sand-rich layers. Therefore, the higher available water capacity is based on the soil texture and not on the effective bulk density in this case.

Hydraulic conductivities, infiltration rates and sealing

Wide ranges in hydraulic conductivities are quite normal. According to Blume et al. (2010) common values of hydraulic conductivities in sandy soils are ranging from 300-

30,000 cm/d, in silt between 4-30,000 cm/d, in loam 1-30,000 and in clay 0.01-30,000 cm/d. In this study, the values of saturated hydraulic conductivities were in the range from 0.25 to 4,000 cm/d and so they were in the ranges given by Blume et al. (2010). Nevertheless, some of the sand layers had lower values than 300 cm/d in this study, which can be an effect of their small silt or clay constituents or the bulk density. The relatively low hydraulic conductivities in many layers can reduce the water transfer in the soils.

The characteristics of the soil surface and the sealing of the surface are other important factors, which influence the infiltration, runoff and evaporation and so the soil water content (e.g. Flöter 2006). In urban areas, the natural infiltration is often reduced because of compaction of the soils (Pitt et al. 2003). Additionally, the sealed and partly sealed surfaces reduce the infiltration. This study showed that the sealing at roadside tree sites is high with a mean surface sealing of 66% in an area of 20 x 20 m around the trees. This leads to reduced areas around the tree, where infiltration of precipitations is possible. The infiltration rates of the unsealed soil around the trees were measured at the sites E1-6 of this study. The highest infiltration rate of 100.2 cm/h was found in the unsealed area at E1. At E6, the infiltration rate was with 34.0 cm/h high, too. In contrast to that, the infiltration rate in the unsealed area at the site E3 was small with 2.7 cm/h. The infiltration rates of the other sites was close together with 7.2 cm/h (E2), 8.8 cm/h (E4) and 11.2 cm/h (E5) (see Kuqi 2017). All these values were all in the range of measured infiltration rates in Hamburg by Wolff (1993, 1996). For instance, Yang and Zhang (2011) demonstrated that the infiltration rates are also very variable in other cities. They measured final infiltration rates from less than 1 to 67.9 cm/h in the city of Nanjing. Another example gave Pitt et al. (2003) with measurements in sandy urban soils in Oconomowoc (USA). They had nearly the same range (0-60 cm/h), whereas the lowest rates were measured at areas with substantial disturbances or traffic, and siltation. The study of Gregory et al. (2006) showed for non-compacted natural forests and planted forest average infiltration rates from 37.7 to 65.2 cm/h, while they had lower rates in the range of 0.8 to 18.8 cm/h for compacted natural and planted forest sites and showed the influence of soil compaction on the infiltration. The two sites of this study with the highest infiltration rates had also the highest percentage of unsealed surface, which were vegetated by grass, the highest sand contents in the top soil layers and the lowest bulk densities of the top layer. These properties benefit high infiltration rates (Wolff 1993). Yang & Zhang (2011) observed high correlations between bulk density and infiltration rates, too.

Chemical properties

Not only the physical parameters varied to a high degree in Hamburg, but also chemical parameters, which may also affect the growth of street trees. In many urban areas, high pH-values occur due to alkaline inputs like mortar, which increase pH values (e.g. Endlicher 2012). In this study, the measured values were not too high for tree growth. Common tree species, growing in Germany, need a pH lower than a threshold between 7 and 8.2, depending on the tree species; e.g. *Acer platanoides* or *Quercus robur* need substrates with a pH lower than 8.2 (Bassuk et al. 2009, Goss & Schönfeld 2014). Most of the measured sites had a pH-value, which was lower than pH 7. Only at the other few sites, where the pH-value is lower, tree species must be selected, which are adopt to these high values, or the soil must be threatened before planting. In other studies, conducted in cities, pH-values in the same range or higher were measured. E.g. Greinert (2015) has measured a median of 7.1 at roadsides in Zielona Góra in Poland, Jim (1998b) measured a mean pH of 8.68 in tree pits in Hong Kong and Craul & Klein (1980) measured pH-values between 6.6 and 9.0 at streetside soils in Syracuse (New York), which were higher than natural soils between 5.1 and 8.4. In all these cities, the pH has a higher potential to influence tree growth and needed tree selection before plantation than in Hamburg.

In cities, a well-known problem for trees are deicing salts like sodium chloride (NaCl), magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$). They can change the soil properties (e.g. pH, nutrient ratios) and damage the trees (e.g. chlorosis, necrosis of leafs) (Ruge 1978, BSU 2012). The analysis of BSU (2012) showed no correlation between the Na-content (ammonium nitrate extraction) of soils and their pH-value. There was only a slight correlation of the Ca-content (ammonium nitrate extraction) and pH values. Our data did not show correlations between the pH values and water soluble Na- or Ca-content. BSU (2012) wrote that pH values >8 occur only together with Ca-contents (ammonium nitrate extraction) higher than 500 mg/kg DM. In our samples, the Ca-contents (water extraction) are lower. The median is 14.4 mg/kg. Those low values may have no significant effect on the pH values, so that this can be a reason for not having the correlation between Ca-content and pH values.

In this study, ion concentrations were analyzed in six profiles in all layers, in the others only in the topsoil. Because of a lack of recommendations for most of the analyzed nutrient and ion concentrations in soils at trees, the values could not be evaluated. Nevertheless, the median of the nitrogen content of 0.06% in the urban soils were in the range of the mean nitrogen contents used in planting pit substrates for the project “Stadtgrün 2021” in Würzburg, Kempten and Hof/Müncheberg. In the used substrates, the mean nitrogen contents were ranging between 0.02% and 0.06% in 2010 and between 0.03% and 0.07% in 2016. It is assumed that these values are low values (Klemisch 2017). Nevertheless, they found mainly normal nitrogen contents in the leafs of the trees, which were planted in these planting pit substrates (Klemisch 2017).

The focus of the analyses of water soluble ions were deicing salts. The Cl- and Na-contents were most important for estimating contaminations by deicing salts. Normally the concentration of these ions is decreasing with the depth, because deicing salts were in winter scattered on the surface, so that there are the highest concentrations. With the time, the ions were relocated e.g. by precipitation in other areas and deeper soil layers (e.g. BSU, 2012). The results show, that the concentrations of these ions are decreasing with the depth in five of the six profiles (see Appendix II: Table 16 and Zander 2016). The values are relatively low, so that it is not expected, that these concentrations damage the trees.

Therefore, in this study, only the water soluble ions in the topsoils of the other soil profiles were analyzed, where the highest values were expected.

In former soil analyses in Hamburg, the salt content was higher. For example in Petersen et al. (1982), chloride contents >100 mg/kg were measured. They found the relationship of high chloride contents in comparison to lower contents and growth of tree species. They found, that different species react to a different degree. At oaks and locust trees, they did not measure changes in growth due to road salts. However, for instance, linden showed less growth in a soil with 100 mg Cl/kg, but the same species had no changes in growth with 28 mg Cl/kg. Same with a red oak located in a soil with 110 mg Cl/kg in comparison to trees with 70 mg/kg. The values in our study were all lower than 26 mg Cl/kg DM of soil substrates. The median of the chloride content with 4.1 mg/kg and the median of sodium content with 8.5 mg/kg were much lower than the averages mentioned in Pfeiffer (1985) between 19 and 30 mg Cl/kg and 43-81 mg Na/kg in the year 1984. This showed that the salt concentrations declined successfully during the last decades, which is consistent with the results of McNeil (2012). The concentrations nowadays are lower than 132 mg Na/kg DM and 39 mg Cl/kg DM, which named Czerniawska-Kusza et al. (2004) as concentrations, which lead to salt injuries at linden trees. 150 mg soluble salts per 100 g, measured in water extract, is given as threshold in the recommendations for tree planting substrates by the FLL (2012). Thus, no intense growth restrictions by road salts in the analyzed streets of this study were expected.

Zander (2016) analyzed trace metal concentrations (arsenic, cadmium, copper, nickel, lead, Chrome, Zink) and organic pollutants (polycyclic aromatic hydrocarbons) at the sites E1b, E2a, E3c, E4b, E5b and E6b. They were sometimes higher than the natural background contents (Zander 2016), but it is not clear, if they are a potential stress factor for trees.

4.2.2 Consequences of given soil properties and soil heterogeneities for urban trees

It is well known, that the water availability is a very important factor for growth of plants. In this study the root distribution was strongest correlated to the available water capacity ($r=0.658$, $p<0.001$; see chapter 4.1.8) and the effective bulk density ($r=-0.521$, $p<0.001$; see chapter 4.1.8). That can be a sign, that the water availability as well as the compaction of soil are important factors for tree root distribution in urban areas in Hamburg. It further shows, that in the city of Hamburg, water can affect the growth of roots, which implies that different layers contain different amounts of water, which causes the root growth in layers with a good water availability.

The positive effect of the available water capacity on the root density shows that low field capacities in single layers can reduce the rooting in these layers. Some profiles had overall a low available water capacity. Here it is possible, that the times, when not sufficient water is reachable for the tree, are longer than in profiles with higher field capacities. Phases of drought are here more probable, which can lead to a reduced growth of trees, which means that water is probably a limiting factor for tree growth in Hamburg. In addition to the problem of soils with low available water capacity, layers with low saturated hydrologic conductivities can reduce the water transfer in the soils and the water transfer into deeper soil layers. That can lead to a lower water availability in deeper soil layers, which can inhibit root growth there and may lead to an increased rooting in the topsoil.

Therefore, the infiltration of water into the soils is very important. The high proportion of sealed surfaces at roadside tree sites reduces the total infiltration of precipitations and leads to higher runoff. In this study, the percentages of sealing around the trees were relatively high. This may lead to reduced growth according to Sand et al. (2018), who found that sealing below the tree crown reduces the growth of trees. This is in accordance with Vico et al. (2014), who found that denser trees benefit from permeable surfaces.

That high compaction can be a problem for root growth is well known. The optimal bulk density is 1.33 g/cm³ according to Brady (1974) and bulk densities over 1.6 g/cm³ are commonly named as limiting for root growth according to Jim (1998a). There are many studies, which name limiting bulk densities for specific plants (e.g. named in the review of Day & Bassuk 1994). Other studies exist, which found, that a constant bulk density alone is not a good measure, because they found for example effects of the texture (Zisa et al. 1980, Daddow & Warrington 1983) or other properties like water content, which modify the limiting value of bulk density (Taylor & Gardner 1962, Day et al. 2000). According to the growth-limiting bulk density texture triangle, described in Daddow & Warrington (1983), the threshold bulk density is about 1.75 g/cm³ for sand-rich soils with more than 79% sand content, a feature which most of the soils in this study exhibit. The threshold value was reached in some of the analyzed profiles in this study. Therefore, it is likely, that in these soils root density is affected by soil compaction even if roots were found in most of the substrate layers with a bulk density of ≥1.75 g/cm³.

In this study, the bulk densities varied at some sites over a wide range in different soil depths. This means, that different layers vary in attractiveness for roots. At some sites, the preference for one layer in the soil was obvious, for instance, when they form root mats, while the other layers have only a few roots. Root mats occurred at the upper parts of the soil, while layers without roots occurred in all depth. In general, more roots were in the upper parts of the soil, where mainly the compaction is lower and the humus content, which is important for the nutrient supply, is higher, too. That the humus content can affect the growth of trees was shown by Scharenbroch & Catania (2012). They found correlations between the soil organic matter and the tree sizes. Further, they found correlations between tree size attributes and the soil pH and texture. In this study, the soils were analyzed to a depth of 1 m. Generally, roots were found in the bottom layer of the profiles, so that deeper rooting is expected. This is in accordance with Kutschera & Lichtenegger (2002), who described rooting in more than 1 m depth for many tree species growing in

Germany. That means that in this study the whole rooting space was not analyzed, further studies are needed to analyze the soil conditions of deeper rooting zones.

The pH values in this study were in the range of general recommended pH values (Goss & Schönfeld 2014, see chapter 4.2.1). Nevertheless, a negative relation between pH and root density was found in this study, which could be a sign that roots were preferentially growing in the layers with lower pH values, even if the pH values in the other layer are not too high for growing.

In comparison to these properties, the skeleton content did not correlate with the root occurrence in this study. In general, there was no positive or negative effect of the skeleton content on roots at the analyzed sites of this study. Other studies measured significant effects like Nehls et al. (2013), who found positive effects of bricks for plants especially in sandy soils because of their water and nutrient storage capability, which can be accessed by roots.

The high small-scale variety of soils in the inner city of Hamburg causes different soil properties in small areas, so that adjacent trees can have different living conditions. This is sometimes caused by small-scale excavations for power lines and pipes, which can lead to cuttings of the roots and/or to changes of the former soil substrates. That was for example the case at the site E3, where the root distribution and occurrence was different at the three profiles (Appendix II: Table 19). Therefore, it is important to analyze soils on small-scales for estimating growth conditions of tree roots.

4.3 Summary

The results of this study show, that tree sites at streets can have very different soils and so different properties, which can affect the growth of plants. Nevertheless, most of the analyzed soils in the inner city of Hamburg were anthropogenic soils with high sand contents and with distinct layering. These layers can have very different characteristics, so that the suitability for tree roots can change with the depth. Nevertheless, at the study sites at the roads, many of the soil layers were comparable with each other, because of their high sand content and low humus content, which lead to similar physical properties and reduce the occurrence of natural soils with other textures.

Another characteristic of the analyzed sites is the high small-scale heterogeneity. There are sites, where trees are growing, which have a high small-scale variability of soil properties, but other sites are very homogeneous. Often the small-scale variability was generated by excavations and refilling of substrates during construction works. These works affected especially the green stripes, because in this area very often wires or pipes lie in the ground. These small-scale changes affect the water and air availability of the soils and so the growth of trees. That means that detailed analyses of the exact location are needed for evaluation of the suitability of the soil for tree growth. This implies that it is necessary to evaluate each site for its own.

In general, the influence of road salts were low and the pH values in the range, where trees can grow. In contrast to that, the physical situation was worse. Altogether, the chemical contaminants in the soils in Hamburg do not restrict the growth of street trees. However, in this study it is not clear, if the nutrients were in all soils sufficient. Here further studies, which involve more the trees in the analyses, would be helpful to lighten the nutrient problem.

In comparison to the chemical situation, this study showed that the physical situation is more critical and can affect the water and air availability and so influence the growth of trees. There are some sites with a high compaction, so that the air capacity is low and has the potential to restrict growth of plants by a lack of oxygen in the rooting zone. In contrast to that, high sand contents of the anthropogenic substrates, which dominated many soils of the analyzed sites, favor low bulk densities, but they also led to a low available water capacity at nearly the half of the profiles. Here, it is possible that water shortages occur in times of less precipitation and result in problems like drought stress of trees. Therefore, the results of this chapter show that further detailed analyses are needed to validate the estimated problems of oxygen and water shortages in roadside soils in Hamburg. This was done for selected urban tree sites in the following two chapters.

Altogether, based on the results of the available water capacity and the air capacity, the following profiles have a high potential for soil drought and good aeration, because of their “low” AWC in combination with a “very high” air capacity according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005): E3c, F5, F7, F8, F10, F11, F12, F18 and F20. Further profiles with “low” AWCs were found at E2a, E2c, E3a, E3b, E5c, F6, F9 and F19. Of these sites with “low” AWCs, E2, E5 and F5 have the highest surface sealing (>80%) at the 20x20 m area around the tree and accordingly the highest risk of potential drought. At the other study sites, the sealing was ranging between 47% and 80%, but the percentage of unsealed surface in the 20x20 m area, which was directly connected to the tree, was 10% or lower at all but two sites (E3, F9). It is not distinct, whether the tree has underground access to unsealed areas, which were not directly connected to the tree.

In contrast to that, F16 was the only profile with a “high” AWC, which had therefore the lowest potential risk of drought. All other profiles had a “medium” AWC. These profiles had a potential drought risk, which ranged between the above named profiles with a “high” or “low” AWC. F13 and F15 have a relative low surface sealing of less than 30%. This might further reduce the risk of drought.

Based on the assumption, that the available water capacity is the most important factor together with the sealing, the profiles rank in the following order (AWC*percentage of the unsealed surface of the 20x20 m surrounding of the tree), beginning with the profile with the highest drought risk: E2a, E2c, E5c, E2b, F3, F2, E5a, E5b, F5, F19, F6, F11, E3c, E3a, F7, E3b, F18, E6a, F8, F12, F20, F10, F1, E4a, F16, E4b, F9, E1a, E1b, E4c, F4, E1c, F17, F14, F15 and F13.

5. Dynamic conditions (weather, soil hydrology and soil gas) at sites of established roadside trees in Hamburg

This chapter shows the potential risk for stress, which occurred because of dynamic conditions at sites with established roadside trees in Hamburg. Dynamic conditions are here the weather, the soil hydrology, which includes the water tension and water content, and the soil gas (CO_2- and O_2-content). These parameters were analyzed at six sites with established trees over two vegetation periods in the years 2016 and 2017. With modeling, the water tensions of the past were analyzed for seven different study sites. Altogether, this chapter will help to identify times with soil drought or insufficient aeration, which may cause stress for trees.

5.1 Results

5.1.1 Precipitation, air and soil temperature during the study period

The precipitation rates from all four measurement stations (Hamburg (HH)-Fuhlsbüttel (DWD 2018) and at E3, E4 and E6) showed in average rainfall on more than every second day in summer 2016. In summer 2016, the precipitation sum of 285 mm was higher at the weather station in HH-Fuhlsbüttel (DWD 2018) than the 30-year average (1981-2010) with 235 mm (Table 6). In July, it rained more often and the intensity per rainy day was higher than in spring. Then the interval between two rainfalls was decreasing again, but the average precipitation rate stayed about the same until mid-September (Figure 26). After that, the precipitation rates decreased on less the half until mid-November and increased again during winter until April 2017 with a one-month-period from the 15th of January 2017 to the 15th of February 2017, when only 6 days with altogether 12.9 mm precipitation occurred at the station in HH-Fuhlsbüttel (DWD 2018). In May 2017, the precipitation rates (intensities and frequencies) increased again, and stayed on a relatively high level until the end of the year with single intensive rainfalls in summer and fall. In comparison to the 30-years average data of the DWD (2018), 2017 had higher precipitation sums in spring, summer and fall (Table 6). The precipitation sum in the year 2017 at the station in HH-Fuhlsbüttel was 990 mm (DWD 2018), while the sums were lower at the other stations: At E3 632 mm, at E4 501 mm and at E6 763 mm. For differences of the daily precipitation sums at the four measurement stations and the distribution of precipitations during the year see Figure 26. The temperatures of the years 2016 and 2017 were similar to the 30-year average (Table 6).

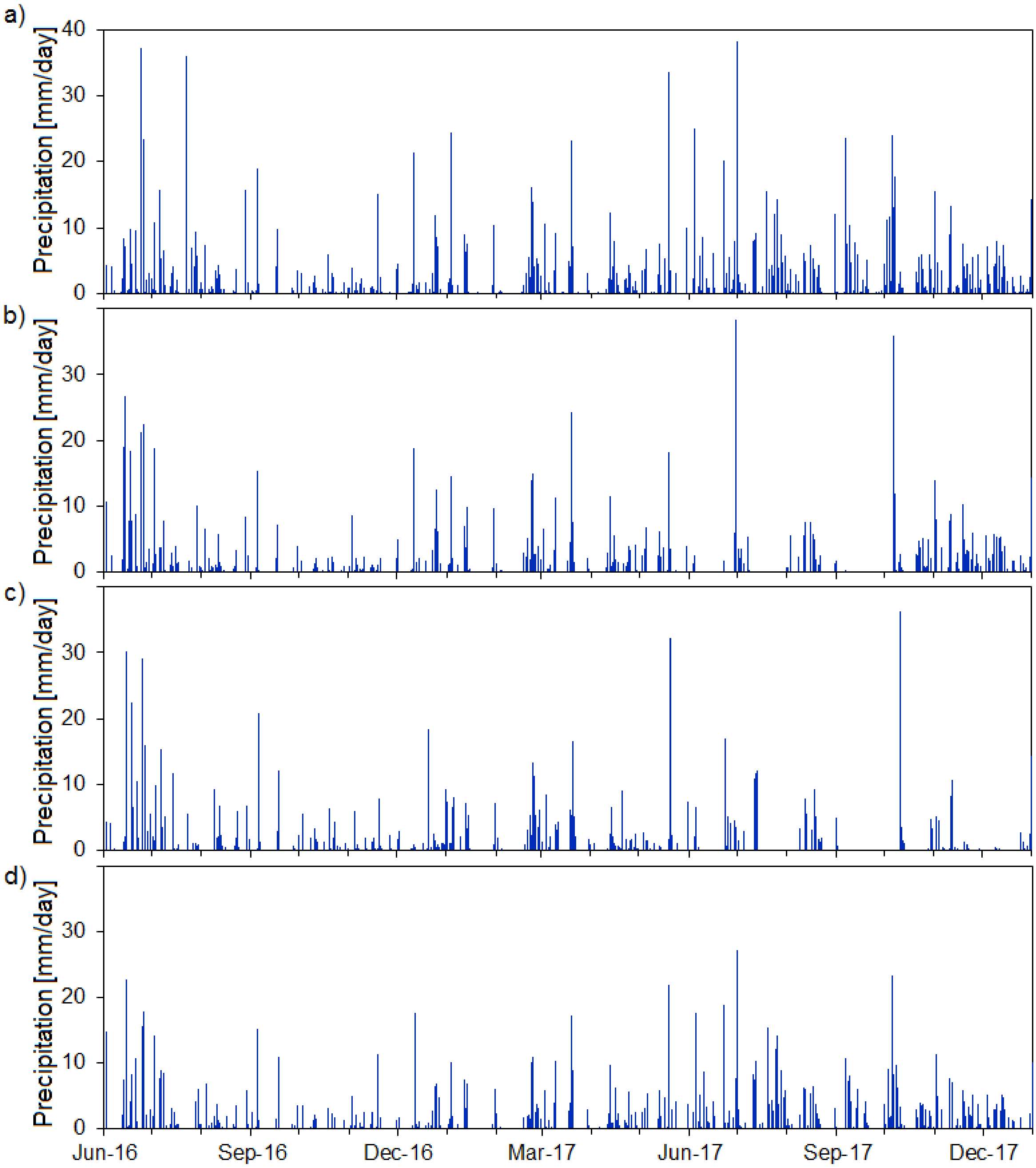

Figure 26: Daily precipitation sums at the weather stations in a) HH-Fuhlsbüttel (DWD 2018), b) at E3, c) at E4 and d) at E6 from June 2016 to December 2017. Data gaps of E3, E4 and E6 were filled with precipitation rates from the station in Fuhlsbüttel (DWD 2018).

Table 6: Air temperature averages and precipitation sums of 2016, 2017 and the 30-year average (1981-2010) of the weather station in Hamburg-Fuhlsbüttel (DWD, 2018).

Season	**Air temperature average [C°]**			**Precipitation sum [mm]**		
	30-year average	**2016**	**2017**	**30-year average**	**2016**	**2017**
Spring (April, May)	10.8	11.1	10.7	100	92	133
Summer (June-August)	17.1	17.6	16.9	235	285	301
Fall (September-November)	9.7	10.2	10.6	204	105	284
Vegetation period (April-October)	13.8	14.5	14.0	469	442	631
Year	9.4	9.9	9.7	793	739	990

The soil temperature was measured in the three profiles at each of the six sites at established trees. In the three adjacent profiles of each site, the temperatures (rounded to integer) were very similar. For example, 99.4% of the data measured in 20 cm depth in the profiles E1b and E1c were identical and 99.1% in 100 cm. The highest difference for a single data pair of the two profiles was 3°C in 20 cm depth (0.02% of the measured values). 1.84% of the measured values in 20 cm depth had a difference of was 2°C; in 100 cm depth, only 1.07% of the data had a difference of 2°C. A difference of 1°C was measured at 52.4% (100 cm) or 39.0% (20 cm) of the time.

Between 20 and 100 cm depth some temperature differences have been observed. In profile E2b, the highest difference was 7°C, which was reached for about 8 hours in November 2016. In winter, the temperature differences in different depths of the same profile were higher than in summer. The soil in 20 cm of E2b became faster cold and reached 1°C in January, while the soil in 100 cm depth did not get colder than 4°C at all. At that time, the soil in 20 cm was already getting warmer, because of the slightly increasing air temperatures. Therefore, the data show that the soil in 20 cm reacted faster to atmospheric temperature changes. At all other sites, the differences between the three profiles were similar to this example. Thus, detailed data are not shown. At E1 the mean soil temperature was in average slightly warmer [around +2K] than the soils at the other sites, where the temperatures were very similar to each other (data not shown).

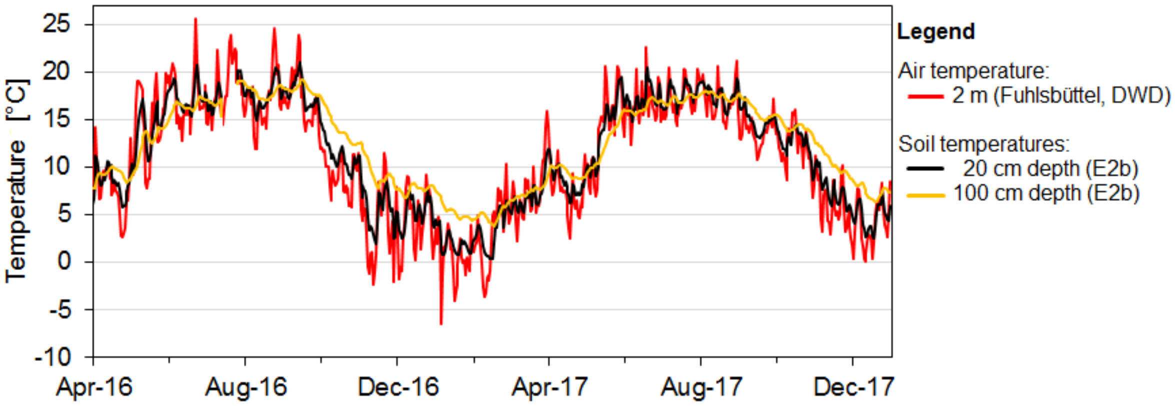

Figure 27: Daily air temperatures at HH-Fuhlsbüttel (DWD 2018) (red) and soil temperatures in 20 cm (black) and 100 cm depth (yellow) of the profile E2b from April 2016 to December 2017.

5.1.2 Soil gas composition

The monitoring of soil gas composition (CO_2 and O_2) started between March and April 2016 at E1 to E5 and in July 2016 at E6.

In all three profiles of each of the six sites, the CO_2 content was increasing with the depth (Figure 28, Figure 30). In summer, the CO_2 content was higher than in winter (Figure 28), so it has a similar course as the temperature curve. In 2016, the highest values of CO_2 were measured at the end of July (E1-E5,) or in the beginning of August (E6). After reaching these peaks, the concentration was decreasing. In the second half of October 2016, the percentages of CO_2 are lower than 3% and reached their minima of around 0.5-2% CO_2 between the end of November and mid of December 2016. Then, in most of the profiles (E1, E2, E4 and E5) the concentration increased slightly - with a short decrease at the end of February - until May 2017, when it started to increase faster until summer. In profile E6c, the increase started not until mid of March. An additional decline of the concentration occurred in June in the profiles E3a-c. In summer and fall, the values reached their maxima. The maxima varied from site to site and was in deeper layers higher. The CO_2 maxima ranged between 2.1% (E1a, 20 cm) and 9.1% (E5b, 100 cm) in summer/fall 2016. In E6a and E6b, the values were stable from December 2016 to June 2017. In 2017, the highest CO_2-concentrations were measured in July/ August, mainly on the 26th of July. During this period, the measured values fluctuated very strongly between the individual measurements, sometimes with more than two percent. The highest values of the measurement period in the deepest measured layers (E1a-E5c: 100 cm; E6a and E6c: 80 cm; M6b: 50 cm) varied between 2.8% (E1a) and 9.1% (E5b) and were in average 6.2% (standard deviation: 1.78%).

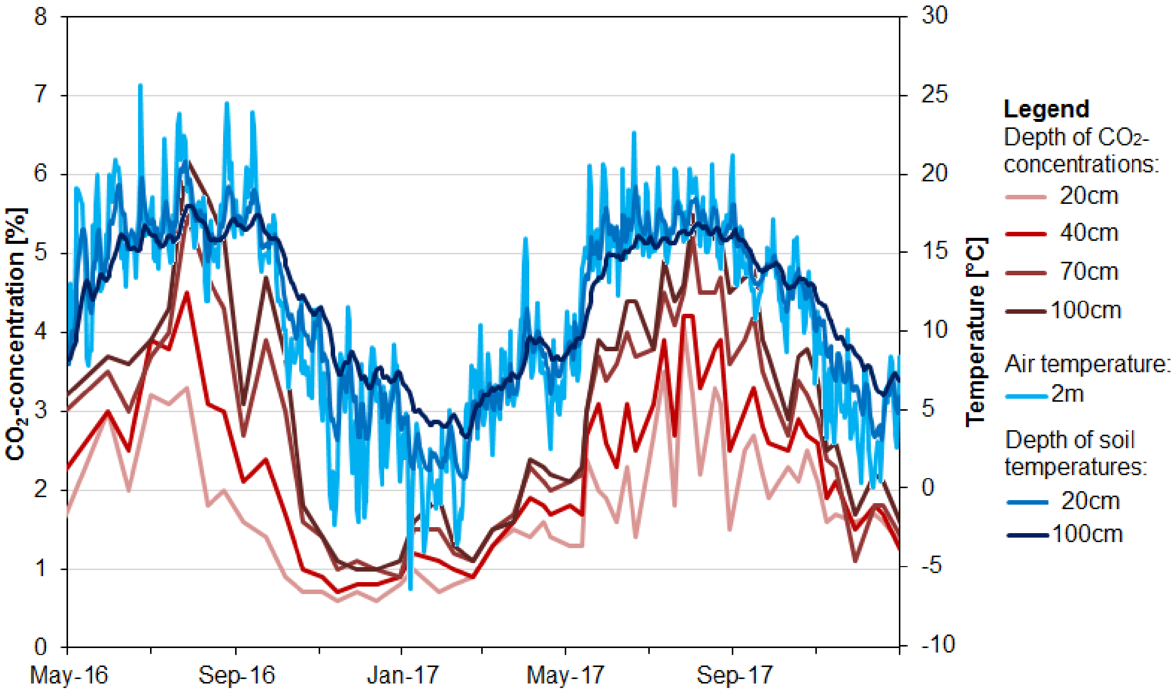

Figure 28: CO$_2$-concentrations in 20, 40, 70 and 100 cm depth, daily mean soil temperatures in 20 cm and 100 cm depth of profile E5a and daily mean air temperature of the weather station in HH-Fuhlsbüttel (DWD 2018).

In contrast to the CO$_2$-concentrations, the O$_2$-concentrations were decreasing with the depth. In general, the O$_2$-content showed an inverse dynamic to CO$_2$ (see Figure 29). Therefore, the minima were reached in summer/ fall, while the highest concentrations were measured in winter. The correlation between the CO$_2$- and the O$_2$-content was high and in all profiles and depths significant ($p<0.01$): the median Pearson correlation coefficient was $r= 0.915$, the minimum was $r=0.658$ (E2c 70 cm) and the maximum was $r=0.987$ (E2b 70 cm). The lowest O$_2$-values of the measurement period measured in the deepest layers (E1-5: 100 cm; E6a and E6c: 80 cm) varied between 9.4% (E5c) and 18.8% (E1b and E1c) and were in average 14.2% (standard deviation: 2.82%). The highest values in the deepest layers were in average 21.1% (standard deviation: 0.59%).

In general, the three adjacent profiles at each monitoring site revealed data with similar reactions of CO$_2$- and O$_2$-concentrations during the different seasons as described. The profiles E1a-E1c were very similar to each other. These profiles were the profiles with the lowest CO$_2$-values and highest O$_2$-values throughout the measuring period. The O$_2$-content stayed above 18% over the whole measurement period. Only at two measurement dates (31.03. and 14.07.2016), CO$_2$-values of three percent or more were reached in the two uppermost depths of profile E1b. In winter, the CO$_2$-values were not much higher than atmospheric concentrations with around 0.1% CO$_2$-content (see Figure 30d). The variation of concentrations with the depth of the profiles were also small in these three profiles. The CO$_2$-concentrations measured in 20 cm were usually less than 1% lower than in 100 cm depth.

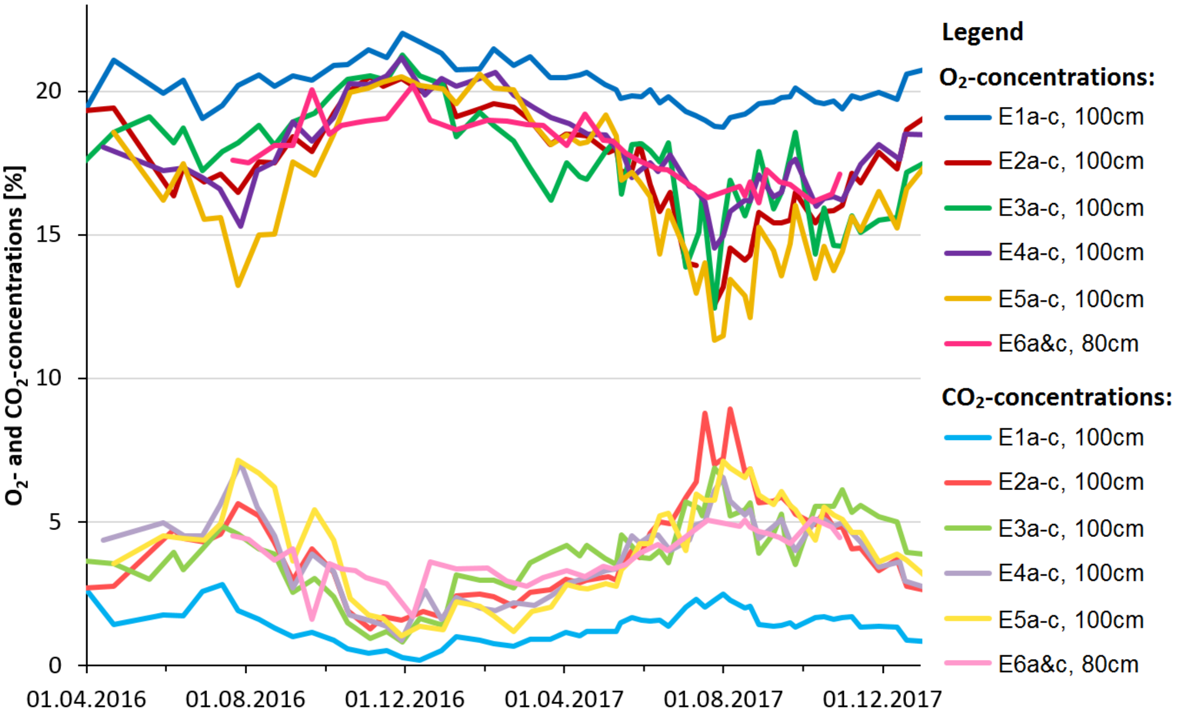

Figure 29: O_2- and CO_2-concentrations of the the six monitoring sites with established trees (E1-6) from April 2016 to December 2017. Shown are the averages of the deepest measured layers of the three profiles of the sites E1 to E5. For the site E6, the average of E6a and E6c is shown.

The profile E6b has similar low concentrations of CO_2 to E1a-c. But the other two profiles (E6a and E6c) of this site reached higher concentrations (data not shown). The maxima of the CO_2-contents of E6c were around 4% in 50 cm depth in summer. In the layer above, they were only for a short time nearly 3% in summer. In winter, the CO_2-content was only a very short time below 2%. The difference of the average CO_2-content in 50 cm depth is 1%.

At the site with the profiles E6a-E6b, the largest differences between adjacent profiles were measured. At that site, the difference between the average CO_2-content of the measurement period in the same depth of different profiles is up to 2.6% (between E5a and E5b in 20 cm depth). These three profiles differ from each other in the height of the maxima reached in summer. E5b has the highest peaks in summer. The highest value in 2016 was 9.2% and in 2017 8.9% (Figure 30a-c).

The other profiles at the sites E2-E4 were more similar to each other and showed only smaller differences to each other, so that the courses of CO_2- and O_2-content were close to their averages in Figure 29.

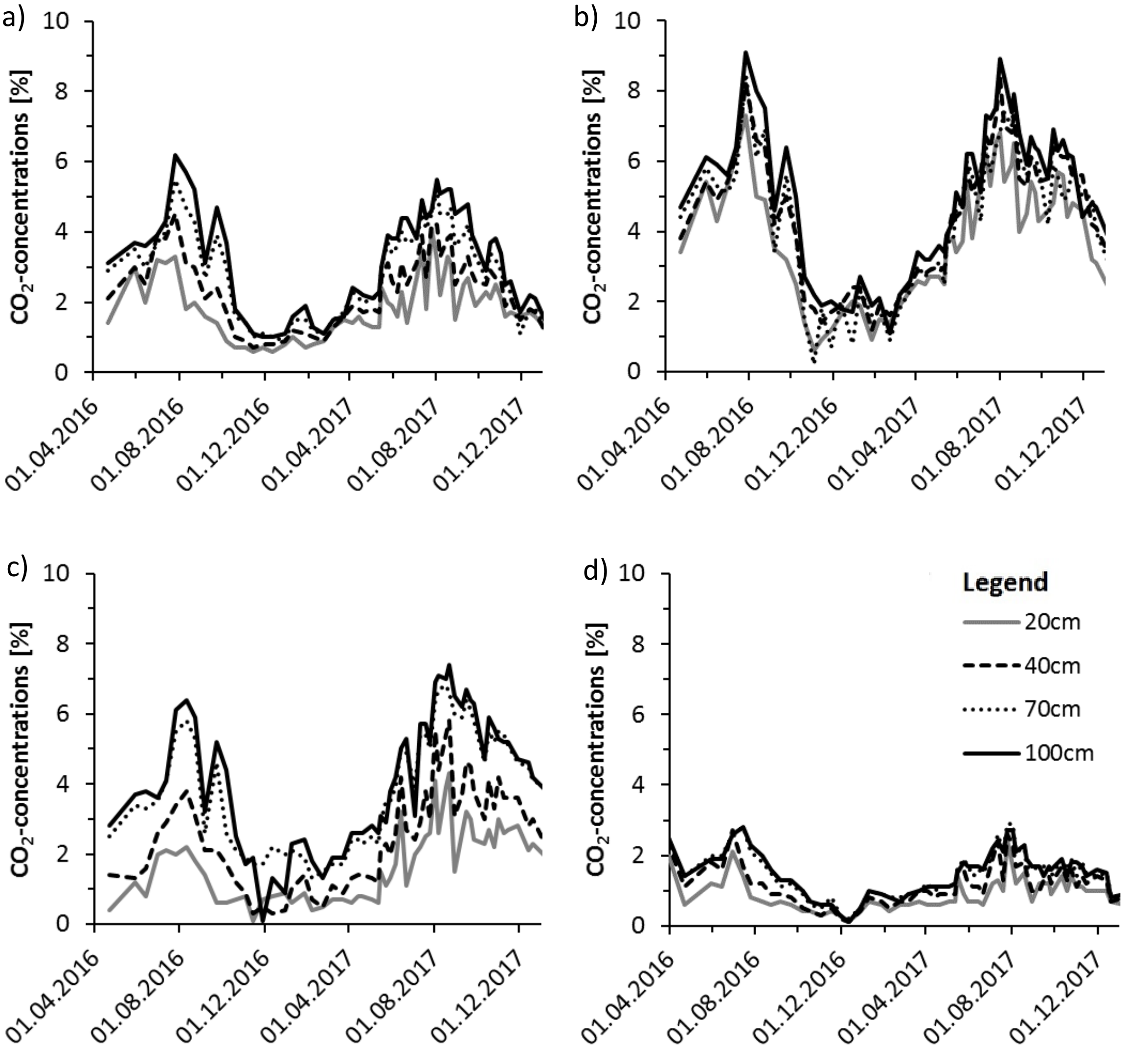

Figure 30: CO$_2$-concentrations from April 2016 to December 2017 of the adjacent profiles (a) E5a, (b) E5b, and (c) E5c in the depth of 20, 40, 70 and 100 cm, which show different heights of summer peaks. As comparison, profile E1a (d) is shown, which had low CO$_2$-concentrations throughout the year.

For most cases, the mean CO$_2$-concentrations of each depth of each site were significantly correlated with the soil temperatures. At most of the sites, this correlation was stronger with the temperatures in 20 cm depth than with the temperatures in deeper soil layers. The strength of the correlations of each site increased with the depth, in which the CO$_2$-concentrations were measured (data not shown). The strongest correlations of $r=0.808$ and $r= 0.802$ ($p\leq0.01$) of the CO$_2$-content were found at site E5 in 70 cm (see Figure 31) and 100 cm depth with the soil temperature in 20 cm. No significant correlations were found in 20 cm (see Figure 31) and 40 cm depth of E3 and in 20 cm depth of E6.

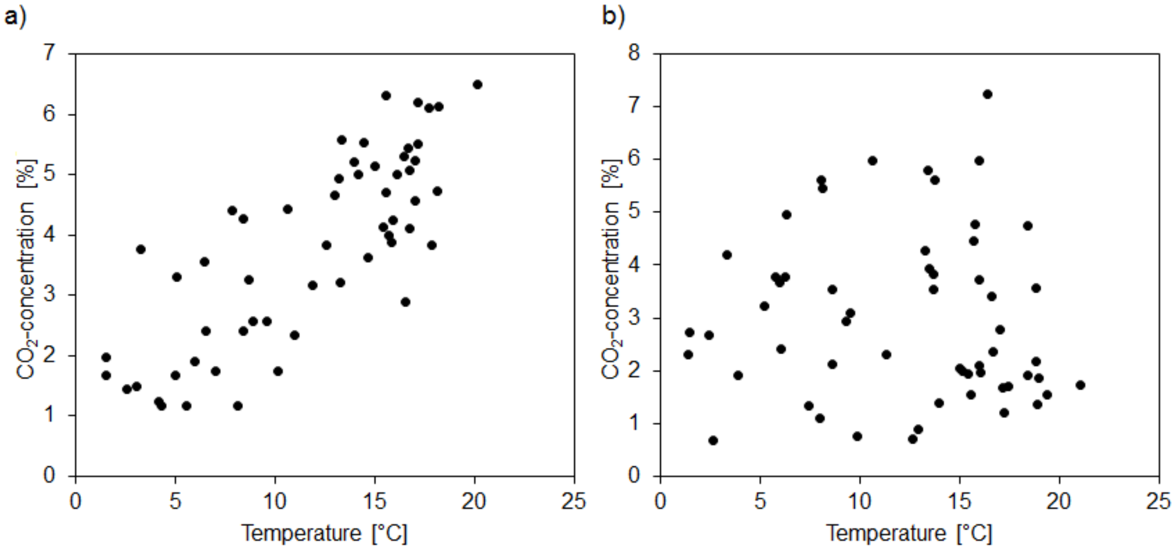

Figure 31: Examples of strong (a) and low (b) correlations between the mean CO_2-concentrations of one depth of the sites and temperatures in 20 cm depth. a) shows a strong correlation between the CO_2-concentrations in 70 cm depth with the temperature in 20 cm depth at site E5. b) shows an insignificant relationship of CO_2-concentrations in 20 cm depth with the temperature in the same depth at site E3.

The correlations of the mean CO_2-concentrations with the mean water content (see chapter 5.1.3) in 20 cm depth of the respective site were calculated after normalizing the CO_2-contents on constant temperature, when the correlation between them was significant. The CO_2-content correlated to the soil water content positively. Over the complete measurement period, the water contents in 20 cm depth (E6: 40 cm depth) were at least in one depth of each site significant correlated with the mean CO_2-contents of the respective site (Table 7). At each site, the highest correlations were found in 20 cm or 40 cm depth, while at half of the sites, the correlations were not significant in 100 cm depth. The correlations were strong at site E6 and E4 and low at sites E2 and E5. The highest correlations were found at site E4, where the Pearson correlation coefficients were up to $r=0.776$ ($p<0.01$). The coefficient reached similar high values in 15 cm and 30 cm depth at E6, but in 80 cm depth, the correlation was not significant.

The minima of the O_2-content in the deepest layers showed the tendency, that the minima were lower at sites, where no grass had grown on the surface. Profiles with a high effective bulk density and a low pore volume (e.g. E5c) often had high CO_2-contents in summer. The profiles with the lowest effective bulk densities (E1a-c) had the lowest CO_2-contents. The three adjacent profiles had more similar gas content values throughout the year when the soil was in all three profiles not too different. Therefore, the measurements in profiles E1a-c and in the profiles E5a-c were very similar at each site. In contrast to that, the measurements of the profiles were more different at the sites E3 and E5.

Table 7: Pearson correlation coefficients of the correlations between the mean water contents in 20 cm (E6: 40 cm) and the mean CO_2-contents in 20, 40, 70 and 100 cm depth at the sites E1-5 and in 15, 30, 50 and 80 cm depth at E6 for measurements from April 2016 to December 2017 (E6: August 2016 to January 2017 and August 2017 to October 2017). Significant values with $p<0.05$ are bold.

		Pearson correlation coefficients			
Site number	Depth of water content	CO_2 in 20 cm	CO_2 in 40 cm	CO_2 in 70 cm	CO_2 in 100 cm
E1	20 cm	**0.597**	**0.627**	**0.584**	**0.556**
E2	20 cm	0.211	**0.273**	-0.106	-0.032
E3	20 cm	**0.454**	**0.293**	**0.412**	**0.405**
E4	20 cm	**0.706**	**0.776**	**0.704**	**0.615**
E5	20 cm	**0.546**	**0.351**	0.249	0.132
E6*	40 cm	**0.770**	**0.768**	**0.584**	0.405

* CO_2 in 15 cm, 30 cm, 50 cm and 80 cm

5.1.3 Water content and water tension in urban soils at established roadside trees

The six monitoring sites can be separated in two groups: the soils of the first group (E2 and E5) had no intensive drought. In 2016 their water tensions stayed below 2000 hPa (≈pF 3.3), which is the maximum that the used water sensors can measure. The second group (E1, E3, E4 and E6) showed a phase with an intensive drying of the soils with water tensions of at least 2000 hPa in late summer of the first year of the measurements (2016). In further analyzes of this chapter, I distinguish between intensive soil drought (≥2,000 hPa, ≈pF 3.3) and moderate soil drought (≥750 hPa ≈pF 2.8). According to Shock et al. (2002), the moderate soil drought can lead to reduced growth of poplar (see chapter 2.1). At first, the results of the analyses of the soils of the first group with moister soils are presented here, before the results of the monitoring of the other sites were described.

Table 8 shows the percentage of time, in which the soils had a water tension equivalent to or higher than 2000 hPa (pF≈3.3). The table shows the data of the three profiles at each monitoring site from May 2016 to end of December 2017. At the sites E2 and E5, a water tension of 2000 hPa was not reached in any depth. The other sites showed a drying especially in the upper soil layers in 20 cm below the surface.

Table 8: Percentages of time with water tension ≥750 hPa (≥2000 hPa) in summer 2016, autumn 2016, winter 2016/17, spring 2017, summer 2017, autumn 2017 and winter 2017, based on hourly data. Percentages ≥30% are in bold.

Profile No.	**Depth** [mm]	**Percentage of soil water tension ≥750 hPa (≥2000 hPa) [%]**						
		Summer 06.-08.2016	Fall 09.-11.2016	Winter 12.2016-02.2017	Spring 03.-05.2017	Summer 06.-09.2017	Fall 09.-11.2017	Winter 12.2017
E1a	20	12.5 (0)	**57.9** (0.8)	0 (0)	0 (0)	11.3 (0)	**37.4** (0)	0 (0)
	40	0.5 (0)	**57.1** (0)	0 (0)	0 (0)	2.4 (0)	26.9 (0)	0 (0)
	70	25.0 (0)	**100** (0)	17.9 (0)	0 (0)	0 (0)	**38.7** (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E1b	20	**50.3 (36.1)**	**99.9 (91.4)**	0 (0)	0 (0)	**82.1** (11.3)	**42.7** (20.4)	0 (0)
	40	**33.0** (0)	**86.2** (0)	0 (0)	0 (0)	19.3 (0)	**38.5** (0)	0 (0)
	70	3.8 (0)	**100** (0)	16.2 (0)	0 (0)	27.8 (0)	**40.8** (0)	0 (0)
	100	23.1 (0)	**100** (0)	**33.5** (0)	0 (0)	**36.8** (0)	**46.2** (0)	0 (0)
E1c	20	**42.8** (0)	**86.7 (40.5)**	0 (0)	0 (0)	0 (0)	**41.1** (0)	0 (0)
	40	21.7 (0)	**50.5** (0)	0 (0)	0 (0)	0 (0)	**35.8** (0)	0 (0)
	70	0 (0)	**74.6** (0)	0 (0)	0 (0)	0 (0)	21.7 (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E2a	20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	40	0 (0)	**77.6** (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E2b	20	25.6 (0)	**48.9** (0)	0 (0)	0 (0)	6.0 (0)	7.1 (0)	0 (0)
	40	0 (0)	**47.0** (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E2c	20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	40	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E3a	20	**64.3** (0)	**68.1** (17.2)	0 (0)	0 (0)	**38.8** (0)	**38.6** (0)	0 (0)
	40	**57.1** (0)	**87.2** (19.4)	0 (0)	0 (0)	**67.6** (0)	**40.3** (0)	0 (0)
	70	16.7 (0)	**100** (0)	24.9 (0)	0 (0)	**78.2** (0)	**62.5** (0)	0 (0)
	100	3.8 (0)	**100** (0)	**43.7** (0)	0 (0)	**75.4** (0)	**81.9** (0)	0 (0)
E3b	20	**39.7** (0)	**76.4 (31.4)**	0 (0)	0 (0)	**34.4** (0)	**38.7** (0)	0 (0)
	40	**42.1** (0)	**91.7** (0)	0 (0)	0 (0)	**80.6** (0)	**42.6** (0)	0 (0)
	70	**36.0** (0)	**100 (75.0)**	14.8 (1.3)	0 (0)	**79.4** (0)	**64.6** (0)	0 (0)
	100	27.1 (0)	**100** (0)	**37.2** (0)	0 (0)	**73.3** (0)	**84.2** (0)	0 (0)
E3c	20	**51.9** (6.4)	**88.5 (82.4)**	0 (0)	0 (0)	**63.5** (0)	**38.3** (0)	0 (0)
	40	0 (0)	**83.8** (0)	8.6 (0)	0 (0)	0 (0)	**36.6** (0)	0 (0)
	70	0 (0)	**81.3** (0)	**30.6** (0)	0 (0)	0 (0)	**36.7** (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E4a	20	0 (0)	**68.8** (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	40	0 (0)	**59.4** (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	**50.0** (0)	21.9 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E4b	20	14.9 (0)	**84.8 (44.3)**	0 (0)	0 (0)	0 (0)	7.6 (0)	0 (0)
	40	0 (0)	**85.5** (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	**76.9** (0)	17.6 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	**69.1** (0)	29.5 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E4c	20	0 (0)	**70.0** (0)	0 (0)	0 (0)	0 (0)	10.4 (0)	0 (0)
	40	0 (0)	**95.3** (0)	0 (0)	0 (0)	0.5 (0)	8.2 (0)	0 (0)
	70	0 (0)	**83.8 (46.6)**	21.3 (0)	0 (0)	0 (0)	1.6 (0)	0 (0)
	100	0 (0)	**79.5** (0)	**37.5** (0)	0 (0)	0 (0)	0 (0)	0 (0)

Profile No.	**Depth** [mm]	**Percentage of soil water tension ≥750 hPa (≥2000 hPa) [%]**						
		Summer 06.-08.2016	Fall 09.-11.2016	Winter 12.2016-02.2017	Spring 03.-05.2017	Summer 06.-09.2017	Fall 09.-11.2017	Winter 12.2017
E5a	20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	40	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E5b	20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	40	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E5c	20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	40	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
E6a	10	**70.2** (19.3)	-	0 (0)	0 (0)	**48.9** (0)	**38.4** (0)	0 (0)
	20	**72.5 (32.6)**	-	0 (0)	8.3 (0)	**57.5** (0)	**38.8** (20.7)	0 (0)
	40	**100 (33.2)**	-	8.5 (0)	0.5 (0)	**99.8** (0)	**41.4 (36.3)**	0 (0)
	80	**60.7** (0)	-	21.9 (0)	0 (0)	**60.5** (0)	**52.2** (0)	0 (0)
E6b	10	**54.3** (8.5)	-	0 (0)	0 (0)	**31.1** (0)	**38.4** (0)	0 (0)
	20	**59.2** (14.0)	-	0 (0)	0 (0)	**35.0** (0)	**38.8** (20.7)	0 (0)
	40	**60.4** (6.7)	-	0 (0)	0 (0)	17.1 (0)	**41.4 (35.7)**	0 (0)
	80	**63.6** (0)	-	0 (0)	0 (0)	6.3 (0)	**52.2** (0)	0 (0)
E6c	10	**57.2** (5.4)	-	0 (0)	0 (0)	**37.3** (0)	**100** (0)	**40.3** (0)
	80	**89.8** (9.2)	-	26.4 (0)	26.4 (0)	**80.3** (0)	3.7 (0)	0 (0)

Sites with constant moist soils

At the sites E2 and E5 the soil profiles were moist or only slightly dry with hourly water tensions less than 2000 hPa (pF≈3.30) during the whole measurement period (spring 2016 to December 2017, Table 8).

In general, the soil water content is increasing after precipitations and so the soil water tension is decreasing (Figure 32 to Figure 37). In spring, the soil water tensions were low and close to zero at E2 and E5. In late summer and fall, the tensions increased, but stayed below 750 hPa at E2c and E5a-c. Only at E2a and E2b, higher values were reached in 20 cm (E2b) and 40 cm depth (E2a and E2b). In winter, the soils became moist again, combined with low soil water tensions. This was observed in both years, but the slight increase of water tension in summer 2017 was lower, shorter and later in the year than in the year before. In 2016, the highest water tensions were measured from September to November. In 2017, the highest water tensions were observed in the end of June and in September. The highest daily mean water tensions were below 1500 hPa (pF≈3.18) at site E2 in 2017, while the values at site E5 reached 350 hPa (pF≈2.54) as a maximum in 20 cm depth at E5a and stayed 2017 below 220 hPa (pF≈2.34) (Figure 36). This low value was in the range of the field capacity of the most common soils, which are between pF 1.8 and pF 2.5.

The soil water content at these two sites (E2 and E5) was higher than at the other sites. Especially the profiles E5a-c had a high water content. In E5a and E5b, the lowest water content was measured in the top of the soil the whole year. With increasing depth, the water content increased. In 100 cm depth, the water content was relatively constant at a high level with an average of 36.6 vol.-% (E5a) and 31.0 vol.-% (E5b). In the profiles E5a-c, the water content reacted only slightly on precipitation in 70 cm and 100 cm depth. Even heavy rainfalls like those at the end of February 2017 or in begin of October 2017 had only a very small effect on the water content in these profiles, while the strong rainfalls increased the water contents of most of the other profiles to a much higher degree. Profile E5c was slightly different. Here the sensors in 20 cm, 70 cm and 100 cm measured similar water contents (averages between 21 vol.-% and 24 vol.-%), but the water content of about 31 vol.-% in 40 cm depth was on average around 10 percentage points higher (Figure 36).

In contrast to the low reaction on precipitation in the subsoil, the sensors in 20 cm depth at E5a-c showed an intensive reaction, which was different from the other sites, too. In the profiles E5a-c, the water content increased more often than at other sites so that the water contents were not decreasing to a higher extent. In addition to that, the increase of water content after heavy rainfalls was lower than at other sites. Therefore, the relative difference between the measured maximum and minimum is smaller than at sites with drying in summer/fall. At E5, the minima of the water content were 46.7% (E5a), 62.2% (E5b) and 54.2% (E5c) of the maxima in 20 cm depth. These values were higher than at the other sites with phases of drying, where the minima of the water content was for example 27% of the maximum at profile E1b or at E4b.

For site E2 and in relation to the texture distribution, the water content is generally decreasing with the depth (see Figure 33). In E2a and E2b in 20 cm depth, the water content (daily mean values) reached their highest values with 24.8 vol.-% and 26.3 vol.-% in April 2016 and November 2017 and the lowest values with 8.2 vol.-% and 11.3 vol.-% in October 2016. In E2c, the water content in 20 cm depth was higher than in E2a and E2b. It varied between 18.6 vol.-% and 32.7 vol.-%. In winter 2016/17 and spring 2017 the increases of water content after precipitations were very small. At this site, the water content in 40 cm depth was nearly every time higher than in 20 cm depth and was lower than 25 vol.-% only from 29th of August to 14th of November 2016. That means that it stayed on a high level during our whole measurement period. The water content in 70 cm and 100 cm depth showed only small reactions on precipitations and were on average at 16.3 vol.-% and 9.5 vol.-%.

Altogether, the profiles of the sites E2 and E5 exhibited low soil water tensions and relatively high water contents in both years of measurement. In deeper soil layers, the variability of the water tensions and water contents were small. Altogether, the soils at these sites were wet or moist and phases of drought did not occur in the measurement period.

Sites with phase(s) of drying of the soil

The second group of sites showed stronger variability of water content and water tension in their soils, so that phases of intensive soil drought (soil water tension ≥2000 hPa) occurred within the monitoring period. However, the four sites with drying (E1, E3, E4 and E6) showed differences in the duration and depth of soil drying. Additionally, the depth and duration of drought phases varied in the neighboring profiles of each site, too.

In the first year of measurement, the site E4 had the shortest phases with dry soils of the four sites. At profile E4b, the sensor in 20 cm depth measured an intensive soil drought (water tension ≥2000 hPa) from the 30th of September to the 11th of November 2016 (40 days); in the deeper parts of the soil in this profile, this tension was not reached. In 40 cm depth of profile E4c, it was slightly longer dry (41 days) during the same season, while such intensive drought of the soils was not observed in the other depth and profiles of this site (Figure 35).

In E4, moderate soil droughts (water tensions higher than 750 hPa) were reached in all but one (70 cm of E4a) analyzed soil layer in the year 2016 (Table 8, Figure 35). The longest period with water tensions ≥750 hPa occurred in 20 cm depth at E4b from 18th of August to 17th of October 2016. At this profile, the rewetting (water tensions <750 hPa) occurred later in the deeper soil layers. In 40 cm death at the 28th of November, in 70 cm at the 16th of December and in 100 cm depth not until the 27th of December 2016. At E4c, the water tensions were similar to the ones of profile E4a, but here, the duration with water tensions ≥750 hPa was higher in deeper layers than in 20 cm depth, because of similar start of the soil drought and the distinct later rewetting in deeper layers (about 1.5 month later in 100 cm depth). In 2017, soil water tensions ≥750 hPa were reached only in profile E4b in 70 cm depth and in E4c in 20, 40 and 70 cm depth for less than 10 days in fall. No intensive soil drought of ≥2000 hPa occurred at site E4 in 2017.

The other three sites with drying (E1, E3 and E6), showed slightly higher water tensions than the above described site E4, but the periods with drought were nearly at the same time of the years. In most of the soil profiles, the soil was starting to dry slowly in May 2016. The surface was drying faster than the deeper layers, but the tensions did not reach high values. In July 2016 the water tensions were rapidly increasing until they stayed at higher levels (mostly around 2000 hPa), which were reached between a half month later (e.g. E1b in 20 cm depth) and three month later in October 2016 (e.g. E1c or E4b in 20cm depth). During the dry phase until the complete rewetting, the water tension decreased at some profiles (e.g. E3a) for a short period in the upper soil layers, especially in 20 cm depth. These decreases were effects of rain, which reached only the sensors in the upper layers and did not infiltrate in deeper soil layers. Later in the year, the precipitations reached also the deeper soil layers and a rewetting occurs there, too. Therefore, the dry phase of the deeper soils started at many soil profiles later and ended later than in the upper layers. Only at a few profiles like E3b, the drying started in all depths nearly at the same time with a similar intensity (Figure 34). In the other two profiles of that monitoring site (E3a and E3c), the drying in different soil layers occurred not at the same time.

The rewetting took place between November 2016 and the first half of January 2017. The water tensions decreased rapidly from the high levels to low values in a few hours or days. The water tension in 70 cm depth in profile E1c decreased for example from about 1700 hPa to 150 hPa over 21 days (see Figure 32). In contrast to that, the water tension decreased from 1627 hPa to 303 hPa within 19 hours in 20 cm depth in profile E3b on the 9th of November 2016. Therefore, there were differences in reactions to precipitations. At first, the layers closer to the surface were faster moistened by rain, before the water infiltrated in deeper soil layers and moisturized them. That causes later rewetting in the depth and therefore longer periods with drought in deeper soil layers at some profiles (e.g. E1a, E3a and E3b). In Figure 32 to Figure 37, it is visible that the different soil layers were not starting to dry at the same time. One can also see that the rewetting occurred not at the same time. Obviously, only longer and intensive rainfalls led to a rewetting of the soil. Short precipitations with low intensities like the rainfall on the 7th of October 2016 with 1 mm/d (in Fuhlsbüttel, DWD 2018) did not reach deeper soil layers.

In the second measurement period from May 2017 to the end of December 2017, a phase of soil drying occurred, too. In that year, the soil became dryer in June and again in August until the first half of October. Between these months, a rewetting occurred at the last day of June. At that day, an intensive rainfall with 38 mm/d (Fuhlsbüttel, DWD 2018) rewetted the soils. Not all profiles were completely rewetted by this rainfall. In the profiles E6a, E3a and E3b, only the uppermost layers were moistened by the rain, while the deeper layers stayed dry (Figure 34 and Figure 37).

In comparison to 2016, in 2017, the intensity of soil drying was lower and the rewetting was earlier in the year, mainly in October. Therefore, the phases with dry soils were shorter. For instance, the water tensions in 20 cm depth of profile E3a were at least 750 hPa during 65% of the summer and fall 2016, while 750 hPa was reached only during 39% of the summer and fall 2017. Another example is the profile E4a, where water tensions of 750 hPa or more were only reached in fall 2016 - and not in the year 2017 (Table 8). In general, the intensities of drought were lower in 2017 than in 2016: In 2016, soil water tensions of 2000 hPa were reached in eleven profiles, while only three profiles (E1b, E6b and E6c) reached that tension in 2017.

The monitoring of the soil water content showed similar results than the monitoring of the water tension. In this group with sites, which showed soil drying in fall 2016 and summer 2017, the water content was decreasing with soil depth at most of the profiles (Figure 31, Figure 33, Figure 34 and Figure 37). In addition to that, the influence of precipitation was mainly slightly decreasing with the depth, but it was higher than in soils of the group with wet soils. The soil water contents started to decrease in July 2016 and increased between November and December 2016. In 2017, there were one short phase of soil drying in June and another phase from August to October, where the water tensions decreased. During these phases, the precipitations did often not even reach the sensors in 20 cm depth. Therefore, rainfall did not increase the water content in many profiles during these drier times. In some profiles (e.g. E1a and E4a), a few precipitations during these phases led to a small increases of water content in the uppermost soil layers, which was not observed in the adjacent profiles.

The difference between the highest and lowest soil water contents in each profile and depth is higher than in the wet soils. Here the minima in 20 cm depth varies mainly between 21% and 28% (average: 27.1%) of the maximum. Only at E3a, the minima with 18.0% of the maximum is lower and at E3b with 41.8% much higher than the average percentage of the minima in relation to the respective maxima.

The soil water contents of the three profiles at E3 had more differences between each other than the profiles at the other sites, where the course and intensity of water tensions were similar to each other. At E3c, the soil water content in 20, 40 and 70 cm depth was very similar to each other and mostly lower than 10 vol.-%, whereas the other profiles of this site had higher values especially in 20 cm and 40 cm depth, which were exceeding 20 vol.-% during winter season. In 40 cm depth of profile E3a, the soil water tension was around 20 and 30 vol.-% and thus about 10 percent points higher than in the other two profiles. In E3c, the sensor in 100 cm depth measured an average water content of 24.0 vol.-% over the measurement period, which is more than the double value of profile E3a (6.4 vol.-%) and E3b (8.9 vol.-%). Therefore, at this site, a high small-scale heterogeneity of water content was given. This is seen in the correlations between the adjacent profiles, too. For example at E1, the Pearson correlation coefficient, measured between the daily mean water tensions of the different profiles in the same depth, ranges between $r=0.957$ and $r=0.865$ ($p<0.01$). At E3, only the correlations between the layers in 20 cm and 40 cm depth of $r>0.900$ were in the similar range. In contrast to that, the Pearson correlation coefficient is much lower for correlations between the deeper layers. There, the lowest correlation of $r=0.471$ ($p<0.01$) was calculated between E3a and E3c in 70 cm depth.

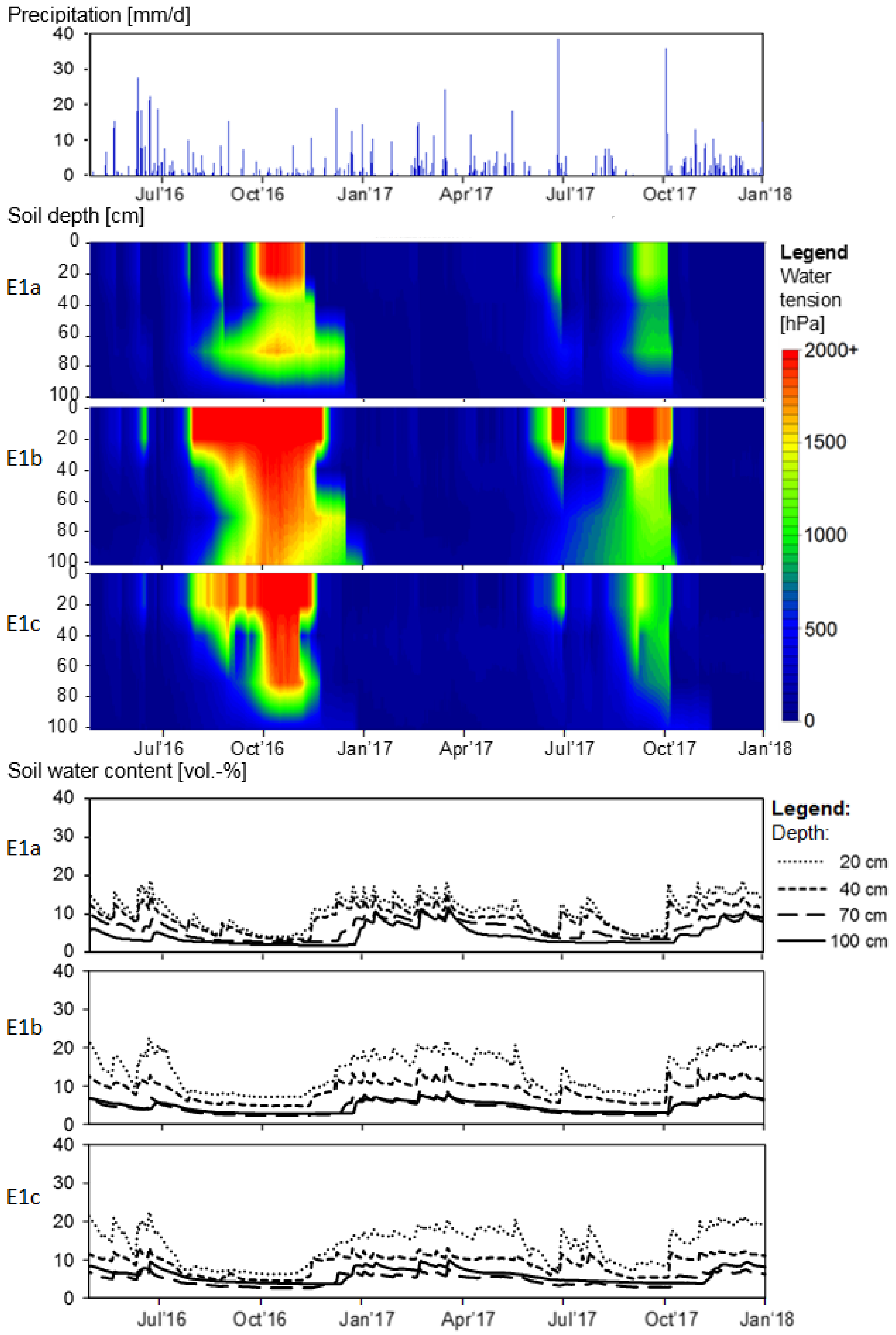

Figure 32: Precipitation [mm/d] of the climate station at E3 (data gaps filled with precipitation rates from DWD 2018), water tension [hPa] and water content [vol.-%] of the profiles E1a-c from 1st of May 2016 to 31st of December 2017.

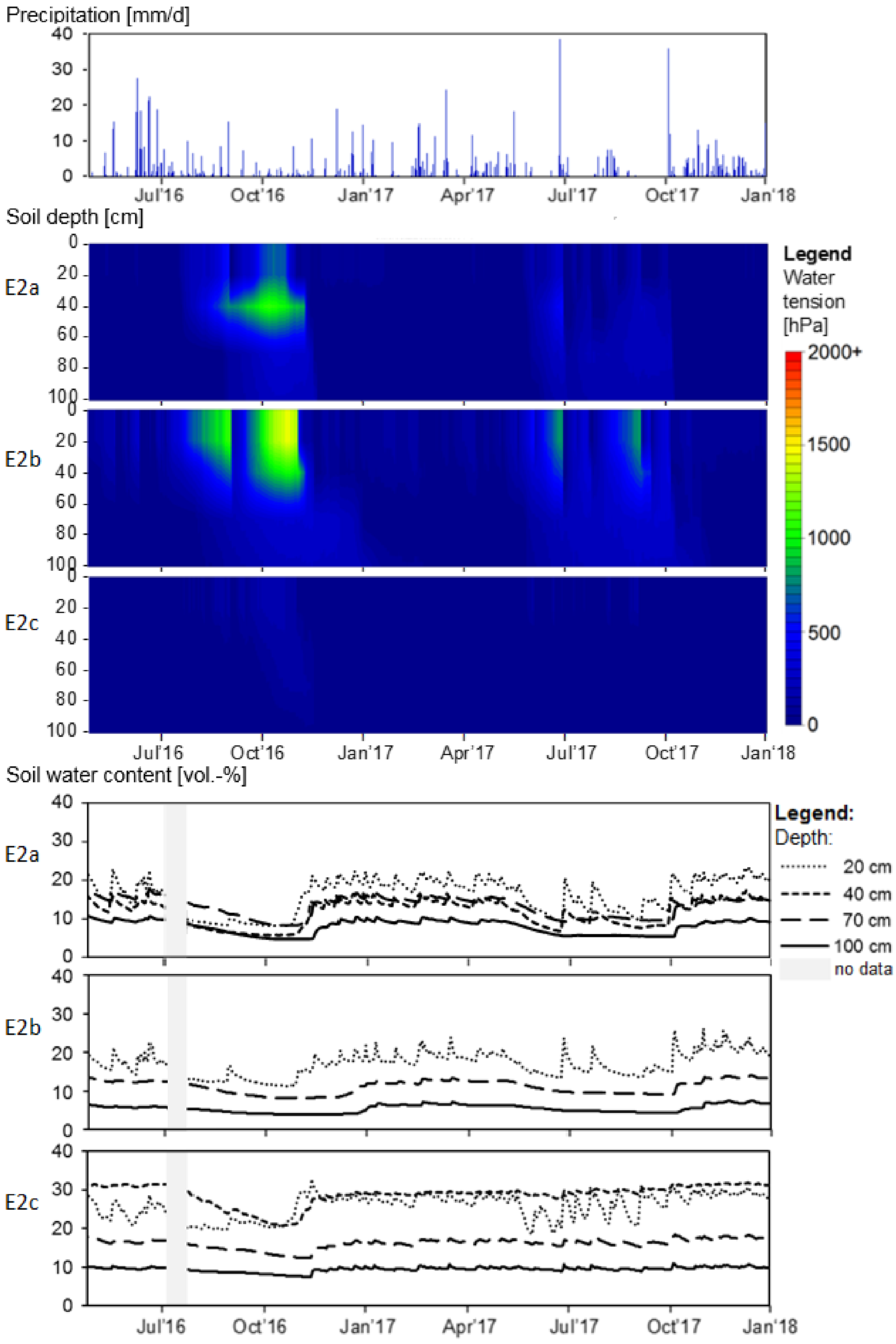

Figure 33: Precipitation [mm/d] of the climate station at E3 (data gaps filled with precipitation rates from DWD 2018), water tension [hPa] and water content [vol.-%] of the profiles E2a-c from 1st of May 2016 to 31st of December 2017.

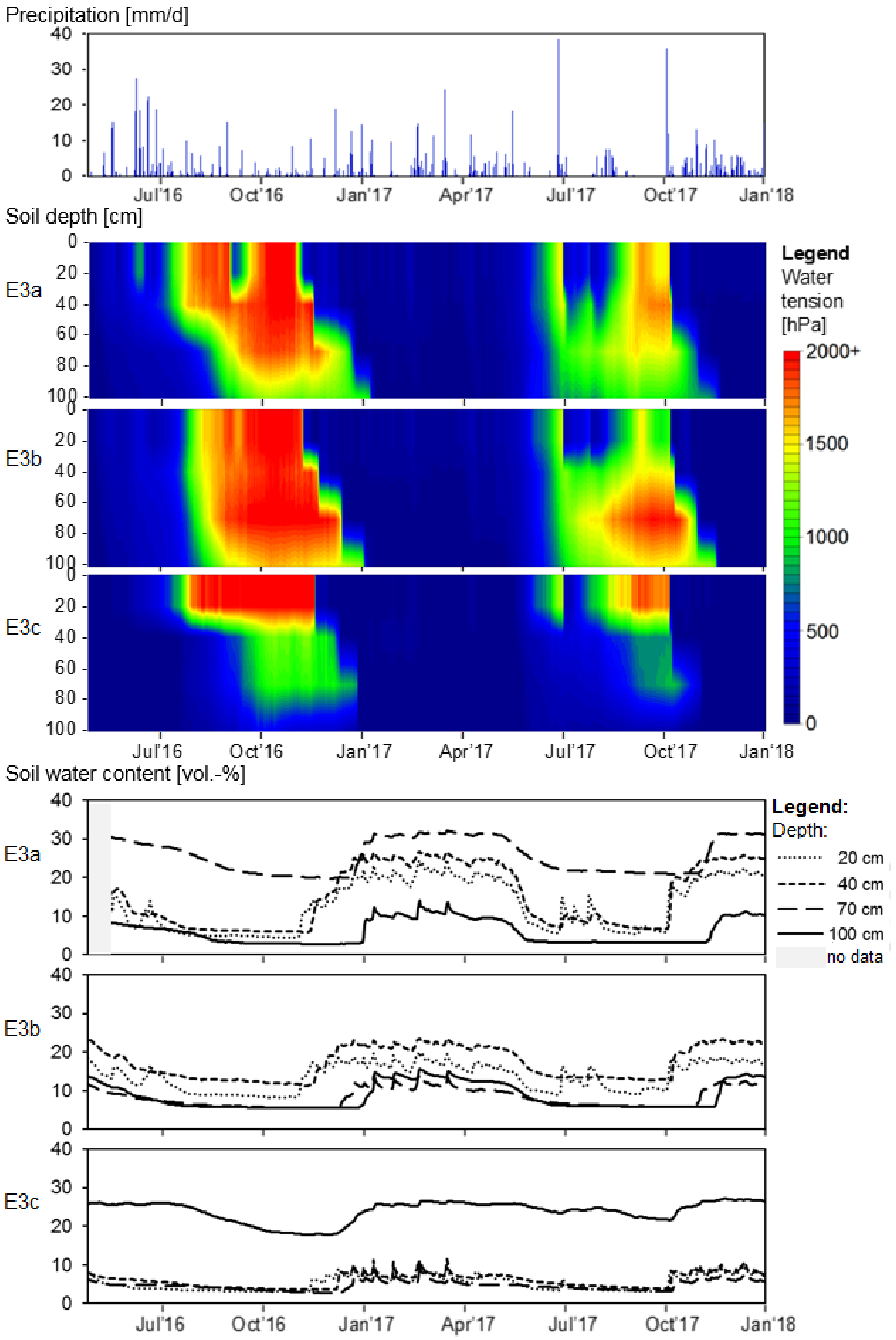

Figure 34: Precipitation [mm/d] of the climate station at E3 (data gaps filled with precipitation rates from DWD 2018), water tension [hPa] and water content [vol.-%] of the profiles E3a-c from 1st of May 2016 to 31st of December 2017.

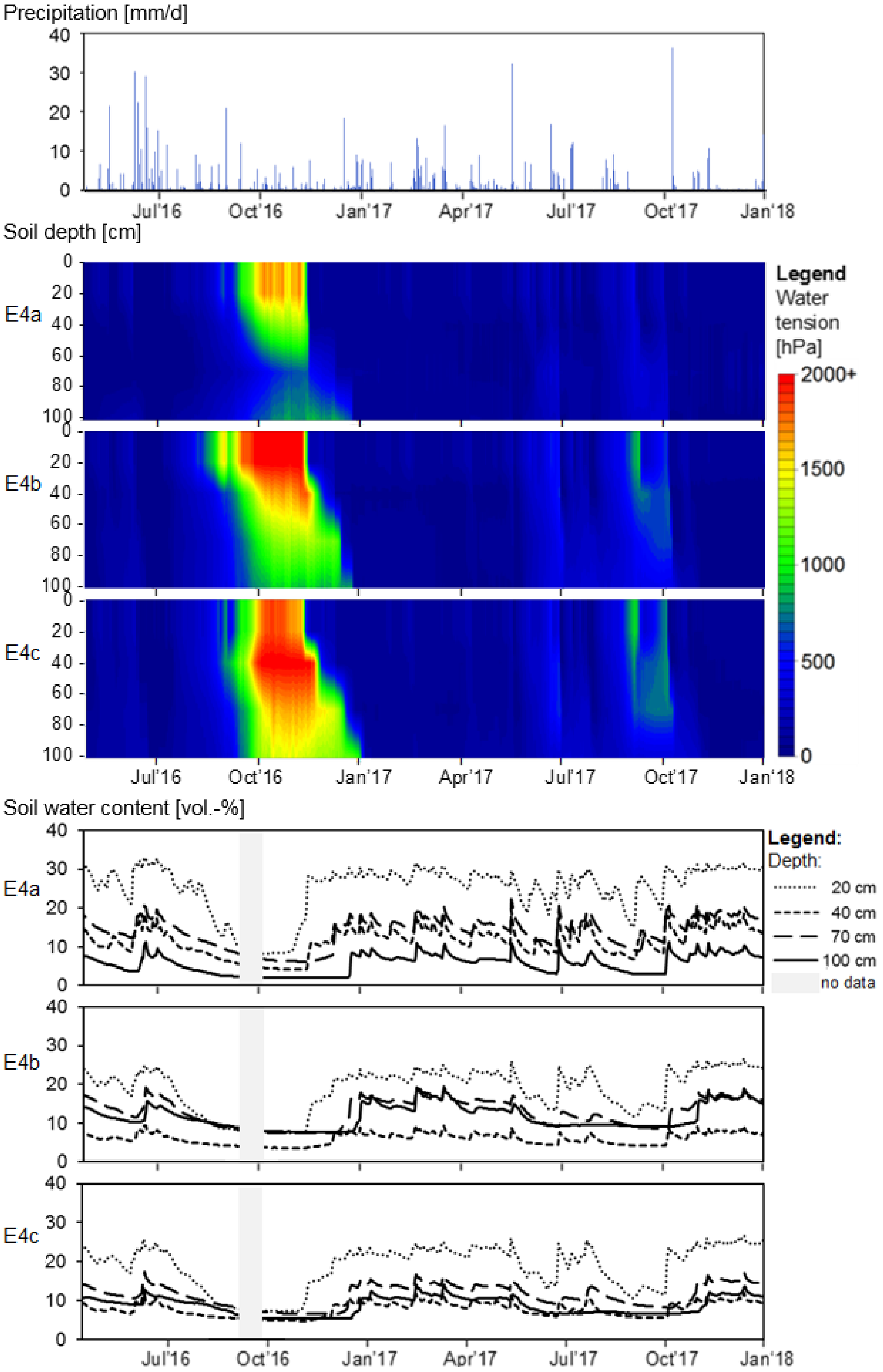

Figure 35: Precipitation [mm/d] of the climate station at E4 (data gaps filled with precipitation rates from DWD 2018), water tension [hPa] and water content [vol.-%] of the profiles E4a-c from 1st of May 2016 to 31st of December 2017.

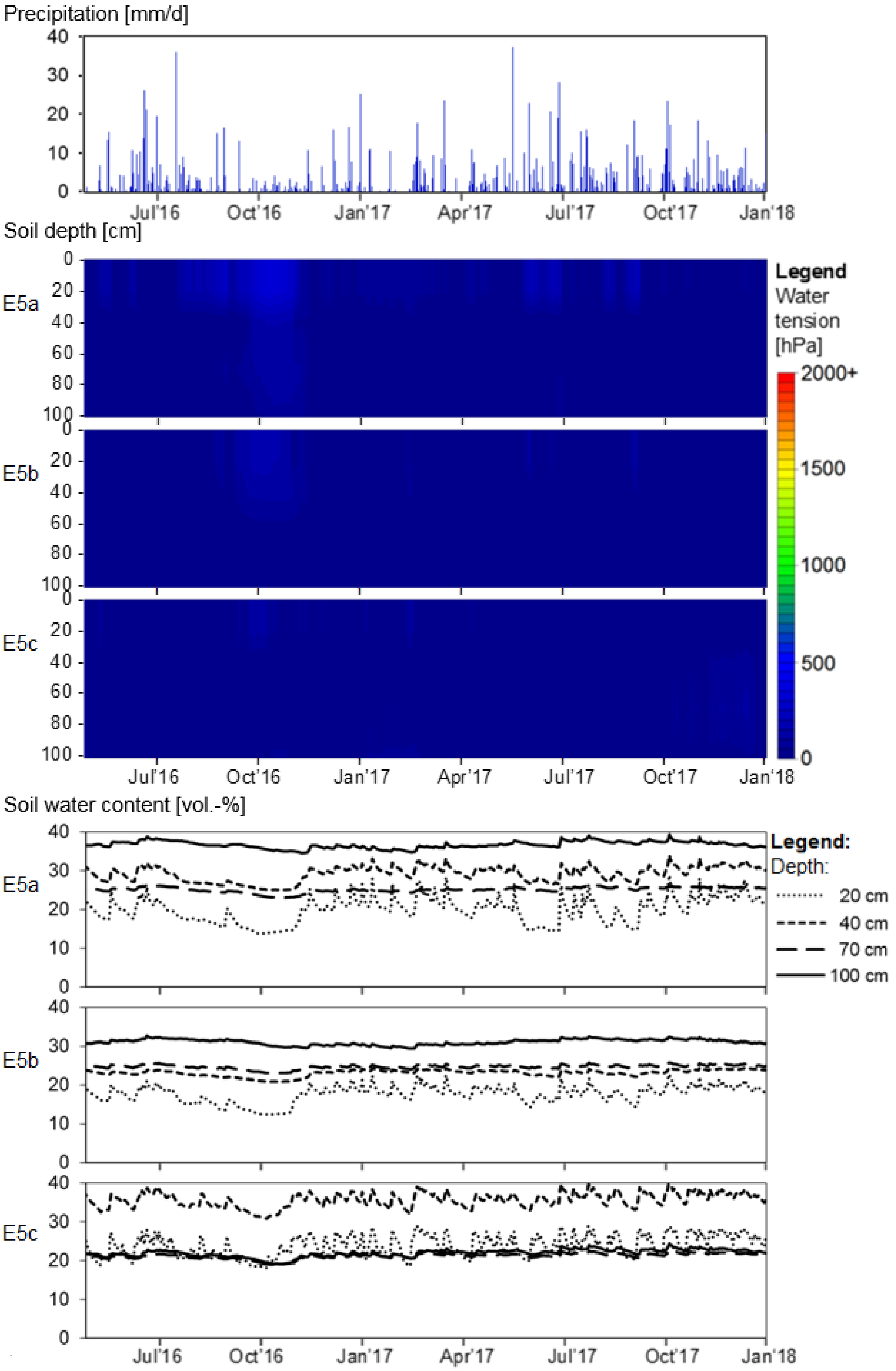

Figure 36: Precipitation [mm/d] of HH-Fuhlsbüttel (DWD 2018), water tension [hPa] and water content [vol.-%] of the profiles E5a-c from 1st of May 2016 to 31st of December 2017.

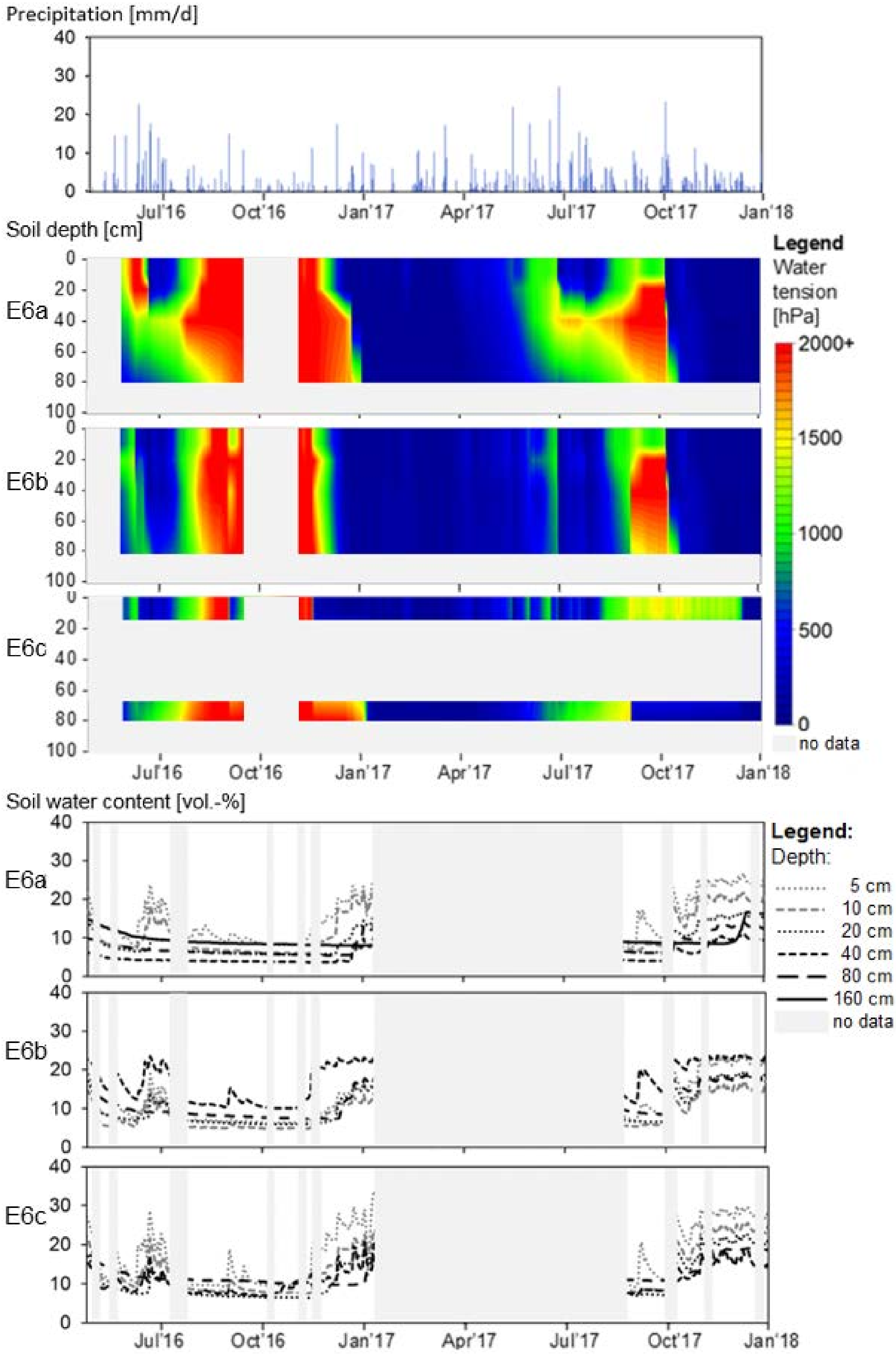

Figure 37: Precipitation [mm/d] of the climate station at E6 (data gaps filled with precipitation rates from DWD 2018), water tension [hPa] and water content [vol.-%] of the profiles E6a-c from 1st of May 2016 to 31st of December 2017.

5.1.4 Correlation of water tension with soil properties

According to the results of the water tension, two sites were wet or moist without drought phases and the others had drought phases of different length and intensities. Therefore, E5 (c, b, a (profiles sorted from wet to dry)) was the wettest site, followed by E2 (c, a, b), E4 (a, b, c), E1 (a, c, b), E3 (c, a, b) and E6 (a, c, b). The order of the last two sites is not distinct: E6 had longer and more intensive drought phases during 2016 in its profiles. In 2017, E6b had only a relatively short drought phase, which was affecting all measured layers, while E3 had a longer phase of drought, but their intensity was very different with the depth. In profile E3c, no intensive drought (≥2000 hPa) was measured below 40 cm.

This ranking order is deviating from the results of chapter 4. In that chapter, E2 and E5 had the highest potential for drought, because of their “low” AWC according to Ad-hoc-Arbeitsgruppe Boden (2005) and the high percentage of surface sealing. However, the measurement showed that these sites were the sites with the highest moisture. All other sites had all a “medium” AWC and less sealing. The laboratory analyses (based on the laboratory AWC measurements) showed the same trend of ranking as the field measurements: E3 and E6 had a higher drought risk than E1 and E4. Nevertheless, the ranking of E3 and E6 as well as E1 and E4 was different at the laboratory based AWC measurements (see chapter 4) compared to the observations of the water tension measurements.

As expected, the water tension and the water content measurements showed relations to each other. At most of the studied horizons, the water tensions decreased with increasing water content (see example of E1b in Figure 38), so that the expected relationship of a pF-curve can be confirmed for the analyses of this study and both sensors (SWC, SWT) seem to work plausible.

The two wet sites had lower relative differences between their minimum soil water contents and their maximum soil water contents (data not shown) compared to the sites with drought phases. However, the differences between the four sites with drought phases were small.

There was no significant correlation (measured with Spearman’s rank correlation coefficient) between the available water capacity and the rank of wetness of the site, when all sites were considered (data not shown). The two wet sites had lower or similar field capacities than the other sites. After excluding of the two wet sites, the site E3 had the lowest available water capacity of its profiles (Figure 18) and had the longest and most intensive drought phases based on the water tension measurements. The sites E1 and E4 had a similar range of available water capacities, but showed differences in water tensions. At site E4, the profile E4c had the highest available water capacities; at the same time, it had lower water tension than the other two profiles of this site.

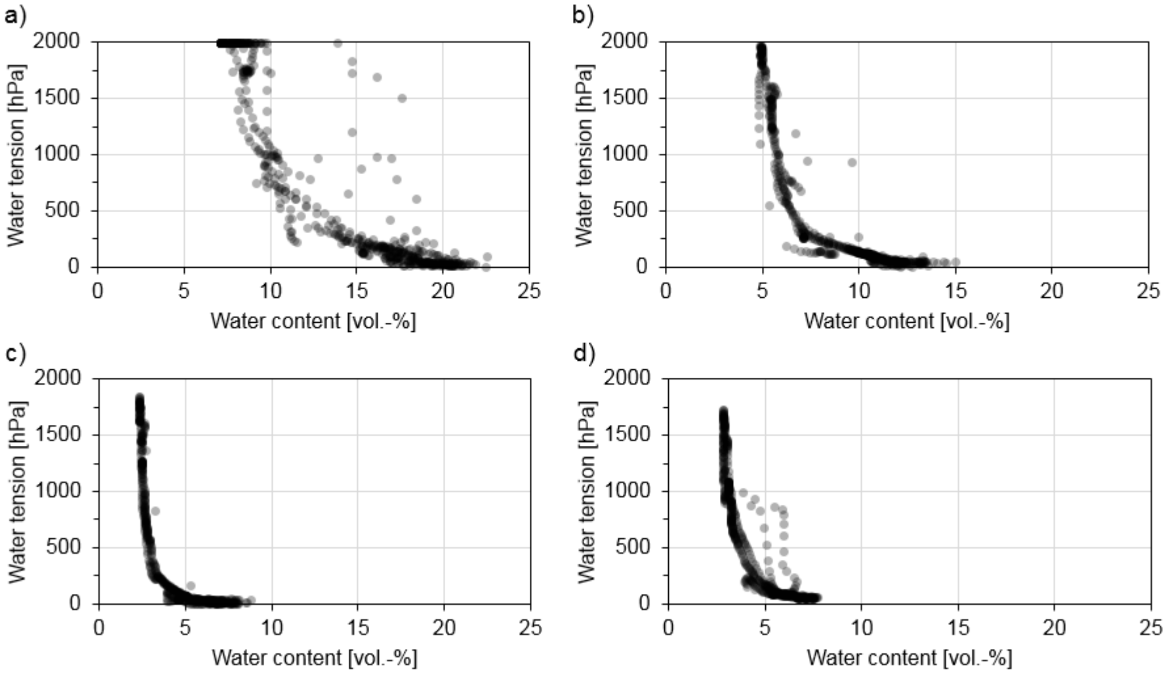

Figure 38: Relations between the water tension and water content (soil water retention curve) in a) 20 cm, b) 40 cm, c) 70 cm and d) 100 cm depth at E1b (daily means from May 2016 to December 2017).

The profiles E5a-c had the highest effective bulk densities and the lowest water tensions. In addition to that, this site had the lowest sand contents, too. However, there is no significant correlation between the water tension and the effective bulk density (data not shown).

Altogether, no significant correlations between the drought intensity and the soil properties were found, when correlations were done over all sites and profiles. Nevertheless, some small-scale variations between the three profiles at each site correlated with the heterogeneity of soil properties. In general, when the variability of the soil properties in the adjacent profiles was low, then the soil water tensions and the soil water contents were similar to each other, too. Examples for such sites are E1, E4 and E5. The profiles in E2 were different to each other, but the water tensions were always very low and indicate wet or moist soils (Figure 33), so that further analyses of differences were not conducted. The three profiles of site E3 differed in substrate layering (see chapter 4), and so the water tensions and water contents (see chapter 5.1.3) differed at these profiles. Especially E3c was different from E3a and E3b. It is likely that the different rooting densities intensified the differences of water tensions in these three profiles. E3b had a uniform distribution of roots in the profile. From the surface to 100 cm depth, the root density was "low" (3-5 roots/dm²) according to Ad-hoc Arbeitsgruppe Boden (2005). In contrast to that the other two profiles had higher root densities, which were decreasing with the depth, whereas no roots were found below 90 cm at E3a and below 45 cm at E3c (Table 19). At E3c, no drought was measured in 100 cm depth, which can be caused by the missing water usage of the tree roots.

In general, the highest water tensions were found in the upper soil layers, detected by the sensors in 20 cm and 40 cm depth. At most of the profiles, here the rooting densities were higher than in the deeper layers. Nevertheless, there was no statistical significant correlation of the root density and the length of moderate soil drought (water tensions ≥750 hPa, data not shown).

At each site, two profiles had the same distance to the tree, and the other about the double distance. Therefore, those with the larger distance were not always under the tree crown, or they were under the crown, but then the density of the tree crown decreased with larger distance to the tree trunk. At most of the sites (E2, E4, E5, and to a smaller degree E3), the profile with the highest distance to the tree trunk (see Appendix I: site plans) had lower soil water tensions than the other two profiles of the site. In addition to that, the water content increased more than in the other profiles in 20 cm depth after precipitations, in particular during summer.

5.1.5 Modeling of water tensions

In this study, the measurements of the soil water tension and content were done over two vegetation periods. For a long-living tree, this time is short. The intensity and distribution of precipitations are changing from year to year. Therefore, it is not possible to estimate the soil water availability for the tree by measuring only two years. With a model, water tensions can be simulated over a longer time, so that soil water tensions of dry years as well as wet or average years can be calculated. In this study, Hydrus 1D version 4.16.0110 was used for modeling of water tensions. Input data (see chapter 3.5.6) were the measured soil properties (depth of soil layers, van Genuchten parameters (Appendix II: Table 19)), daily climate data of 2016 and 2017 (see chapter 3.5.5) and biological data like the leaf area index and the distribution of roots.

In a first step (chapter 5.1.5.1), the results of the model were validated with the measured soil data of the monitoring at E1-6. Later, in chapter 5.1.5.2, the model is used to calculate the water tensions from their planting time to 2016 for selected sites of felled trees. With these longer time period, changes of the potential water content between the years could be estimated. Therefore, it can be verified, whether the different soil properties of the sites have effects on the potential soil drought. The felled trees were selected by the criterion of availability of successful performed dendrochronological analyses, which were done by the co-workers of the department of Biology (Biozentrum Klein Flottbek, Universität Hamburg). In further studies, these results will be combined, so that the potential soil drought can be verified by the yearly thickness growth.

5.1.5.1 Modeling of water tensions for the years 2016 and 2017

The results of the modeling of the six sites (E1-6), where the monitoring of the soil water was conducted (see chapter 5.1.3), with Hydrus 1D showed a similar behavior of water tensions as the measured data in the uppermost measured soil layers in 20 cm and 40 cm depth for the year 2017. In July 2016, the soil started to get dryer and in the end of December 2016, the water tension is decreasing again. In some profiles (e.g. E1a and E1c), the rewetting of the deeper soil layers occurred not before March 2017. In 2017, the dry period started in June and ends mainly in October, where the rewetting started (Figure 39 and Appendix IV). In the beginning of July, a higher precipitation leads to a short decrease of the water tension of the upper soil layers. In E5a and E5c, the top soil layer did not dry. The precipitation did not reach 70 cm depth, so that in this depth, a long dry period occurred in each year. In some profiles (e.g. E1a and E1b), it is the same in 100 cm depth, but in other profiles like E1c, E2a or E2b, the substrate in 100 cm depth stayed the whole year wet (Figure 39 and Appendix IV).

The results of the modeling with the soil data from laboratory measurements like the van Genuchten parameters (Appendix II: Table 19) showed only small variations between the different sites, which were much greater in reality. Most of the differences between the profiles appeared between the surface and the depth of 30 cm.

Noticeable were the steep increases of water tensions in the results of the model. In the measurements, the water tensions increased slower.

The correlation with the measured data was high at the profiles E1a, E1c, E3a, E3b and E3c in 20 cm depth with a Pearson correlation coefficient higher than 0.8 for the year 2017 (see Table 9). The correlation coefficients were low at the two wet sites (E2 and E5) as well as in 70 cm and 100 cm depth (Table 9). An exception was profile E3c, which had correlations of r=0.87 and r=0.70 in 70 cm and 100 cm depth.

Table 9: Pearson correlation coefficients of the modeled soil water tensions and the measured data for the profiles E1a to E6a in 2017.

Depth								**Profile No.**								
[cm]	E1a	E1b	E1c	E2a	E2b	E2c	E3a	E3b	E3c	E4a	E4b	E4c	E5a	E5b	E5c	E6a
20	0.65	0.91	0.86	0.47	0.62	0.37	0.86	0.83	0.93	0.48	0.70	0.58	0.58	0.36	-0.20	0.28
40	0.55	0.65	0.57	0.51	0.72	-0.19	0.75	0.91	0.77	0.26	0.42	-0.30	-0.30	-0.24	-0.36	0.60
70	0.20	0.55	0.30	0.64	0.32	0.32	0.14	0.65	0.87	0.20	0.40	0.08	0.08	-0.18	-0.28	0.84*
100	0.02	0.53	-0.22	-0.02	0.08	0.07	-0.17	0.06	0.70	-0.20	0.52	-0.02	-0.02	-0.10	-0.13	

*80 cm depth

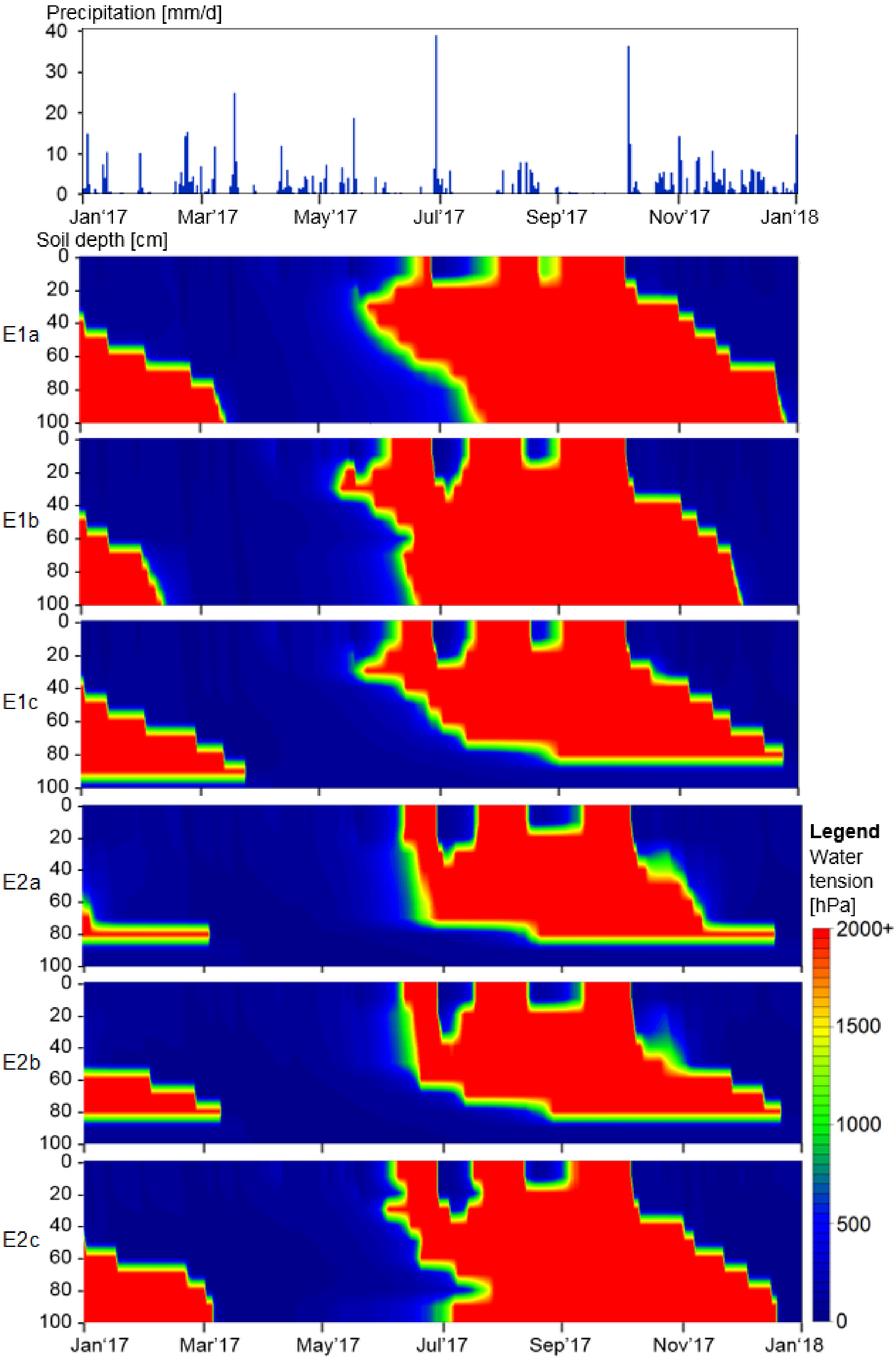

Figure 39: Precipitation [mm/d] of the climate station at E3 (data gaps filled with precipitation rates from DWD 2018) and the modeled water tensions [hPa] of the profiles of site E1 and E2 from 1st of January 2017 to 31st of December 2017.

Modeling with soil data changed with inverse Modeling:

Because of low correlations between the resulting water tensions of the modeling and the measured soil water tensions at some sites (Table 9), it was tested, if the results of the modeling could be improved by running the inverse model of Hydrus 1D. With the inverse modeling, the van Genuchten-Mualem soil data were changed by the model to fit the water tension data from the conducted measurements (chapter 5.1.3). The monitoring data of E1-6 of the year 2016 were used as input data. After adapting the soil parameters, the normal model of Hydrus 1D was run to calculate the water tensions for the whole measurement period (June 2016 to December 2017). The results were again compared with the measured data as well as with the results of the modeled water tensions, which were received by using the van Genuchten-Mualem soil parameters from the laboratory analyses.

The results of the inverse modeling were not satisfying. The model increased the correlation to the measured data and the RMSE was reduced (data not shown), too. However, the problem is, that the model changes the soil data in a way, that especially the high water tensions (>1000 hPa) were reduced. Therefore, the variations of the data were smoothed. That resulted in less fitting of the data of the low water tensions (below 1000 hPa), which were of interest in this study.

The results of the inverse modeling were not used for further modeling in this study.

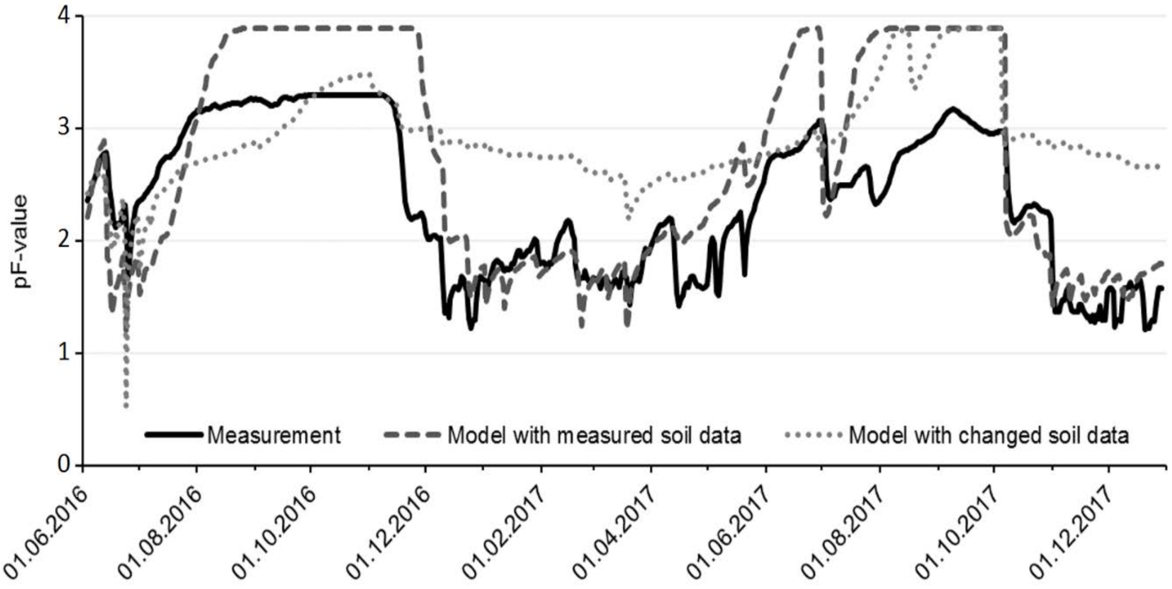

Figure 40: Example of the comparison of the measured water tension (black) to the modeled data with use of the measured soil data (dashed grey) and with the with inverse modeling adjusted soil data (dotted grey) in 20 cm depth at E1c from June 2016 to December 2017.

5.1.5.2 Modeling of water tensions of the past

At seven sites with felled trees (F1, F3, F6, F8, F12, F19, and F20), from which dendrochronological analyses and isotope ($^{13}CO_2$) analyses were planned for comparison of potential soil drought and growth reactions of trees in further studies, modeling of the water tensions were conducted. The length of modeling was depending on the planting year of the tree at the specific site and ended in 2016. In each year, the modeled soil water tensions showed a similar tendency between the simulated soils: In summer and fall, the water tension was high and in winter and spring low. The point of time, when the water tension is increasing and decreasing again, varied from year to year. Therefore, the length of the phase with moderately dry soil differs from year to year. Here, moderately dry soil is defined as water tensions of ≥750 hPa. The different depths were different intensive effected by drought, similar to the results of the modeling of the years 2017 (chapter 5.1.5.1). Because of the best correlation of the model with the measurement data in 20 cm depth (see chapter 5.1.5.1), the further analyses focused on this depth of 20 cm.

Very wet years with short phases of moderately dry soil were for example the years 1962, 1965, 1985 and 2007, when less than 20 days had lower water tension than 750 hPa in 20 cm depth in profile F1 during the vegetation period (April to October). In contrast to that, the years 1976, 1999, 2009 and 2014 had longer periods with dry soil (Figure 41). In these years, more than 120 days had a soil water tension of 750 hPa or higher during the vegetation period (F1, 20 cm depth). Normally, there were only one or two drought periods per year, which were not disturbed by phases with low water tensions. Nevertheless, sometimes more than two drought phases occurred (e.g. 2008 in 10 cm and 20 cm or 2015 in 20 cm depth at F1). At F1, the number of dry days had the trend to increase from 10 cm to 60 cm depth. The mean number of days of the vegetation period with a soil water tension of at least 750 hPa was 40 days in 10 cm, 71 days in 20 cm, 120 days in 40 cm and 128 days in 60 cm depth for the years 1963 to 2016. In the depth from 70 cm to 100 cm, the soil of this profile was always wet.

At the seven sites, the number of days with moderate drought during the vegetation period varied. From 1980 to 2016 in 20 cm depth, the mean number of days ranged from 68 days (F20) to 120 days (F12) with a mean of 88 days. The standard deviation was high for the years 1980 to 2016, for example 34.4 days at site F1. The sites had the following order according of their average number of moderately dry days in 20 cm depth, beginning with the highest amount: F12, F19, F8, F6, F3_1, F3_2, F1, and F20 (Table 10). All sites had in the same years a relative high or a low number of dry days, so that the yearly differences were depending on the weather, while the individual length of dry days per year at the different sites was controlled by the site specific soil parameters and biological data.

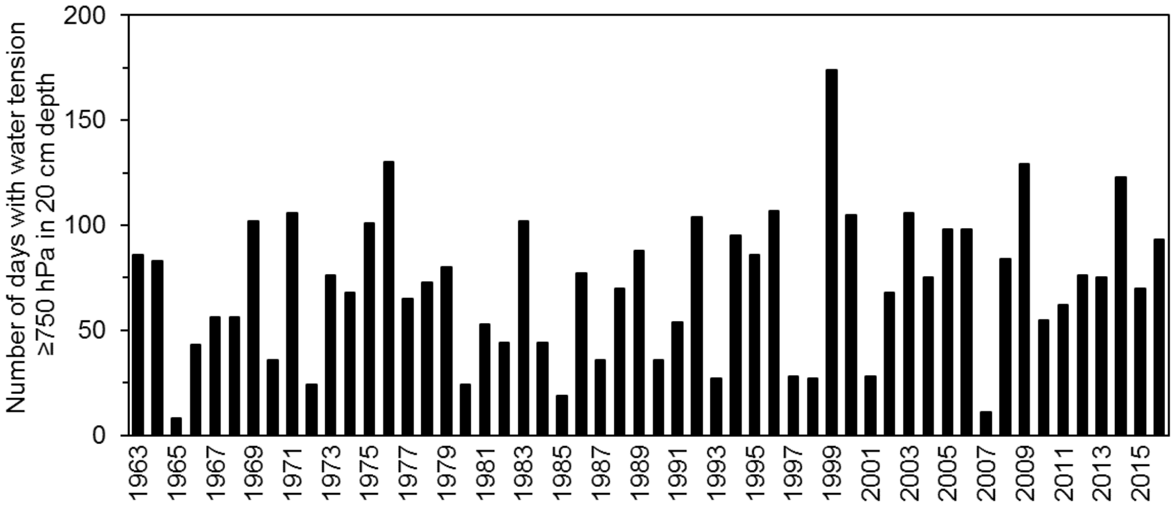

Figure 41: Modeled numbers of days with water tensions of ≥750 hPa in 20 cm depth in profile F1 during the vegetation period (April to October) for the years 1963 to 2016.

F12 and F19 had the highest drought risk according of this modeling and both sites were modeled with the LAI of oaks, while the other sites were maples. The order with the length of dry days per year was in accordance with the results of the soil analyses of chapter 4. The site F12, which had the highest average number of potential dry days per year from 1980 to 2016, as well as F6, F8, and F19, had “low” AWCs according to Ad-hoc-Arbeitsgruppe Boden (2005). In comparison, F12 had the lowest AWC of 101 mm, followed by F19 (107 mm), F6 (128 mm) and F8 (131 mm) (see chapter 4.1.3 and 4.3). F1 (185 mm) and F3 (195 mm) had a “medium” AWC and less dry days in the modeled years. The only exception was site F20. The analyses showed the lowest AWC (94 mm) and so the highest potential of drought risk, but the results of the modeling show the opposite: here the soil had the lowest amount of drought days in 20 cm depth. That might be caused by the missing root water uptake in this layer, because no roots were found in 0 to 8 cm and in 14 to 58 cm depth.

All modeled water tensions were very similar to the water tension of profile F1 at most of the sites, so that the numbers of dry days were similar, too. Only in the subsoils, higher differences were found in some cases, when the soil is drying in deeper layers than in F1, too. That was for example the case in the F19 profile, where drought was modeled down to 90 cm depth. Another exception was F12. At this profile, the water tensions were mainly staying on a low level in deeper layers than 20 cm and the values increased there to a level higher than 750 hPa only in some years. That might be caused by the very high sand contents (≥95%) of the fill sands below 20 cm depth, where no roots were growing and therefore no root water uptake occurred.

Table 10: Mean yearly number of days with water tensions ≥750 hPa in 20, 40, 70 and 100 cm depth of the sites F1, F3_1, F3_2, F6, F8, F12, F19 and F20 during the vegetation period (April to October) for the modeled years from 1980 to 2016. Additionally, the standard deviations, minima, and maxima are displayed.

Depth	**Number of days with ≥750 hPa per year from 1980 to 2016**	**Profile no.**							
		F1	F3_1	F3_2	F6	F8	F12	F19	F20
20 cm	Mean	71	82	74	89	100	120	101	68
	Standard deviation	36	37	37	42	37	41	43	43
	Minimum	11	13	6	6	23	18	18	0
	Maximum	174	176	172	180	172	181	182	163
40 cm	Mean	119	134	129	119	104	8	157	120
	Standard deviation	34	32	34	40	37	36	35	39
	Minimum	19	27	23	9	22	0	91	15
	Maximum	174	181	176	163	174	161	194	163
70 cm	Mean	0	130	120	95	117	0	160	98
	Standard deviation	0	30	33	37	33	0	18	37
	Minimum	0	25	8	0	0	0	98	0
	Maximum	0	161	155	214	214	0	214	214
100 cm	Mean	0	0	0	0	0	0	4	0
	Standard deviation	0	0	0	0	0	0	18	0
	Minimum	0	0	0	0	0	0	0	0
	Maximum	0	0	0	0	0	0	79	0

Because of the high annual variation of drought days, the small increasing trends of all sites from the past to today are not significant. For instance, at F1, the trends for the number of days per year with at least 750 hPa in the vegetation periods from 1963 to 2016 are: on average +0.2 day per year in 10 cm depth, +0.4 day per year in 20 cm depth, +0.3 day per year in 30-50 cm depth, +0.1 day per year in 70 cm depth, and no trend in deeper layers. The trends in the other profiles were similar as the trends of F1 and they were not significant, too.

5.2 Discussion

5.2.1 Soil gas composition around established roadside trees

It is well known that the CO_2 and O_2 contents in soils are different from the concentrations in the atmosphere. It is known that the soil gas is in general influenced by the biological activity in the soil, which effects the soil respiration and therefore the CO_2-production below the surface. The biological processes, which are often temperature dependent, are responsible for the occurrence of typical fluctuations of gas concentrations in the course of the year. Additionally, the concentrations of CO_2 and O_2 in the soil were depending on the gas exchange with the atmosphere (gas diffusion etc.). That causes the concentration gradients with increasing CO_2- and decreasing O_2-contents with the depths. The exchange processes were affected by soil properties like pore volume and pore size distribution, which were affected by soil compaction and soil moisture distribution, and by surface sealing. Therefore, it is possible that the CO_2-concentrations can increase and the O_2-concentrations can decrease, when the aeration of the soil is generally low or disturbed or low of high water contents. (e.g. Blume et al. 2010)

These above named soil gas characteristics and their underlying processes were confirmed in the soil gas measurements of this study. The monthly fluctuations of CO_2-concentrations were similar to the monthly fluctuations of air and soil temperatures: high values were reached in summer and low values were measured in winter (see chapter 5.1.1 and 5.1.2). The O_2-concentrations had the opposite course, which was found for example by Conlin & van den Driessche (2000), too. With increased temperatures, the vegetation and soil biota is more active: During the vegetation period, the roots of the plants were growing and using more O_2 for their growth and respiration than in winter based on higher photosynthesis rates. At the same time, microorganism are more active, too, and produce more CO_2. Accordingly, the higher temperatures are connected to the activity in soil, which can lead to a faster use of O_2 and a higher production of CO_2 (e.g. Burton et al. 1996, Zogg et al. 1996, Meier & Kress 2000, Gaertig 2001, Tang et al. 2005, Blume et al. 2010). In general, the O_2-content is decreasing and the CO_2-content is increasing with the depth in the soil according to Blume et al. (2010). This is caused by the production of CO_2 in the soil and the gas exchange at the soil surface. This depth dependent gradient of gas concentrations was observed for instance in the study of Conlin & van den Driessche (2000) and at most of the profiles of this study, too.

When precipitation has moistened the topsoil, it is expected, that the O_2-concentration decreases and that the CO_2-contencentration increase, because of lower gas diffusion through the remaining air-filled pores (Ott 1997) and because of limited gas exchange through a wet soil crust (Bakker & Hidding 1970). This effect of precipitations on the O_2 and CO_2-concentrations was in this study observed. Here, at most sites a negative correlation between the soil water tensions in 20 cm depth with the CO_2-concentration were found.

A sufficient aeration in the rooting zone is essential for root growth and the living of plants. The aeration can be restricted by the compaction of the soils, which can lead to decreases of the O_2-levels and the increases of CO_2 concentrations (e.g. Kozlowski 1999, Conlin & van den Driessche 2000) in the soils. For the aeration, the top layer plays a very important role, because the exchange of atmospheric air and soil air takes place here and influences the aeration of deeper layers (e.g. Gaertig 2007, Gaertig 2012). For instance, Gaertig (2007) has shown that the CO_2-concentrations are higher in forest areas, where machine driving has compacted the soil surface. In addition to that, the fine roots were partly or complete dead near the surface of lanes and less roots were in the deeper layers of the soils, too. That high CO_2-concentrations reduce the respiration of tree roots was shown for example by Qi et al. (1994), Burton et al. (1997), McDowell et al. (1999) and Gaertig (2001). Gaertig & v. Wilpert (2005) had shown that only around half of the amount of fine roots in 80 cm depth were present in oak forest stands with low gas diffusion in the topsoil compared to forest stands with a sufficient gas diffusion. Furthermore, they saw, that oak populations with a high percentage of damaged trees occurred only in areas with low gas diffusion in the topsoil. Therefore, Gaertig & v. Wilpert (2005) concluded that the intensity of compaction of the top soil layers is very important. Urban soils are often compacted, which can increase the problem of a sufficient aeration for roots in the soils (e.g. Craul 1985). In four of the six monitoring sites around established trees, where soil concentrations were measured, a higher effective bulk density were found in the uppermost layers than in the substrate layers below them. However, in none of the top layers of the studied profiles, the effective bulk density could be classified as “high” according to of Ad-hoc-Arbeitsgruppe Boden (2005). In this study, those high values of >1.80 g/cm³ were only measured in deeper layers of E5; therefore, in only one of the six sites with gas measurement. At this site, the lowest air capacities were measured, too (see chapter 4.1.3). In addition to that, the lowest O_2-concentrations and the highest CO_2-concentrations were found in the profile E5b during summer season. That site had in general a finer texture than the other sites. That is consistent with the results of earlier studies like from Bouma & Bryla (2000), who showed, that CO_2-concentrations were higher in finer textured soils than in sandy soils. That can be explained with the higher percentage of coarse pores in sandy soils, which led to a better gas flow compared to soils with fine pores. In contrast to that, the differences between the textures of the soils at the different sites of this study were much smaller than in the study of Bouma & Bryla (2000), because of the choice of typical roadside sites in Hamburg, which were sand-rich (BSU 2012, Wolff 1993). Therefore, here, the amount of CO_2 in the soil air can not only be explained by the texture.

Not only the texture and the compaction affect the gas exchange of the soil. The kind of surface (e.g. sealing, vegetation) is important, too (Weltecke & Gaertig 2012). At the site E5, which had the highest CO_2-rates in the single profiles (data not shown), the surface was mainly bare soil only with little moss and grass. That bare surfaces have a lower gas diffusivity than vegetated sites was discussed in other studies like Weltecke & Gaertig (2012). This site had in general the lowest water tensions and highest volumetric water contents, too. This affects the gas contents according to Blume et al. (2010), who found that the O_2-content is lower in wet soils compared to dry soils. In addition to that, the correlation between the soil water content and the CO_2- and O_2-content were high. Therefore, many of the short time variations of the CO_2- and O_2-content can be explained with changes of the water content in the soils. Especially the water content near the surface in 20 cm depth affected the gas content, even in deeper layers. This supports other studies (e.g. Gaertig 2012), which pointed out the importance of the topsoil layers for the aeration. Altogether, different soil properties, which can inhibit the aeration, were existing at the same sites, so that the given gas concentrations were always a consequence of all soil and site specific properties and the meteorological conditions together.

In contrast to the site E5 with the high CO_2-concentrations in summer, the lowest concentrations of CO_2 were found at site E1. The surface at this site was a lawn. Weltecke & Gaertig (2012) reported that lawn and other vegetated sites permits a better gas diffusivity in urban areas than sealed or surfaces without vegetation. There was no driving or parking on this site and only few people walk over this lawn, so that there was only very low compaction according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005) at the top soil layers, where a low effective bulk density was between 1.4 and 1.6 g/cm³. The effective bulk densities in the depth were reaching medium effective bulk densities (1.6 to <1.8 g/cm³); but they stayed close to the borderline to low densities. These low effective bulk densities with medium to high air capacities of its sandy soils allowed a good exchange of atmospheric air. During sampling, the very dense root system near the surface was an obvious and specific feature of this site as well as the white sand in a depth of around 30 cm (E1b and E1c) or 80 cm (E1a) and deeper, where only a few roots were growing. The low density of roots and small humus content (see Appendix II: Table 17 and Table 19) in deeper soil layers can be a hint for low biological activity and so low CO_2 production by biota in the depth at this site.

At the other sites, the connection between the soil gas contents and the soil properties was not that clear. For instance, the mean CO_2-content of the three profiles of the other moist site (E3) had the highest values in summer 2017. However, in summer 2016, two other sites had higher values, so that the intensity of CO_2-production and retention in the soil is obviously changing slightly to a different extent at different sites from year to year.

In addition to the differences of the gas contents between different sites in the city of Hamburg, differences of CO_2- and O_2-concentrations between neighboring profiles at one site were observed in this study. They were higher at sites with a higher small-scale soil heterogeneity like on site E3, and small at sites with low small-scale heterogeneity (e.g. E1 and E4). For example, the concentrations of CO_2 and O_2 in the profiles E1a-c were very similar throughout the whole measuring period. The profiles are located close to each other on the same lawn. This may be caused by the homogeneousness of the three profiles. The particle size distribution as well as the humus content, the depth of the layers and the air capacities were similar. These similar soil properties of the profiles led to a very similar soil gas content. The O_2-contents were constant on a high level above 18% in 100 cm depth in all three profiles; the mean values were about 20%. Only at two measurement days in different months, CO_2-concentrations of about 3% were reached for a very short time in these profiles, while the concentrations stayed clearly below this value during the rest of the measurement period.

Plants need a minimum concentration of O_2 in the soil for root respiration (e.g. Lyr et al. 1992). Costello et al. (1991) found that O_2-concentents ≤4-5% leads to a more than 50% reduced growth of oak trees (*Qercus lobata* Née, *Q. suber* L. and *Q. douglasii* HOOK. & ARN.). According Blume (1992) and Blume et al. (2010), a percentage of 10% O_2 in the soil air is a threshold value for plants in general and also for many tree species (Kozolowski 1985). Higher threshold values are given by Kretschmar (1992) with 13% and by Leh & Sünder (1989) with 15%. That means that the aeration for plant roots was good at site E1, where no stress triggered by O_2 is expected. At one other site (E6), the thresholds were not reached, but at the other four sites (E2, E3, E4, and E5), the highest threshold was reached.

The lowest threshold was only reached at two sites: The profiles E5b and E5c had lower O_2-contents than 10% in 100 cm depth at one measurement time and the profile E2c in 20 cm depth during two not adjacent measurements in July/August 2017. Therefore, the time, when this threshold was reached in this study, was very short and only measured in one depth. In case of E5, the low concentrations were in layers with a small amount of roots, so that no stress by a lack of O_2 is expected at this site. At E2c, there was a root mat in the layer with the low O_2-contents. The high amount of roots with the root respiration might have contributed to the appearance of the low O_2-contents. At the adjacent profiles, the O_2-content was higher, so that the mean value of this site did not fall below the threshold of 10%.

Under the assumption, that the threshold of 15% by Leh & Sünder (1989) is more suitable for the trees at the sites of this study, the times, where the measured values felt below the threshold were much longer. For example in E5c, there were lower values in 100 cm depth from end of July to August 2016. In 2017, the phase with low O_2-content was longer. In 100 cm depth of profile E5c, the values fell on the 12th of July below 15% and reached again 15% not until the 13th of December (minimum: 9.4%). That means that the O_2-content was five month below the threshold of 15% and the roots, which were at this profile only in 45 to 100 cm depth (see Appendix II: Table 19) might not have an optimal oxygen supply. In 70 cm depth, the situation was nearly the same, but here the shortage was in one week in September interrupted with a slightly higher value than 15%. In 20 and 40 cm depth, the O_2-content varied to a higher amount and weeks with shortage were followed with weeks with higher O_2-content. In E5b, the situation was similar but the depths 40 cm, 70 cm and 100 cm were more similar to each other. The length of shortage was the same than in 100 cm at the site E5c, but it was interrupted for times with higher measured values. In E5a, the O_2-content was higher than at the other two adjacent profiles and fell below 15% at some measurement times in July and August 2017. The same situation with single measurements in summer with O_2-contents below 15% happened at the sites E2, E3 and E4.

Therefore, in most of the sites a longer phase with shortage of O_2 was not found, but especially in profiles E5b and E5c the differences between the lengths of O_2-content below the threshold depends on the used threshold. However, even short lacks of O_2 can lead to death of root tips (Balder 1998), so that short-term deficiencies should be avoided.

The situation is similar for the thresholds of CO_2-concentrations. Gaertig (2012) emphasized the importance of the topsoil for the aeration of deeper parts of the soil and named a CO_2-content of 1% as a maximum for the topsoil, which is relating to the uppermost 5 to 10 cm of the soil. The measurements of this study were conducted in deeper soil layers. Therefore, thresholds were used, which were not only related to the topsoil, but to plant growth in general. Leh & Sünder (1989) and Balder (1998) named a threshold of 3 vol.-%. A maximum of 5% was named by Horn (1992), who noted that the value is depending on the tree species. A threshold of 10 vol.-% with an air capacity of at least 5% for growing of the crops was found by Blume et al. (2010). The CO_2-concentrations of this study were always lower than 10%, but they lay over the other thresholds at five of the six sites during some months in summer. In this study, these thresholds were exceeded for a longer time in the year 2017 than in 2016. The highest concentrations were measured in both years between the end of July and begin of August. In 2016, the mean CO_2-content of the three profiles of site E3 in 100 cm depth was over three month higher than 3%, but did not reach 5%. In 2017, the mean value in 100 cm depth of the three profiles of this site was reaching 3% in January and did not fall below 3% in this year again. 5% was exceeded in July and August and from mid-October to mid December 2017. Therefore, the exceeding of the lower threshold was over eleven month and the higher threshold was exceeded in 100 cm depth two times for two month in the year 2017. At the sites E2, E4 and E5, the 5%-threshold were reached by the mean CO_2-contents of the three profiles at each site in 100 cm depth in 2016. The increase was smaller in the second half of 2017, so that the mean values of the three profiles at each site had only high peaks in summer 2017. Nevertheless, the 5%-threshold was exceeded for one (E4) to three and a half month (E2) in 100 cm depth. In the higher soil layers, the 3% threshold was exceeded at five of six sites for up to six month (E5). The 5% threshold was exceeded at five of six sites in deeper soil levels, too, but sometimes not at the two uppermost layers in 20 cm and 40 cm depth and mainly only for short times, because of high variations between the measurements.

That means that further measurements are required to prove which of the thresholds for O_2 and CO_2 are the most suitable for the oaks and maples along roadside sites, so that it is possible to better estimate the phases of O_2 deficit and CO_2 surplus. Nevertheless, the results show, that some thresholds of CO_2 were often and over a long time exceeded, so that it is possible, that the tree roots had below optimum conditions to grow, although the soils were mainly sandy soils, which have in general fewer problems with the aeration than loamy or clayey soils. In addition to that, the air capacity was mainly medium to high according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005). However, the CO_2-content was increasing, which can indicate a slow gas diffusion and can be a potential stress factor for the trees growing on these soils. Therefore, this study shows that even urban soils with good initial conditions for a good soil aeration can have problems with increasing CO_2-contents in summer. In comparison to that, urban locations with silt or clay soils as well as sites, which get additional water inflow for example from water management solutions with water penetrations in planting pits, may have even more problems with the aeration.

5.2.2 Soil hydrology at established roadside tree sites

In general, the water budget of soils is given by the common equation of the water balance. This equation says that the change in the soil water storage is on the one hand composed of the elements, which lead to an inflow of water. These are precipitations and other water sources like irrigation or surface flow. On the other hand, the other variables of the equation describe the amount of water, which leaves the stored water. These are the evapotranspiration, deep drainage and surface runoff.

Therefore, water in the urban soils at roadside trees is effected by the precipitation, which varies locally and is reduced for example by interception of trees. In urban areas, the percentage of surface sealing is often high, which can lead to runoff from sealed surfaces and which can cause a higher inflow of water in adjacent unsealed areas, depending on the inclination. Compacted or hydrophobic surfaces can have similar effects than sealed surfaces. The groundwater depth is another important parameter, which can influence the water content in the soil. At sites with trees and other vegetation, the water abstraction by the roots of the vegetation may have large effects. The heterogeneity of water tension and water content in urban soils can also be affected by the properties of the soil (e.g. soil texture) in the investigated depth as well as the properties in deeper soil layers, which may lead for instance to perched water. (e.g. Nielsen et al. 2007, Blume et al. 2010)

In this study, the sites E1-E6 have been divided into sites with and without dry phases (see chapter 5.1.3), because of the wide range of reactions in the soil. These differences did not correlate with the preselection of potential wet and dry sites with maps of groundwater depth in the wet hydrological year 2008 (BUE 2015a), sealing (BUE 2012) and evapotranspiration potential (BUE 2015b). Clark & Kjelgren (1990) pointed out that the reduction of water supply in urban soils could vary widely. This statement is supported by other studies (e.g. Wiesner 2013) and this study.

In all profiles – except E5a-c and E2c in the year 2017 - lower water contents were measured in times of low precipitation during summer and fall in 2016 and 2017 compared to periods with more precipitation. Therefore, the precipitation rates were one of the most important factors at most of the sites for the variation of water content and water tension.

The decrease was mainly stronger near the surfaces. That was seen for instance by Pfeiffer (1985), Bréda et al. (1995) or Wiesner (2013), too. Pfeiffer (1985) assumed that the tree roots contribute to this effect. Last et al. (1983) measured a higher decrease of soil moisture near pine trees than in a higher distance to the trees during the vegetation period. This was also seen by Thomsen (2018) and in this study at four of six sites in a depth of 20 cm. That the soil water content of the upper parts of the soils did not variate very much in this study, when the soil water content reached a low level, did Bréda et al. (1995) observe, too. While the water contents were low, the water tensions were high, which shows, that it takes much more energy to remove the remaining water from the soil.

In the two monitoring years the soil rewetting took place at different phases of the year. The rewetting times can be explained with the end of the vegetation period (e.g. Pfeiffer 1985), which a) leads to a higher percentage of precipitation reaching the soil and b) a reduced uptake of water by the trees. At the four moist sites of this study, the rewetting of the topsoil layers was faster than in the layers below them. No rewetting because of capillary rise of groundwater or water from deeper layers was observed, which could be explained by the large distance to the groundwater (between 3.6 m to more than 10 m, BUE 2015a, BUE 2015d) at the different sites.

In general, increases of water tensions in soils can be caused by water uptake by plants, especially in the topsoil (Blume et al. 2010). Therefore, in layers with large amounts of fine roots, a higher water removal by plants was expected, but the rooting density did not significantly correlate with length of drought (≥750 hPa) in the respective layers. Nevertheless, main rooting area was above 40 cm depth, where the water tensions were higher and the drought phases longer than in 100 cm depth, so that effects of the rooting were probably contributing to the increased water tensions, even if the correlations were not significant.

In chapter 5.1.4 it was demonstrated, that the correlation of soil properties and the duration of drought phases was very small, even it is known that compaction leads to higher bulk densities and so to altered soil hydrology, decreased infiltration capacities and increased water runoff (e.g. Kozlowski 1999, Yang & Zhang 2011). Other aspects (for example radiation, temperature, soil structure below 1 m depth, sealing, root water demand, …), which affect the soil water budget, are important, too, so that it is not possible to predict wetness of the soil only by soil properties at the sites of this study. That is confirmed by the modeling (see chapter 5.1.5.1). The different runs of the modeling of each monitoring site (E1-E6) were conducted with changing the soil layering, the hydrologic properties of the soil layers and the climate data. In this modeling, no additional information about groundwater depth, shading by buildings or other specific site information were added. The correlation between the modelled soil water tensions and the measured data was very low at the sites without intensive drought in summer. That were hints, that the soil properties at these sites were not the most important factors for the soil water budget, while other site properties have higher effects. Nevertheless, the three profiles at site E3 had a high heterogeneity in their texture (see chapter 4.1.7) and so different soil properties, which led to different water contents in the three profiles and caused the different hydrologic structure of the profiles and the different intensities and depths of drying in summer and fall. At the sites with more homogenous soils, the water content did not vary as much as at that heterogeneous site. That shows that the small-scale variability of soils can lead to small-scale variability of water availability.

It is possible, that the two wet sites were affected by deeper water bearing soil layers. Especially at E5a-c the measurement shows with the high water contents in the deeper layers indication for water-impermeable layers under the measured soil profile with 1 m depth. E5a and E5b seem to be water saturated from 40 cm to 1 m depth, because of the small changes of the water content in times of precipitations. That was observed at groundwater-affected sites by Wiesner (2013). In addition to that, the volumetric water content was here with 25% to nearly 40% high and close to the pore volume of the soils, which were between 30.7% and 39% in the depth from 10 cm to 100 cm. Only the topsoil reacted on precipitation and was not the whole year water saturated. The groundwater level was there according to BUE (2015a) 7-10 m deep, so that a significant influence of groundwater is not expected at this site. That means that there were probably other water sources or low-permeable soil layers shortly below the measured profiles. At E3, no fine roots were found below 55 cm depth and therefore no water removal by roots can be expected in this depth. This might have contributed to the high water tensions in the deeper soil layers.

The surface cover characteristics of the near-by surrounding area of the sites were slightly related to the soil water characteristics. The two sites with the lowest intensities of soil drying in summer (E2 and E5) are located in bare soil strips without or very little grass vegetation. The tree crowns are close to higher buildings, so that higher shading rates and lower evapotranspiration rates is expected. Because of the little grass vegetation on the green strip, the removal of water by these plants is small. In addition to that, the two wet sites had the smallest green strips. The surrounding of them was mainly non- and partly permeable surfaces, always with pavement stones on the sidewalks next to the green strips. Flöter (2006) had shown that the runoff on concrete pavement stones is with 41% very high. That is why high percentages of the rainwater can possibly flow according to the inclination (see Appendix I: Figure 53 and Figure 56) from the sidewalks on the green strips and onto the streets and into the sewers. Even if the green stripes of these sites had low infiltration rates (chapter 4.1.1, Kuqi 2017), additional water from the sidewalks can infiltrate in the soils. Because of the high sealing of the sites, the evaporation rates are assumed to be low, so that the sites remain wet. But not only the runoff from the partly sealed surfaces can contribute to the high water contents in the green strips: Other studies like Wagar & Franklin (1994) give hints, that sidewalks can increase the moisture in the soil below and close to them. Mullaney et al. (2015) confirmed this for permeable pavements, which increased moisture levels in drier sandy soil in their study.

Near all studied sites, roads were prominent. In literature, the infiltration through roads was measured with 6% to 9% of the annual rainfall by Ragab et al. (2003). This infiltrating water affects the water content below the roads (Ragab et al. 2003). They estimated evapotranspiration of 21-24% on roads. In other studies, the difference of infiltration rates through roads with cracks were highlighted, whereas the crack width is the most important factor (Dan et al. 2011, Dan et al. 2017). Nevertheless, the infiltration through roads and pavements is small compared to the infiltration through the unsealed green areas and green strips. Therefore, these unsealed areas are very important for the trees for infiltration of water into the soil. The infiltration rates of this study were mainly higher at sites with grass surfaces (E1, E6), which had lower bulk densities in the topsoil, in comparison to sites with bare or nearly bare surfaces (E3, E2) (see chapter 4.1.1 and 4.2.1).

5.2.3 Consequences of given water availability for urban trees

It is well known that the growth of trees in natural habits is depending on the water availability. Dendrochronological analyses of trees in cities (e.g. Eckstein et al. 1981, Gillner et al. 2014, David et al. 2015) revealed that the water availability is an important factor, which modifies the growth rates of urban trees. These studies worked with climate data, but less is known about the water availability in urban soils at sites with trees.

The soil water at roadside trees is depending on the weather conditions like the precipitation and temperature, the soil properties and the site properties like sealing, tree management activities, and the demand of water, which the tree uses (e.g. Clark & Kjelgren 1990). Therefore, many factors interact with each other, which makes it complicate to estimate drought stress.

In many studies, the water deficits or drought stress of trees was measured by ecophysiological reactions of trees, namely midday stomatal closure (e.g. Kjelgren & Clark 1992), predawn water potential in leafs (e.g. <0.5MPa in Whitlow et al. 1992, Bréda et al. 1995, Gillner et al. 2017) or sap flow measurements (e.g. Thomsen 2018). Sometimes these measurements were done in combination with measurements of growth rates of the trunk, shoot, leafs or tree ring width (e.g. Kjelgren & Clark 1992) or with supplementary soil water measurements (e.g. Bréda et al. 1995). The frequency of stomatal closure was low in some studies. For example, Whitlow et al. (1992) measured water deficits at trees in New York City only at two days in 1983, which could lead to stomatal closure. They calculated with the climate parameters of these days and climate data of 21 years that such days occur between 5 to 45 days in the time from June to September in each year, on average 13.4% of this periods of time.

Bréda et al. (1995) showed that the pre-dawn leaf water potential of the mature oaks (*Quercus robur* and *Quercus petraea*), which they analyzed in a forest in France, were close to the soil water potentials in 140 cm depth and had a good correlation between them, even if the main rooting zone was within the upper 70 cm depth. Nevertheless, Bréda et al. (1993) thought, that some other tree parameters (like stomatal conductance) can be reduced, when low water deficits occur; in contrast to the pre-dawn leaf water potential, which reacts at higher water deficits. Goldhammer et al. (1999) had shown for peach trees that the daily trunk diameter and the maximum daily trunk shrinkage react faster to deficit irrigations than stem or leaf water potentials or than photosynthesis. Additionally, they had shown that it reacts slower than the soil water content.

Former studies at the site E6 by Thomsen (2018) showed that the water potential in 5 cm to 80 cm depth were decreasing from nearly 0 MPa to less than -0.2 MPa in summer and fall 2013 and 2014, but the sap flow measured in the tree followed the potential sap flow. Therefore, the tree did not react to the water shortage in the soil. At the site E6, the soil was containing more moisture in 2017 than in the measured years before (2013, 2014 (Thomsen 2018) and 2016 (Figure 37)). In contrast to that, the water tension was faster reaching a high level in 40 cm depth during summer 2016 than in 2013 and 2014, so that the soil was longer dry. Nevertheless, no reactions to that by the tree were expected, because the measurements of Thomsen (2018) did not give any hints for it. Further measurements with water isotopes by Thomsen (2018) gave hints that oaks probable use water from deeper layers or from higher distance to the tree, because the same isotope signatures in steam and soil water were not found at all sampling sites. Thomsen (2018) analyzed old trees with an established root system and concluded that these trees are well adapted with their root system to their location, so that they can survive times with low precipitation and reduced soil water availability. At this site of my study, the tree was planted more than 100 years before, while at the other sites with established trees, they were planted between 1960 and 1984 and therefor younger. Younger trees, which do not have a huge well-established root system, may react stronger to soil drought. It is possible, that they use other water sources (e.g. more dependent on water from precipitations) than old trees, which was for example observed in forests by Dawson (1996).

In this study, the soil water tension was used to identify phases of soil drought (chapter 5.1.4), which can lead to drought stress for trees, because the soil water tension measurement is a well-established method in agriculture for scheduling irrigation of crops (Shock & Wang 2011). The problem is, that different tree species react different to drought periods and start to react to them at different levels of soil water tension (e.g. Fahey et al. 2013). In addition, there are different types of reaction to drought (e.g. Ranney et al. 1990, Clark & Kjelgren 1990). In cities, many different tree species are planted, e.g. in Hamburg about 300 tree species are planted as road trees (BUE 2015f). Therefore, the selected thresholds of 750 hPa and 2000 hPa (see chapter 2.1) show soils with reduced moisture, but it does not have to mean, that the trees at the sites of this study had reduced growth or vitality because of drought stress, when this value was reached. For instance, Shock et al. (2002) could prove reduced growth of poplar trees with irrigations at 750 hPa compared to poplar trees, which had been irrigated earlier, but other tree species may react different. Here, further research is needed to detect thresholds for individual tree species and tree ages. Nevertheless, the used thresholds can give hints, when drought stress might occur.

The topsoil layers seem to be the main rooting zones at most of the sites, but it is not clear where the roots of the trees exactly grow, which distance and which depth they reach. This small knowledge about the real rooting zone is one of the main problems of the interpretation of the effects of the measured soil droughts on trees. According to Kutschera & Lichtenegger (2002), the common oak has cordate roots with sinker roots. The rooting depth is about 210 cm in Central Germany, but varies with the quality of soil and the precipitation. In contrast to the oak, *Acer pseudoplatanus* has a shallower cordate root system (compiled in Kutschera & Lichtenegger 2002). In cities, the roots can grow different because of root pruning before planting at the urban site and because of disturbed soils. Only few measurements of root systems have been done in urban areas. Krieter & Malkus (1996) and Schönfeld (2017) found intensive rooting in planting pits, which had for trees beneficial substrates properties. In contrast to these relatively new planting methods, the rooting of trees, which were planted not in planting pits or in planting pits with not optimized substrates can be very different. Čermák et al. (2000) measured for example roots of two Field maple trees (*Acer campestre* L.) in a city site, which reached with a distance of 8 m to the tree an unsealed garden. The roots had a depth up to 1.7 m, while a second tree grew only to a depth of 1.4 m. Both trees had only few roots below the road. These were not reaching further than about 1 m. That study demonstrated that roots were preferentially rooting in unsealed areas and not below roads. Additionally, they were able to root below pavements into the near gardens. Other studies like the study of Wagar & Franklin (1994) give hints, that sidewalks can increase the moisture in the soil below and close to them, which can be attractive for roots. Therefore, it is possible, that the trees reach and use additional water resources like groundwater or water at old slightly damaged sewage water systems. They also may reach unsealed gardens of the houses next to them, where they might be able to use more infiltrated precipitation. This means that even during the dryer period in summer and fall 2016, the trees of this study did not necessarily had drought stress. In the study conducted by Thomsen (2018), phases of high water tension in the years 2013 and 2014 were described at E6a to E6c. However, during these periods the tree did not react with reduction of the sap flow to it. Thomsen (2018) assumed that the tree has a well-established root system and uses water from other sources, too. The other trees of my study were younger than the tree at E6, and less is known about their reactions to decreasing soil water potential.

However, the water tension in the upper soil layers seems to be important for the trees in these sites of this study, because the main amount of the fine roots was found in the upper soil layers of the soil profiles and was mainly decreasing with the depth. In one third of the profiles, no roots were in the lowest layer.

Our measurements showed no sign of drought stress in winter. In both analyzed winters, the soil temperatures did not fall below 0°C (data not shown). Further measurements are necessary to analyze colder winters, because cold stress, which decreases the hydraulic conductivity of root membranes, increases the viscosity of water and decreases the hydro-active stoma closure, can lead to drought stress in plants and freezing of soil water increases its effects (Schopfer & Brennicke 2016).

In contrast to the water tension in winter, the soil of the sites showed different behavior in summer and fall, so that wet soils could be distinguished from soils with dry phases, which has different consequences for the trees growing on them. In the moist soils of E2 and E5, no phases of dry soil with water tension higher than 2000 hPa were measured. Based on these results, it is not likely that drought stress of trees occurred in 2016 and 2017 at these sites. Therefore, drought stress is unlikely in years with similar precipitation intensities and distribution, too. This means, that in wet and average years, drought is not a problem or a stress factor at these sites. However, at the site E5, the stagnant moisture may cause problems.

In contrast to that, at the four sites of this study with dry phase(s) in the soil, the decrease of water tensions started at first in upper soil layers, because of evapotranspiration and probably root water uptake in summer 2016 and 2017. The rewetting of the topsoil layers was earlier than in the layers below them. The length of soil tension ≥750 hPa was exceeding three months in some depth at some profiles of the measurement in 2016 (e.g. in E1b). A water tension of more than 750 hPa might reduce the growth of the trees (Shock et al. 2002). This study showed that even higher water tensions were reached. That could lead to restricted growth of plants. At some sites, the lowest measured soil layers in 100 cm depth stayed wet (e.g. E1a, E1c). Therefore, it is possible, that the trees used water from there during dry phases of the soil layers above them, even if the main rooting zone was in the topsoil. However, it is not clear, if the tree showed a reduced growth or stress symptoms during these phases. This will be analyzed in further studies.

The first results of the sap flow measurements at the sites E1-6, which were conducted by the department of Biology (Biozentrum Klein Flottbek, Universität Hamburg), showed differences between the sites. As an example, the results of the sap flow analyzes of the sites E1 and E3 are shown in Figure 42. At both sites, the same tree species (*Acer pseudoplatanus*) was analyzed. The comparison between the two sites indicated that the trees at E3 had higher stress than the trees at E1 in September 2016. Thomsen & Reisdorff (2018, unpublished data) found, that the measured sap flow was lower than the modeled potential sap flow in September 2016 at E3. This means that the tree had a lower sap flow than the possible sap flow with the given weather conditions. Therefore, it is assumed that the tree had stress and had according to this closed his stomata to reduce water loss. In contrast to that, the measured and the modeled potential sap flows were very similar at E1, which means, that this tree had less stress.

Further, they showed, that the relation between the measured and the potential sap flow was reduced, when the soil water potential was high (≥1000 hPa) (Figure 42). This highlighted the relation between the dry soils and the reactions to these reduced water availabilities by the trees. These first results gave hints, that drought stress differs between the study sites and that the soil water availability seems to be a very important factor, which influences the drought stress at roadside trees. Nevertheless, further research will be done for detailed characterization of the influence of soil water availability on drought stress of trees. Therefore, the conducted sap flow measurements of the years 2016 and 2017 will be analyzed and compared with the soil data of this study in future. With the results of the combination of the data, the effects of low water availabilities in the urban soils on trees will be estimated.

In both years with measurements (2016 and 2017) of this study, the soil did not dry in spring, when the vegetation period started, but later in the second half of the vegetation period. The rewetting was mainly in winter, when the trees had already no leaves anymore, so that the dry soil may not affect the growth of the trees as much as a dry phase in spring and summer might have.

The modeling of the past years shows, that the phases of soil drought variated strongly from year to year at all seven modeled roadside tree sites, whereas the same years had relatively long or short phases of drought at all sites. Therefore, the variations from year to year depended on the weather conditions. In addition to that, the modeling showed that phases with high water tensions, which can affect the growth of trees, occurred regularly and not only in the last years.

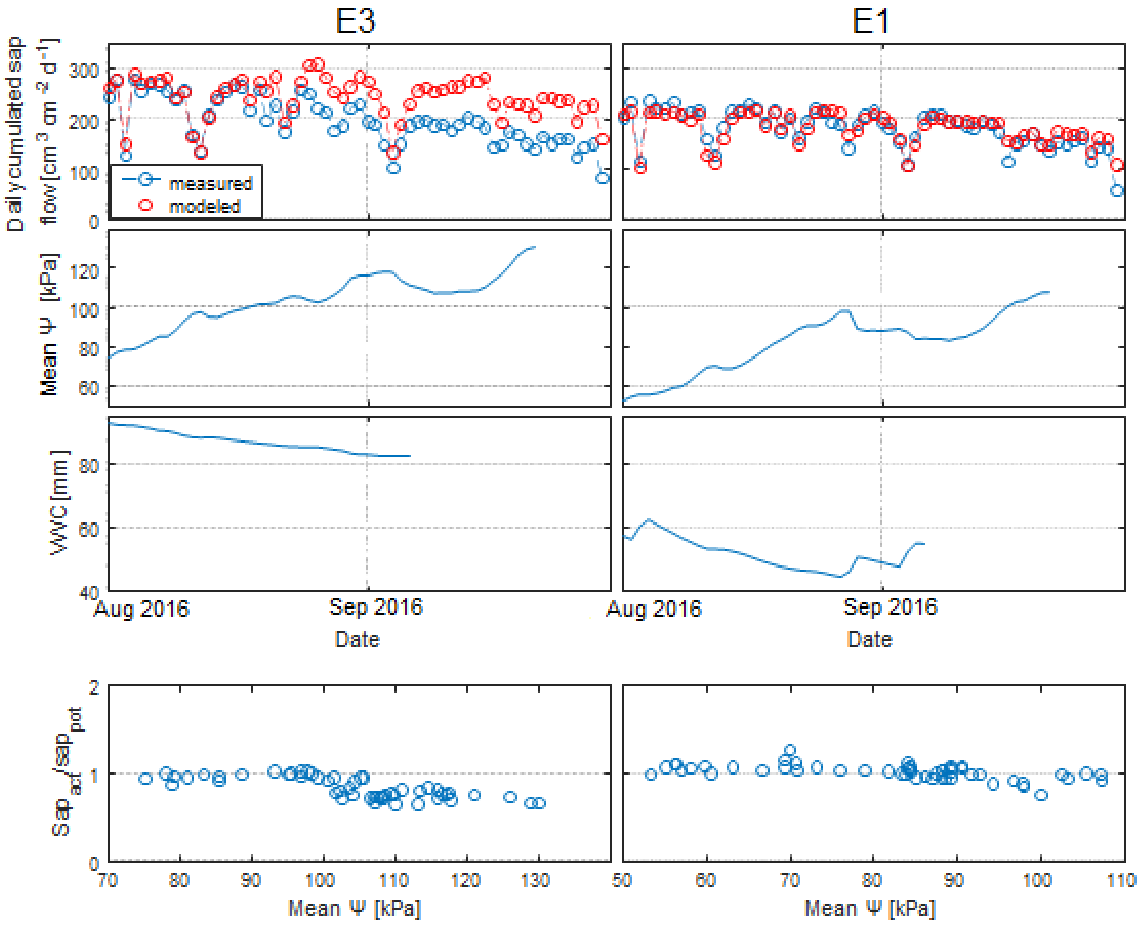

Figure 42: Daily accumulated sap flow, mean water potential and volumetric water content at E3 and E1 from August 2016 to September 2016. On the bottom, the relation between the actual and the potential sap flow in dependence of the water potential is shown. Source: Thomsen & Reisdorff (unpublished data, 2018), changed.

The trend of the number of days with dry soil layers is increasing, but not significant, because of high variations from one year to another. In contrast to that, other studies found trends of tree growth. Brèda et al. (2006) noted that drought was identified as an important factor for the increasing rates of forest tree decline and morality in Europa. Allen et al. (2010) had shown in their review that tree mortality because of drought and heat stress in forests was a worldwide problem during the last decades. They expect that the mortality will increase in future because of the climate change and the expected increase of temperatures and droughts. The modeling of this study showed that the climate in Hamburg could have contributed to soil drought and stress of trees during the last 50 years. That is in accordance with the findings of Meinecke & Frank (2018), who found that drought stress reduced tree growth in temperate cities. In contrast to that, Dahlhausen et al. (2018) found that higher air temperatures and less precipitation led to higher growth rates of small-leafed lime trees in high-dense areas of Berlin. Additionally, they showed that the age of the trees is an important factor, which influenced the growth of trees in relation to the housing density.

Further, the modelling of the past with soil data of the seven sites with felled trees showed, that the intensity and length of drought variated strongly from site to site. The mean number of drought days ranged from 68 to 120 days for the years 1980 to 2016. Therefore, at some sites the average drought lasted the double time. These site differences were affected by the soil properties and the used leaf area index (LAI) of the two different trees. Two of the seven sites were modeled with the LAI of oak trees, while the others were modeled with the LAI of maple trees. The LAI of oaks is higher than the one of maples, so the interception was higher, too. That might have led to the longer drought phases at oak tree sites. The differences between the five sites with maple can not be effected by the interception, because the interception was the same, when the same tree species was modeled. The differences were effected by the different distribution of roots in the soils and the differences of the soil properties, which were included in the model by the van-Genuchten-parameters. The length of potential drought was in accordance with the available water content in the soils (see chapter 4.1.3 and chapter 5.1.5.2). This demonstrated that the soil parameters were important factors for the length of the potential drought period.

5.3 Summary

The results of this study demonstrate that drought stress is a very important problem for roadside trees in cities. Even in cities with humid climate conditions like Hamburg, some sites are existing, where urban roadside trees can suffer from water shortage in the soils. This study shows that some sites have problems with water shortage, while others experienced for both monitoring years (2016 and 2017) high water contents and low water tension (<750 hPa). At these sites, further measurements would make sense to analyze if accumulated water is affecting the living of tree roots negatively.

At sites with soil drought, the intensity of drought was mainly affected by climatic factors like precipitation rates. Therefore, in 2016 the drought period was longer and more intensive than in 2017. While precipitation rates in summer 2016 were close to the 30-year average, the fall had only half of the precipitation sum. That led to decreased soil water contents and increased soil water tensions. In contrast to that, 2017 was a wet year with precipitation sums above the 30-year average, which led to mainly moist soils with only short dry phases in the upper soil layers. In winter, the soils rewetted fully and stayed moist during spring, so that drought stress occurred in 2016 and 2017 primarily in summer and fall.

The study indicated that the small-scale heterogeneities of soil texture and the compaction of the soils led to small-scale variations of soil water availability. Further, the sealing and the surrounding of the tree sites seems to be an important factor, which influences the soil water dynamics at some sites. The soils of two sites in narrow streets with increased shading from of adjacent high buildings, a high percentage of soil sealing and trees growing in bare green strips were moist and showed no drought phases in the observation period. In contrast to that, the other four sites with higher radiation, larger distance to buildings and lower proportion of sealing had drought phases of soil layers in 2016. Nevertheless, the impact of the single factors of surrounding and soil (e.g. texture) could not be determined, because of low and mainly no significant correlations. That might be caused by the low number of six study sites and by the similarity of the analyzed sand-rich urban soils, which were chosen because these were typical urban soils in Hamburg, so that the differences between their soil properties were small (see chapter 4).

The modeling of the past showed, that the length of soil drought varied strongly from year to year, which was depending on the weather and that moderately dry soils (water tensions ≥750 hPa) occurred during the last about 50 years, too. The number of days with dry soil were very different from site to site, whereas the mean ranged from 68 to 120 days in the years 1980 to 2016, which means, that at some sites the potential drought takes the double time than at other sites. This was effected by the biological input data and especially the soil properties. This showed, that the soils were very important factor, which influence the potential drought at roadside tree sites to a high amount.

In further studies, these results will be correlated with the conducted measurements of the department of Botany of the Universität Hamburg, which were sap flow measurements, dendrochronological analyses and isotope ($^{13}CO_2$) analyses, to gain more insight in the connection between the soil drought and the drought stress of trees.

Another problem observed in this study, was the low aeration in the urban soils at many studied roadside tree sites. The CO_2- and O_2-contents had seasonal variations with high CO_2-contents in summer and low ones in winter. The O_2-content was strongly negative correlated to the CO_2-content. Short time variability of the gas contents correlated with the water content in the soil, whereas the water content in the upper part of the soils played an important role for the aeration in deeper soil layers. A high soil water content led to an increase of the CO_2-content and a decrease of the O_2-content. The CO_2-content was during summer and fall at many sites higher than 5% over some months in 100 cm depth, which may lead to root damages and to additional stress for the roadside trees.

In conclusion, soil drought as well as an insufficient aeration of the soil at urban roadside tree sites have the potential to cause stress for trees. Therefore, it is important to gain more knowledge about the rooting of the trees (extent and intensity of rooting) and their reactions to the stress factors and thresholds, which exceeding should be prevented by adapted tree management.

6. Soil hydrology at sites of young urban roadside trees

In this chapter, the problem of drought at roadside trees in Hamburg is widened to young roadside trees, which were planted in planting pits. In chapter 4, it was demonstrated, that constant soil conditions like the sandy texture of the urban soils can increase the potential drought at tree sites. In chapter 5, the dynamic conditions at the tree sites were analyzed. They showed that the soils became dry in summer and fall in different depths over a longer period at some sites, while other sites stayed moist.

In comparison to established trees, young urban trees are planted in planting pits with special planting substrates. Another difference is that they do not yet have wide expanding root systems. Therefore, they depend on the water availability in the planting substrates of their planting pits during the first years after planting. With analyses of the different soil substrates around the young trees and with the monitoring of the water tension, it is analyzed in this chapter, if water availability is given at sites of young roadside trees over the course of the year.

6.1 Results

6.1.1 Sealing and soil temperatures at young roadside trees

The young roadside tree sites (see chapter 3.1) could be divided in sites with high sealing (>90%), medium sealing (60-90%) and in sites with very low sealing (<15%) of the soil in an area of 20 m x 20 m with the analyzed tree in the middle. Here, sealing means completely sealed as well as partly sealed surfaces like paving stones. High soil sealing percentage were found at Y7, Y8, and Y9. Here, the trees were planted in single tree pits. The highest sealing of 98% was at Y8 in the area of 20 m x 20 m (here the open water surfaces of a harbor channel was not included in the percentage of unsealed surfaces, because their height was in about four meter below the tree stand and the water being separated with steel retaining walls from the soil). In addition to the high sealing rates, the tree pit surfaces at Y7 and Y8 were special: in contrast to all other study sites of this study with young trees, no vegetation was growing on the surfaces. Here, the surfaces were made for pedestrians to walk on them. A medium sealing rate was found at Y2a, Y2b and Y2c, where three trees were located in single planting pits along a street, at Y3a-c, where the trees were located in a green stripe along a street, at Y5, Y6, Y10 and Y11. Very low sealing were found at Y1 and Y4a-c. Y4b and Y4c were the only sites with no sealing in the surrounding of around 10 m (Figure 43). These trees were planted in larger green areas (see site plans in Strachwitz 2017). Whereas the trees at Y4 were next to the same sidewalk, which was separated from the street with a planted noise protection embankment.

At this site (Y4), the lowest soil temperatures in 30 cm depth were measured in summer and fall. Y1 had similar low temperatures. This site was on square and was shaded by established trees. These four sites had an average temperature between 14.3°C (Y4c) and

16.5°C (Y1) from June to August 2017 in 30 cm depth and maxima between 17°C (Y4c) and 20°C (Y1, Y4a). Other more exposed soils at young trees like Y5, which was located on a traffic island, or Y3a, had a temperature average of 20.4°C in the same time period and reached maxima up to 26°C. The other sites had temperature averages, minima and maxima, which were between the ones of the sites described above (data not shown).

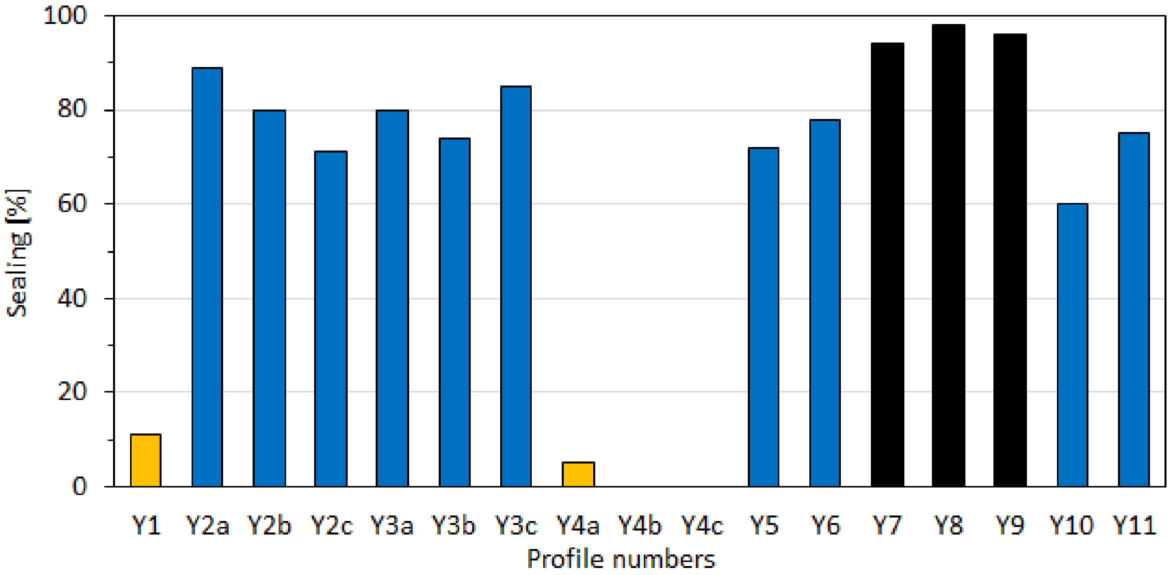

Figure 43: Sealing rates near the young urban roadside trees Y1-Y11 in an area of 20 x 20 m. Sites with high sealing (>90%) are marked in black, sites with very low sealing (<15%) are marked in light orange and others are in blue. Y4b and Y4c were unsealed in the area of 20 x 20 m.

6.1.2 Soil Properties

Young urban trees are planted in planting pits by horticulture companies under application of defined rules (FLL 2012, FLL 2015). Therefore, three different types of soil substrates can be found around the trees: the soil substrate in the root ball from the tree nursery, the planting pit substrate, which is usually an anthropogenic substrate mixture and should have good physical and chemical properties for root growth of trees. The third soil substrate group around the young trees is the urban soil around the planting pit. In this chapter, the soil properties of the last two substrate types were analyzed and compared with each other. Because of dense rooting in the root ball and a high risk of damaging roots during soil sampling, the root ball substrates were not sampled.

6.1.2.1 Morphological and textural soil parameters of planting pit substrates and surrounding urban soils

At the young tree sites, the planting pit substrates and the surrounding urban soil substrates were analyzed, if possible. Based on the sampling method (see chapter 3.5.2), the depths of the layers could not exactly be specified. It is possible, that they were not complete and small layers could not be included in the measurement, because it was not possible to gain enough material of them during the digging.

With regard to the planting pit, in thirteen planting pits we found two layers of different substrates and in four pits just one substrate. Two of the two-layer planting pits (Y7, Y8) had as a second layer a thin layer of a different substrate to make the surface usable as a sidewalk. This material was not provided for root growth of the tree. Nevertheless, it is part of the planting pit and therefore it is put in the category of planting pit substrates in this study. These two planting pit substrates had a red color, while the thin top layer was grey. All other planting pits had dark brown substrates with exception of the deeper layer of Y3c, which was brown-yellow (see Appendix III: Table 21).

The planting pit substrates were dominated by sands (median: 84.2% sand content) with a high content of skeleton. Regarding texture, the planting pit substrates were mainly loamy sands (63.3%) or pure sands (33.3%), while a higher percentage of surrounding urban soils were pure sands (56.1%) (Figure 44). The median of the skeleton content of 34.7% (n=31) of the planting pit substrates was nearly four times higher than the skeleton content of the substrate layers outside of the planting pits. Their median was 8.9% (n=41). The skeleton contents varied in the planting pit substrates between 1.9% and 57.8% and in the surrounding urban soil from 0.1% to 33.5% (see Figure 45). In ten of the thirteen planting pits, where two different layers of planning pit substrate were identified, the upper layer had a higher skeleton content (see Appendix III: Table 21). In the other three two-layer planting pits, the substrates had a very similar skeleton content, which were only slightly higher in the deeper layers.

Typically, the substrates around the planting pits were different from the planting pit substrates: The soil texture was often pure sand in the urban soil with a lower coarse particle and humus content than in the planting pits (see above, chapter 6.1.2.2, Appendix III: Table 21 and Table 22).

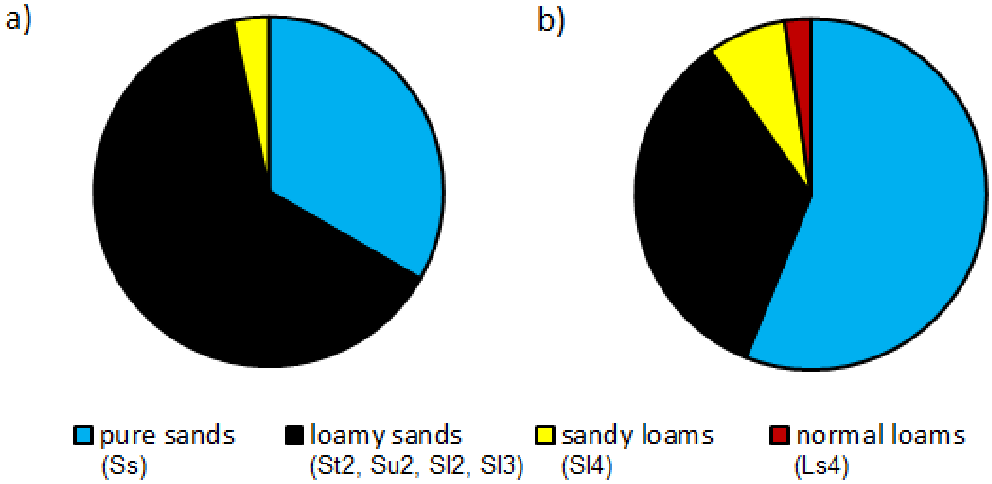

Figure 44: Soil texture of a) the planting pit substrates (n=30) and b) the layers of the surrounding urban soils (n=41) according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005).

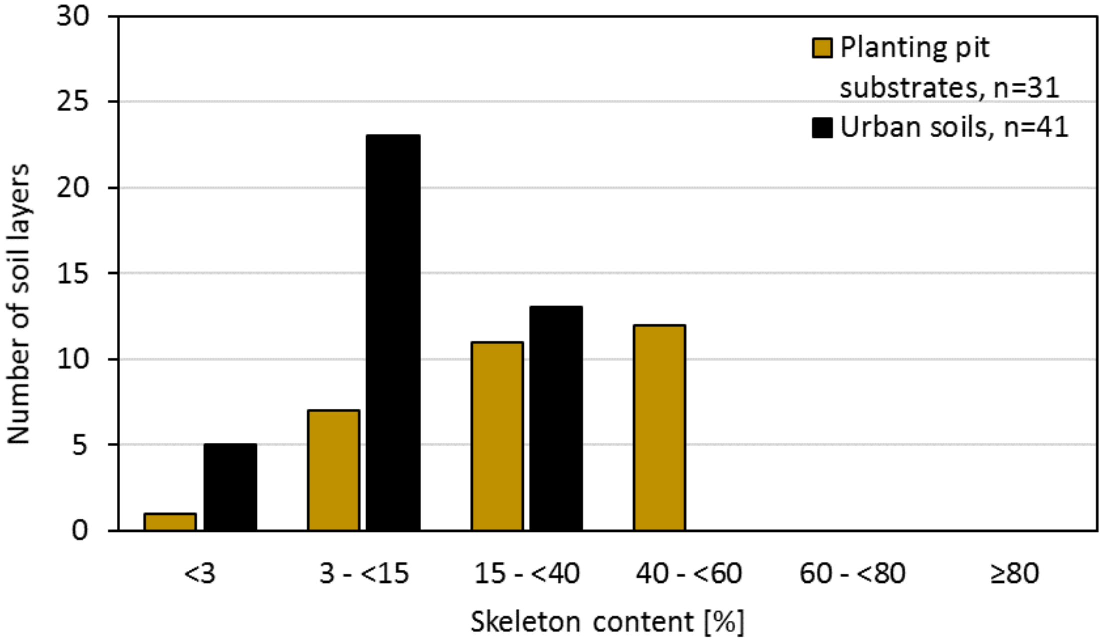

Figure 45: Skeleton contents of the planting pit substrates of young roadside trees and of the layers of urban soils next to the planting pits (Y1-Y11). Categories of the skeleton content were classified according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005).

6.1.2.2 Chemical characteristics of planting pit substrates and surrounding urban soils

Chemical analyses of the C-content, humus content, N-content, C/N ratio, pH and electrical conductivity were conducted in the planting substrates and the urban soils next to young roadside trees.

The carbon (C) content reached from 0.18% to 12.63% in the planting pit substrates and the median was 2.36%. In the surrounding urban soil, the C-content varied between 0.04% and 8.63% and had a median of 0.76%.

Planting pit substrates had higher humus contents than the surrounding soil. The median of the humus content of the planting pit substrates was 4.1%, the maximum 21.7% (Y4c, 0-10 cm) and the minimum was 0.3% (Y4a, 40-70 cm). Six of these substrates were “extreme humous” according to the classification of Ad-hoc-Arbeitsgruppe Boden (2005). If the planting pit was composed of two layers, generally the humus content was higher in the upper layer than in the second layer. In the median, the humus content of the surrounding urban soils was with 1.3% less than one third of the humus content of the planting pit substrates (see Figure 46). In general, the humus content was decreasing from the topsoil to the depth in the urban soils (see Appendix III: Table 22).

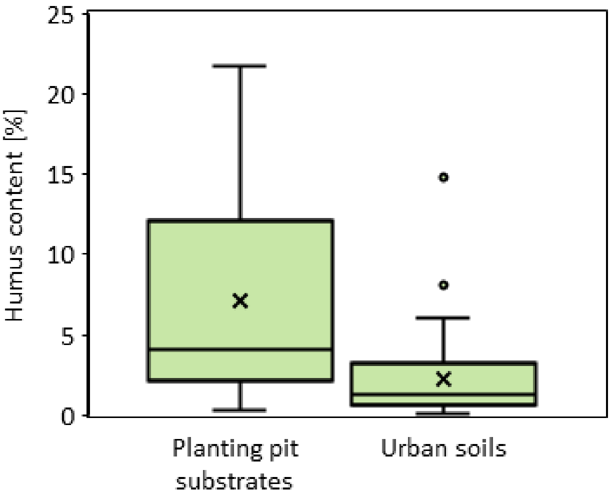

Figure 46: Humus content of planting pit substrates (n=31) and urban soils next to young roadside trees (n=41). The Bars show the quartiles. The lines in the bars mark the medians, the outer lines the range without outliers, the crosses mark the average values, and the points the outliers.

The distribution of nitrogen was similar to humus. The highest values were in the top layer of the two-layer planting pits. In the planting pits, the nitrogen content (median: 0.21%) was higher than in the surrounding soil (median: 0.12), where the values decreased with the depth (see Appendix III: Table 22).

A median C/N ratio of 13.4 was measured in the planting pit substrates, and a median C/N ratio of 11.8 in the surrounding urban soils (see Appendix III: Table 22).

The median of the pH (measured in $CaCl_2$) value of planting substrates was with 6.7 only slightly higher than the median of the surrounding soil with pH 6.4 (Figure 47). Most of the planting pits had a pH between 6.4 and 6.9. Only the planting substrates of Y4a, and Y4c were slightly lower and the substrates of Y4b were with a pH 5.0 and 5.3 more than 1 value lower than the mean of all planting substrates. The pH of the surrounding soils were similar (pH 5.0 in 0-60 cm and pH 5.5 in 60-100 cm depth). The pH values of the substrates of Y7, Y8, Y11 and the deeper layer of Y1 were slightly above pH 7, and therefore higher than the average.

The pH of the surrounding soil was similar or slightly lower than the planting pit materials in most of the profiles. The median pH was 6.4 and the variations between the sides were higher than the variations of pH in the planting pit substrates. Profiles with a pH lower than 6 in most of the layers were at Y3b, Y3c, Y4b and Y4c. At Y4b, the planting pit substrates had a similar pH than the surrounding soil. Here the planting material looked like the urban soil substrate. In the other three pits with low pH in the surrounding soil (Y3b, Y3c and Y4c), the planting pit substrates had in average a pH of 6.5, which was 0.6 pH values lower than the pH of the surrounding soil. The pH values increased with the depth in the surrounding soils at all sites, where measurement was conducted in more than one depth. In average, the pH increased with 0.4 pH values from the highest to the lowest measured layers (see

Appendix III: Table 22). Most of the sites where no layer of the surrounding soil was lower than pH 6.4 were located in the inner city (Y1, Y5, Y6, Y9-11).

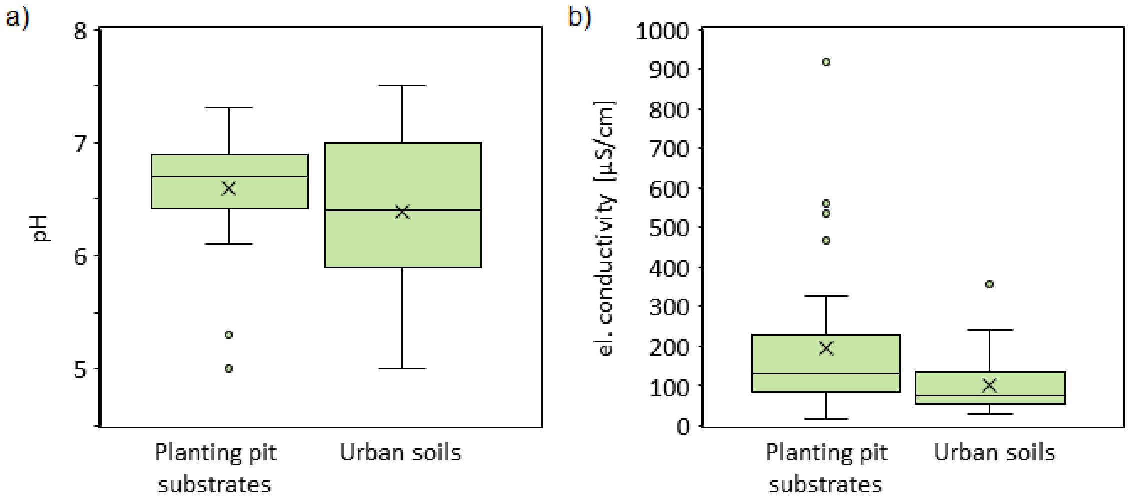

Figure 47: pH values in $CaCl_2$ (a) and electrical conductivity in 1:2.5 (b) of planting pit substrates (n=31) and urban soils (n=41) next to young roadside trees. The Bars show the quartiles, the lines in the bars mark the medians, the outer lines the range without outliers, the crosses mark the average values, and the points the outliers.

Surrounding soils with layers below pH 6.0 were closer to the city borders and were located in greener residential areas. Exceptions were Y3a and Y2c. There, the soil had a pH higher than 6.5. They were not located in the city center, but each of them were close to two other sites in the same street, which had lower pH values. Therefore, the pH variated along the streets. Y2a, Y2b and Y2c were located in the same street with the distance of around 130 m between the outer two young trees. Y2a and Y2b had very similar pH values from around 5.6 in the topsoil to 6.5 in the depth. In comparison to that, Y2c had a pH 6.6 in the topsoil and pH 7.2 in the depth. Similar differences in pH values were on the site of Y4a-c.

The electrical conductivity (EC) in the planting pits was often higher than in the surrounding soil. The median of the EC was 132 µS/cm in planting pit substrates and 77 µS/cm in the surrounding soil (Figure 47). The variability was relatively high. The second highest (560 µS/cm) and the lowest EC (17 µS/cm) were measured in the same planting pit at Y6 (see Appendix III: Table 22). In seven of 13 planting pits, where measurements were done in more than one depth, the EC was decreasing with the depth. In the other four planting pits, the values were higher in the deeper planting pit substrate, while the EC was in two planting pits nearly the same in both layers. In 62% of the profiles of the urban soils next to the planting pits, the EC decreased with the depth. The EC along streets, where the monitoring was conducted at three young trees (Y2a-c, Y3a-c and Y4a-c) at each of the streets, variated from tree to tree as well as in the planting pit as well as in the urban soil around them. For instance, the surrounding soil had EC of 54 µS/cm (Y2a), 67 µS/cm (Y2b), and 107 µS/cm (Y2c) in the topsoil and values of 193 µS/cm (Y2a), 325 µS/cm (Y2b) and 535 µS/cm (Y2c) in the top layer of planting pit substrates (see Appendix III: Table 22).

6.1.3 Soil water tension and drought at young roadside trees

The course of the soil water tension (SWT) showed a strong variation from summer 2016 to winter 2017. The SWT varied over the course of the year with low intensities in spring and winter and with higher values in summer and autumn (Figure 48). The SWT increased in periods with no or less rain and decreased after precipitations and irrigations during summer and fall.

In winter and spring, the SWT were found to be low in all substrates of all observed young tree sites (Y1-Y11). This means, that SWT were <250 hPa, often around 100 hPa. That indicated wet or moist soil conditions where additional water from precipitations did not change the water contents and tensions significantly as the surplus of water is seeping to deeper layer. In summer and fall, the soils of the studied tree sites showed differences in their water tensions. In general, the water tensions were slightly increasing at the end of May 2017. Most of the soil substrates were completely rewetted between September and November 2017. In 2016, the rewetting took place until December 2016. For 2016, the start of the soil drying could not be specified, because our measurements started in June, when the SWT already had started to increase.

Typically, in phases of increasing SWT the SWT were higher in the root ball substrates than in the planting pits and the surrounding urban soil in the same depth. The SWT were lower in deeper layers and slightly lower in the surrounding soil in comparison to the planting pit substrates (Figure 48).

Most of the studied trees were irrigated three to four times in 2016. These irrigations led to a fast and strong decrease of SWT, similar to intensive precipitations. Nevertheless, the higher soil water availability last only for a short time. For example, at Y2c, after the irrigation on the 27th of July 2016 the SWT were starting to increase 4 hours later (Strachwitz 2017). At many of the trees, the soil wetting after irrigations was observed in the root ball substrates and in the planting pit substrates, but not in the surrounding urban soils (Figure 49). That shows a targeted water input into the planting pits. After irrigations, the root ball substrates tended to become dry earlier again than planting substrates in deeper layers (Strachwitz 2017). For instance, the hourly water tensions measured at two sensors in the root ball substrate of profile Y2c were decreasing from 1518 hPa and 787 hPa to 0 hPa and 39 hPa respectively from 10 am to 11 am on the 22nd of August 2016. One hour later, the water tensions started to increase again and were reaching water tensions higher than 750 hPa one week later, on the 29th of August.

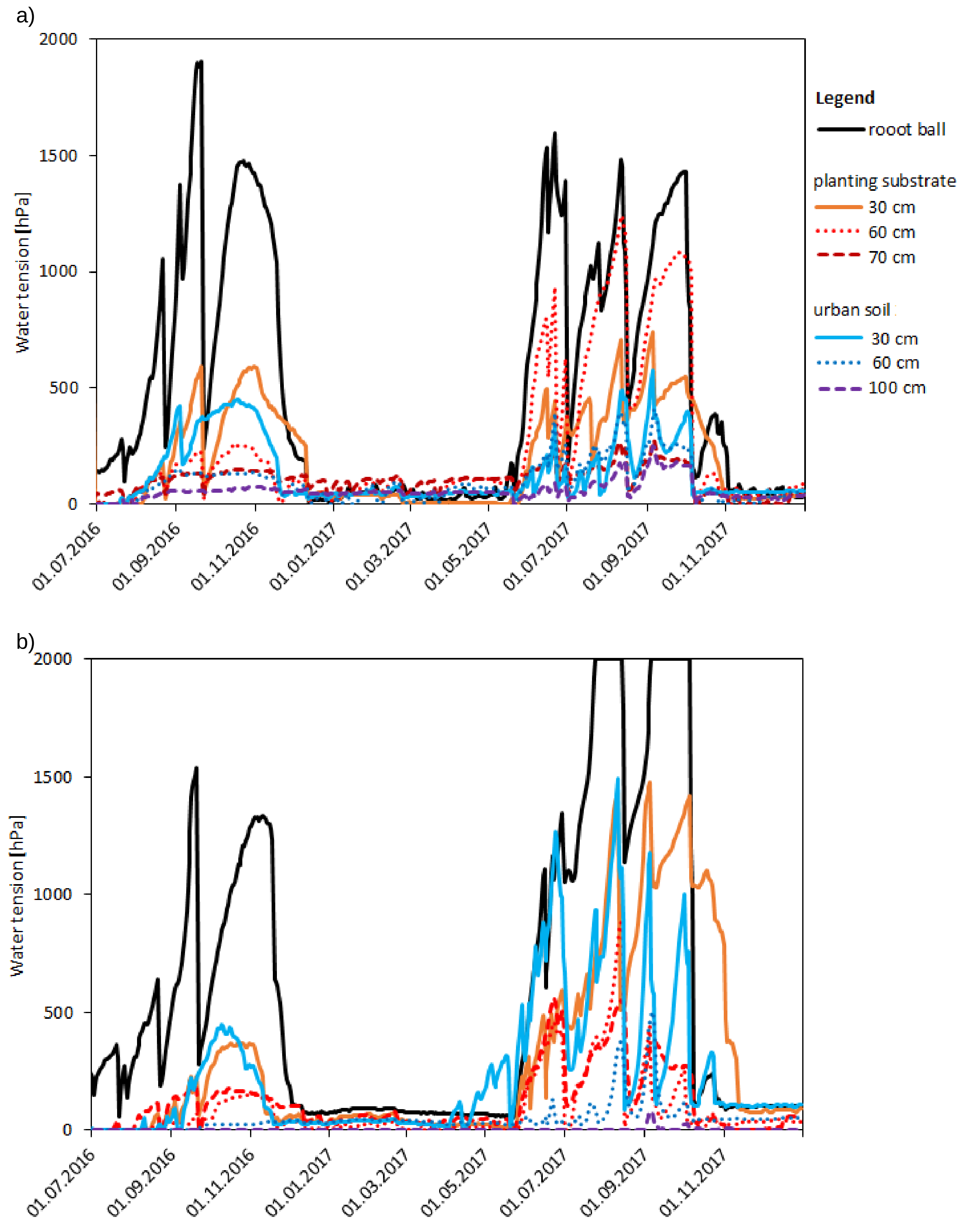

Figure 48: Average daily mean water tensions at the trees Y2c (a) and Y2a (b) in the root ball substrate, in the planting substrate and in the surrounding urban soil in 30 cm, 60 cm, 70 cm and 100 cm depth, respectively from July 2016 to December 2017. Except for 70 cm, all values are averages from two sensors.

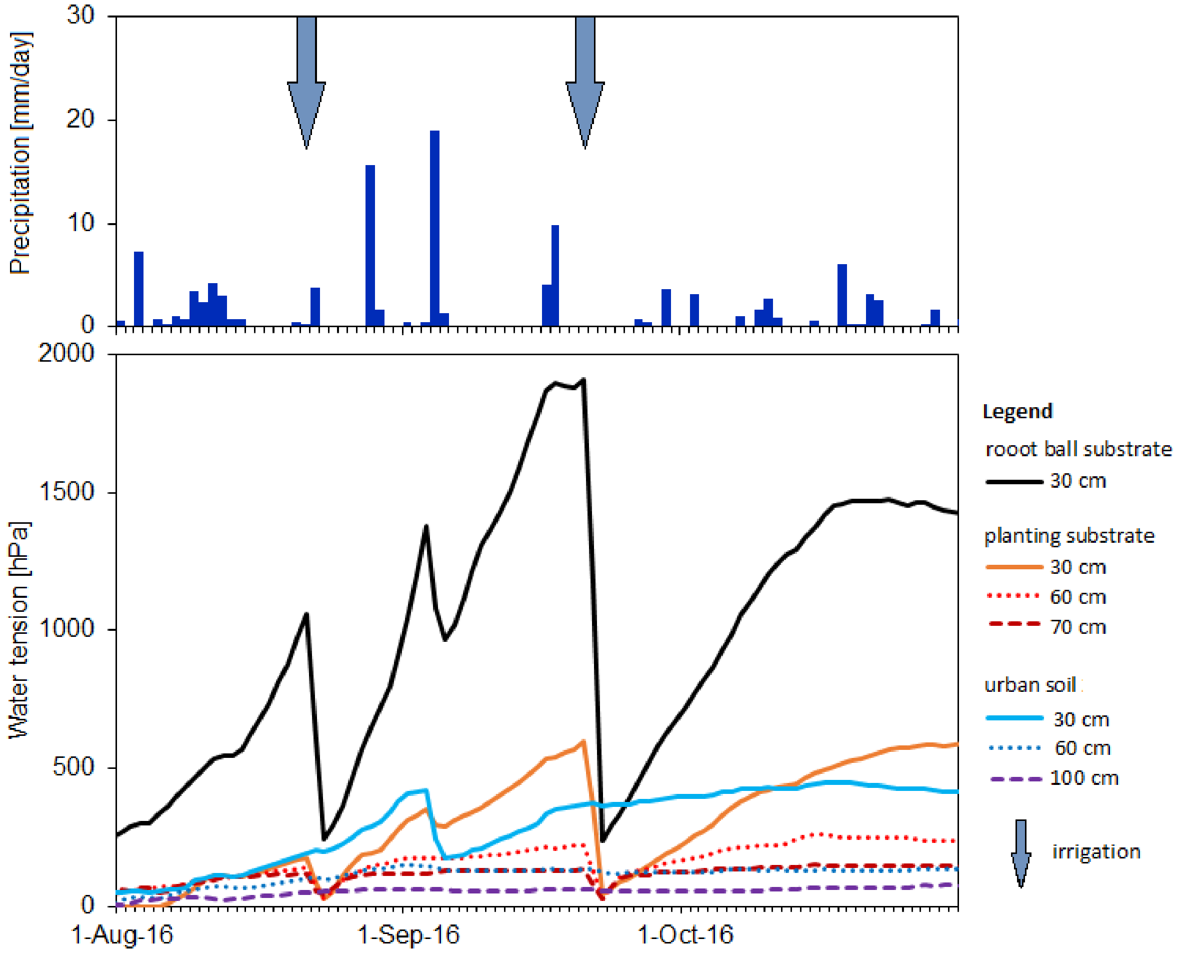

Figure 49: Daily precipitation sums (HH-Fuhlsbüttel, DWD 2018) and daily mean water tensions at the tree Y2c in the root ball substrate, in the planting substrate and in the surrounding urban soil in 30 cm, 60 cm, 70 cm and 100 cm depth, respectively from August 2016 to October 2016. Except for 70 cm, all values are averages from two sensors. Days with irrigation are marked with gray arrows.

The SWT were not increasing to the same amount in 2016 and 2017. At ten young trees, measurements were conducted in both years, while the other seven sites were instrumented later. At these ten sites, three different types of variations were observed. The soils of the first type were reaching higher SWT in 2017 than in 2016. The periods with SWT ≥750 hPa were also longer. Eight of the sites showed these reactions – in spite of higher precipitation in 2017 (see Table 6). The second type had lower SWT in 2017 compared to 2016. This was the case at the site Y4a. One site belongs to the third type: At Y4c, both years were similar and had only low values of SWT (<750 hPa in both years). Therefore, this was the only young tree pit, where no soil drought (water tensions ≥750 hPa) occurred.

All three water tension-variation-types occurred in the same street at the site Y4 (Figure 50). Here, *Quercus cerris*, with similar height and more or less similar age, were planted in the year 2016. They were delivered from the same tree nursery, so that it is assumed that they were kept under the same conditions and had the same initial position after planting at Y4. The analyzed young trees at Y4 were not more than 100 m apart from each other, nevertheless, the intensity of drought differed. The root ball and planting pit substrates at Y4a were dry in summer and autumn 2016 and 2017. In contrast to that, at Y4b, they were dry in the top layers only for a short time in autumn 2016, but in 2017, the bottom of the planting pit was dry in about 70 cm depth during 41% of the autumn (Appendix III: Table 11). At these young tree sites, the groundwater level differed from about 1 m at Y4c to around 3 m depth at Y4a (BUE, 2015a). In addition to that, Y4c was located closer to an embankment. This site (Y4) had the lowest sealing and a high amount of vegetation around the trees (see chapter 6.1.1).

In 2016, at eight of ten young trees, SWT ≥750 hPa were measured in at least one measuring depth and at three sites, SWT ≥2000 hPa was measured (see Table 11). In 2017, SWT ≥750 hPa were measured at 15 of 17 young trees and SWT ≥2000 hPa were measured at nine locations.

At most of the sites, the highest SWT were found in the root balls. Further more, SWT of 750 hPa was exceeded there for more days than in the planting substrate or the urban soil in all measured sites in 2016 and in nine of 15 sites, which had higher values than 750 hPa, in 2017 (Table 11). The length of moderately dry phases of the root ball substrates variated from site to site, for example between 0% (Y4c) and 100% (Y1) of the days in summer 2017 (June to August). At nearly all of the sites, the dry phases were interrupted by short phases with lower SWT, triggered by irrigations and precipitations.

In summer and autumn, the planting substrates were typically dryer than the surrounding urban soils in the same depth. The urban soils in 100 cm depth were wet or moist with SWT <750 hPa all the year. The only exception was Y4a. At this site, in 100 cm depth SWT was ≥750 hPa for about a week in autumn 2017. At Y7, in the planting pit substrate SWT <750 hPa in 100 cm depth was observed for more than a month (autumn 2017), while at Y8 the SWT of the planting substrate stayed <750 hPa (Table 11). In these two exposed single planting pits with trees that were older (planting years 2007 and 2012) than the trees of most of the other sites (see Table 1) the substrates became dry in 60 cm and 70 cm in the greater distance to the trees. In comparison to that, the urban soils at the other young tree sites stayed moist in 60 cm depth. Only at the site of Y5, the urban soil substrate reached SWT ≥750 hPa during summer and fall 2017. This site is a very exposed site, located on a traffic island, with slightly higher temperatures in the soil (see chapter 6.1.1).

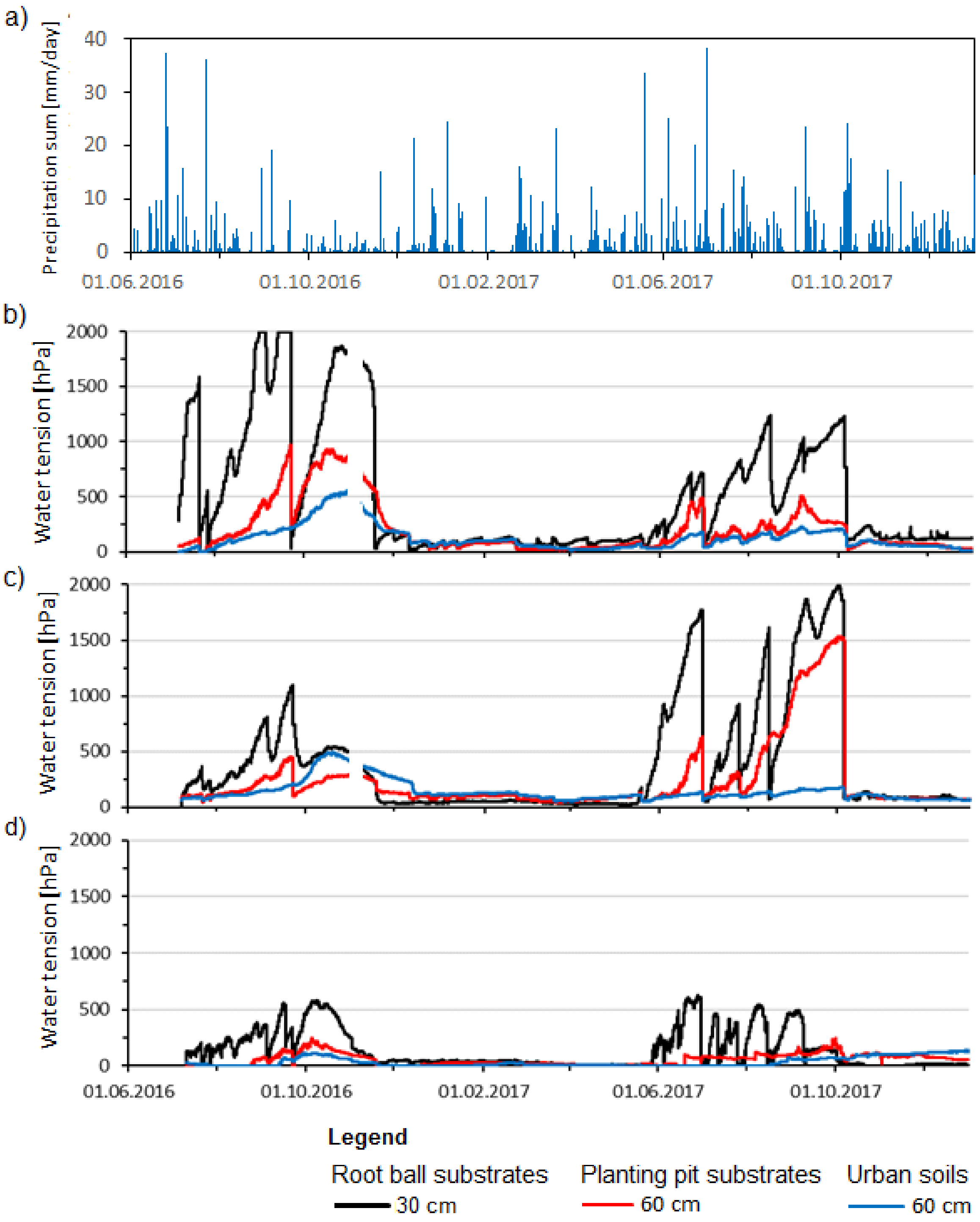

Figure 50: a) shows the daily precipitation sums at the station in Fuhlsbüttel (DWD, 2018). The graphics below a) show the water tensions of root ball substrates (30 cm), planting pit substrates (60 cm) and urban soils (60 cm) at the three tree sites b) Y4a, c) Y4b, and d) Y4c from July 2016 to December 2017. All water tension values are averages from two sensors.

Table 11: Percentage of time with soil water tension ≥750 hPa (≥2000 hPa) in summer 2016, autumn 2016, winter 2016/17, spring 2017, summer 2017, autumn 2017 and winter 2017. Data are shown for root ball substrate (R), planting substrate (P) and surrounding urban soil (U) in 30, 60, 70, 100 cm depth. In Y7 and Y8, measurements of planting substrate with larger distance to the tree were done (D), instead of urban soil measurements. Except for 70 cm, all values are data from the average water tension of two sensors, based on hourly data. Percentages ≥ 30% are in bold.

Profile No.	**Depth**	**Percentage of soil water tension ≥750 hPa (≥2000 hPa) [%]**						
	[cm]	Summer 06.-08.2016*	Fall 09.-11.2016	Winter 12.2016-02.2017	Spring 03.-05.2017	Summer 06.-08.2017	Fall 09.-11.2017	Winter 12.2017
Y1	30 (R)	**36.5** (8.9)	**87.7** (6.9)	0 (0)	22.9 (0)	**100** (0)	**37.8** (2.5)	0 (0)
	30 (P)	0 (0)	19.7 (0)	0 (0)	20.1 (0)	**100** (18.8)	**37.8** (7.1)	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	13.2 (0)	**100** (0)	**41.0** (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	**40.2** (0)	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	7.3	0 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y2a	30 (R)	0 (0)	**61.1** (0)	0 (0)	0 (0)	**88.3** (24.6)	**40.6 (33.2)**	0 (0)
	30 (P)	0 (0)	0 (0)	0 (0)	0 (0)	28.0 (0)	**68.3** (0)	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	0 (0)	5.5 (0)	0 (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	**42.0** (0)	12.6 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y2b	30 (R)	0 (0)	**46.0** (0)	0 (0)	0 (0)	**57.8** (0)	**34.0** (0)	0 (0)
	30 (P)	0 (0)	0 (0)	0 (0)	0 (0)	-	-	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	0 (0)	-	-	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	-	-	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y2c	30 (R)	11.0 (0)	**74.7** (0)	0 (0)	0 (0)	**76.6** (0)	**37.6** (0)	0 (0)
	30 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.2 (0)	0 (0)
	60 (P)	0 (0)	**35.8** (0)	0 (0)	0 (0)	**35.8** (0)	**38.5** (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y3a	30 (R)	6.7 (0)	**64.9** (0)	0 (0)	1.9 (0)	**100** (8.8)	**77.8** (0)	0 (0)
	30 (P)	0 (0)	**63.1** (0)	0 (0)	0 (0)	**85.8** (0)	**64.2** (0)	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	0 (0)	35.3 (0)	12.0 (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (U)	0 (0)	27.6 (0)	0 (0)	0 (0)	**99.5** (2.0)	**49.2** (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y3b	30 (R)	0 (0)	0 (0)	0 (0)	0 (0)	**69.6** (0)	**37.7** (0)	0 (0)
	30 (P)	0 (0)	0 (0)	0 (0)	0 (0)	**47.8** (0)	**31.0** (0)	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	0 (0)	13.6 (0)	7.2 (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	2.6 (0)	4.6 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

* Y2a-c, Y3a-b: July-August 2016

Profile No.	**Depth**	**Percentage of soil water tension ≥750 hPa (≥2000 hPa) [%]**						
	[cm]	Summer 06.-08.2016*	Fall 09.-11.2016	Winter 12.2016-02.2017**	Spring 03.-05.2017	Summer 06.-08.2017	Fall 09.-11.2017	Winter 12.2017
Y3c	30 (R)	11.1 (0)	29.3 (0)	0 (0)	2.7 (0)	**46.6** (2.2)	**38.6** (0)	0 (0)
	30 (P)	0 (0)	0 (0)	0 (0)	9.1 (0)	**35.9** (0)	**37.8** (2.0)	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	2.4 (0)	4.6 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y4a	30 (R)	**49.8** (0)	**70.6** (0)	0 (0)	0 (0)	19.3 (0)	**38.5** (0)	0 (0)
	30 (P)	3.0 (0)	**73.0** (14.8)	0 (0)	0 (0)	**33.9** (0)	**35.3** (0)	0 (0)
	60 (P)	0 (0)	**37.9** (6.8)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (U)	0 (0)	**42.5** (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	8.7 (0)	0 (0)
Y4b	30 (R)	0 (0)	13.1 (0)	0 (0)	0 (0)	**53.0** (0)	**37.9** (0)	0 (0)
	30 (P)	0 (0)	1.3 (0)	0 (0)	0 (0)	**43.9** (0)	**38.5** (0)	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	0 (0)	5.0 (0)	**39.1** (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	11.3 (0)	**41.3** (0)	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y4c	30 (R)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	60 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	70 (P)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	30 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	60 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y5	30 (R)	-	-	0 (0)	2.9 (0)	**80.9** (10.8)	14.7 (5.1)	0 (0)
	30 (P)	-	-	0 (0)	0.7 (0)	**67.8** (0)	14.7 (0)	0 (0)
	60 (P)	-	-	0 (0)	0 (0)	**37.7** (0)	14.7 (14.1)	0 (0)
	70 (P)	-	-	0 (0)	0 (0)	**57.1** (0)	7.1 (6.0)	0 (0)
	30 (U)	-	-	0 (0)	0 (0)	**31.1** (0)	20.3 (0)	0 (0)
	60 (U)	-	-	0 (0)	0 (0)	7.4 (0)	7.0 (0)	0 (0)
	100 (U)	-	-	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y6	30 (R)	-	-	0 (0)	0 (0)	**94.3** (0.7)	**39.1** (2.1)	0 (0)
	30 (P)	-	-	0 (0)	0 (0)	9.1 (0)	8.8 (0)	0 (0)
	60 (P)	-	-	0 (0)	0 (0)	11.3 (0)	5.7 (0)	0 (0)
	70 (P)	-	-	0 (0)	0 (0)	27.5 (0)	6.0 (0)	0 (0)
	30 (U)	-	-	0 (0)	0 (0)	19.6 (0)	7.6 (0)	0 (0)
	60 (U)	-	-	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	100 (U)	-	-	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y7	30 (R)	-	-	0 (0)	0 (0)	**77.1** (27.9)	26.6 (6.1)	0 (0)
	30 (P)	-	-	0 (0)	0 (0)	**66.5** (19.7)	**37.6** (6.1)	0 (0)
	60 (P)	-	-	0 (0)	0 (0)	**74.9** (2.2)	**55.1** (8.7)	0 (0)
	70 (P)	-	-	0 (0)	0 (0)	**34.8** (8.9)	**80.5 (64.7)**	0 (0)
	30 (D)	-	-	0 (0)	0 (0)	**52.4** (0)	16.0 (0)	0 (0)
	60 (D)	-	-	0 (0)	0 (0)	25.8 (0)	**40.6** (0)	0 (0)
	100 (D)	-	-	0 (0)	0 (0)	2.0 (0)	**38.6** (0)	0 (0)

* Y3c, Y4a-c: July-August 2016

** Y7: January-February 2017

Profile No.	**Depth**	**Percentage of soil water tension ≥750 hPa (≥2000 hPa) [%]**						
	[cm]	Summer 06.-08.2016	Fall 09.-11.2016	Winter 12.2016-02.2017**	Spring 03.-05.2017	Summer 06.-08.2017	Fall 09.-11.2017***	Winter 12.2017
Y8	30 (R)	-	-	0 (0)	0 (0)	**72.1** (25.4)	**100 (38.4)**	0 (0)
	30 (P)	-	-	0 (0)	0 (0)	**61.2** (15.8)	-	0 (0)
	60 (P)	-	-	0 (0)	0 (0)	**69.6** (20.3)	-	0 (0)
	70 (P)	-	-	0 (0)	0 (0)	**37.1** (7.5)	-	0 (0)
	30 (D)	-	-	0 (0)	0 (0)	-	-	0 (0)
	60 (D)	-	-	0 (0)	0 (0)	**35.0** (9.8)	**40.5 (38.3)**	0 (0)
	100 (D)	-	-	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Y9	30 (R)	-	-	-	-	16.4 (0)	6.2 (0)	0 (0)
	30 (P)	-	-	-	-	**77.2** (8.5)	**37.7 (37.6)**	0 (0)
	60 (P)	-	-	-	-	**81.5** (0)	**38.6** (13.3)	0 (0)
	70 (P)	-	-	-	-	23.1 (0)	**37.9** (0)	0 (0)
	30 (U)	-	-	-	-	**50.5** (0)	**38.3** (0)	0 (0)
	60 (U)	-	-	-	-	0 (0)	0 (0)	0 (0)
	100 (U)	-	-	-	-	0 (0	0 (0	0 (0)
Y10	30 (R)	-	-	-	-	8.0 (0)	6.1 (0)	0 (0)
	30 (P)	-	-	-	-	22.4 (0)	8.2 (0)	0 (0)
	60 (P)	-	-	-	-	23.6 (0)	6.1 (0)	0 (0)
	70 (P)	-	-	-	-	0 (0)	0 (0)	0 (0)
	30 (U)	-	-	-	-	28.5 (0)	7.1 (0)	0 (0)
	60 (U)	-	-	-	-	0 (0)	2.9 (0)	0 (0)
	100 (U)	-	-	-	-	0 (0)	0 (0)	0 (0)
Y11	30 (R)	-	-	-	-	-	0 (0)	0 (0)
	30 (P)	-	-	-	-	-	-	-
	60 (P)	-	-	-	-	-	-	-
	70 (P)	-	-	-	-	-	-	-
	30 (U)	-	-	-	-	-	0 (0)	0 (0)
	60 (U)	-	-	-	-	-	0 (0)	0 (0)
	100 (U)	-	-	-	-	-	0 (0)	0 (0)

** Y8: January-February 2017

*** Y11: October-November 2017

6.2 Discussion

6.2.1 Soil properties at young roadside trees in Hamburg

Young trees in Hamburg were planted in planting pits as a rule. These planting pits were established to support the growth of the young trees and contain planting pit substrates. Therefore, these planting pit substrates must fulfill special requirements for the usage in urban areas, e.g., they should not be too compact, but should have a good water holding capacity. Existing recommendations for planting pit substrates, given by the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) (FLL 2012, FLL 2015), are used as basis for the building of planting pits in Hamburg by the district administrations in general. The goal of these guidelines is to avoid high compactions, and to guarantee good water and air availability for the tree. Therefore, they define not only the necessary properties of planting substrates, but also the size of the planting pit, the build-up of the substrates and how the trees should be planted to receive optimal results.

Accordingly, the planting pit substrates analyzed in this study should fulfill the different requirements, which were described in those recommendations.

For planting pits in Hamburg, it is assumed, that the tree roots can leave the planting pits and grow into the urban soils at many locations (Doobe, BUE, personal communication, 2015). According to FLL (2012), planting pits should have a minimum size of about 12 m^3 or the planting holes should have a minimum diameter of 1.5-fold of the root system, if the soils are suited for the trees. In this study, only the planting pits of Y7 and Y8 were bigger than the 12 m^3, while all others were smaller. Most of the used planting pit substrates were mixed according to the properties described in the FLL (2012) and should therefore have a good suitability as a substrate for young trees.

The FLL (2012) recommends different particle size distributions for two different types of planting pits (Table 12). They differentiate between planting pits, which are overbuildable, and pits, which are not allowed to be overbuilt. Overbuilt means, that the planting pits additionally fulfill the function as building ground for traffic areas. Y7 and Y8 are overbuilt planting pits; the others seem to be not overbuilt planting pits.

Table 12: Requirements for planting pit substrates and their production/installation. Source: adapted from FLL (2012).

Property	**Requirements**	
	not overbuildable planting pit	**overbuildable planting pit**
Texture	0/11 to 0/32 mm	0/16 to 0/32 mm
	≥ 30% by weight of diameter = 0.0063- 2.00 mm	
Water permeability k_f	≥ 5.0 x 10^{-6} m/s and ≤ 5.0 x 10^{-4} m/s	
Water capacity	≥25 vol.-%	
Air capacity	≥ 10 vol.-% at max. water capacity or ≥15 vol.-% at pF 1.8	
pH value	pH 5.0 – pH 8.5	
Soil organic matter	1 – 4% by weight	1 – 2% by weight
Salt content	150 mg/100 g (water extract) 100 mg/ 100 g (saturated gypsum dissolution)	
Nutrient content	Declaration according to Düngemittelverordnung[2], nutrient addition during planting	
Deformation modulus	-	≥ 45 MN/m^2
Degree of compaction	83% - 87%	≤ 95%

The data of the particle size distribution of this study are not directly comparable to the recommendations of the FLL (2012), because in this study, the skeleton content was not analyzed in detail and they used other sieve-widths than the standard sieve-widths used

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[2] Verordnung über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln (Düngemittelverordnung - DüMV) vom 5.12.2012, BGBl. I S. 2482. https://www.gesetze-im-internet.de/d_mv_2012/D%C3%BCMV.pdf

commonly in soil science. That is why not all recommendations according the texture like the sizes of the skeleton content could be checked. First, the recommendation that at least 30% of the material should be sand with an equivalent diameter of 0.063 to 2 mm was checked (Table 13). Further, the FLL (2012) recommends, that the percentage of smaller particles (<0.063 mm) should be 5 to 25% (not overbuilt) or 5 to 15% (overbuilt). The first recommendation was fulfilled in all substrates; the sand content ranged between 35% and 88% (Table 13). The second requirement was not fulfilled for all substrates: At one site (Y4b), the deeper planting pit substrate had a lower percentage of clay and silt content (4.9%) and at site Y8, clay and silt the uppermost covering substrate summed up to 3.5%. The maximal values of fine particles were only exceeded in the lowest planting pit substrate of Y4c (37.0%). A graphic in the FLL (2012) showed that the skeleton content should be 17-61% in not overbuildable planting pit substrates and 25-61% in overbuildable planting pits. The planting substrates in Y4a (8.2% and 7.1%), Y4b (8.2% and 7.1%), Y5 (12.3%) and the lower planting pit substrates in Y3c (9.5%) and Y4c (11.9% and 3.8%) had lower values (see Appendix III: Table 21).

Nevertheless, the texture requirements given in the FLL (2012) is only meant as guidelines; they wrote that the properties of the substrates were more important, so that substrates with other textures can fulfill the requirements for tree planting substrates. Therefore, the physical properties of the substrates, which do not fit exactly into the given range of texture properties, have to be checked for final evaluation. In the urban soils next to the planting pits, the content of soil particles smaller than 0.063 mm was lower than 5% in 9.8% of the analyzed layers (data not shown). That shows, that at these sites, the urban soils are very sandy, which may lead to soil properties, which are not optimal for tree growth.

The humus contents in Table 22 (Appendix III) were often higher than the soil organic matter content of 1-4% or 1-2% depending on the planting pit type, which is recommended by the FLL (2012). That is caused by different ways of calculating the humus content: The values of Table 22 (Appendix III) are the percentages of humus in soils fine earth, which means particles <2 mm. In contrast, the values recommended by the FLL (2012) relate to the total soil with skeleton.

They recommended 1% to 4% organic matter in not overbuildable planting pits and 1% to 2% in overbuildable pits (Table 12). Because of the high skeleton content of 32% in average in the planting pit substrates of this study, the humus contents were often higher (Appendix III: Table 22). However, with considering the skeleton content, the values of the analyzed soils fit the recommendations at most sites in the deeper planting pit layer (Table 14).

Table 13: Sand and silt+clay content in relation to the soil substrates including the skeleton content of the planting pit substrates of Y1 to Y11.

Profile no.	**Depth of planting pit substrate** [cm]	**Sand content in relation to the soil with skeleton content** [%]	**Silt+clay content in relation to the soil with skeleton content** [%]	**Profile no.**	**Depth of planting pit substrate** [cm]	**Sand content in relation to the soil with skeleton content** [%]	**Silt+clay content in relation to the soil with skeleton content** [%]
Y1	0-25	43.5	5.6	Y4b	0-40	79.6	12.1
Y1	25-55	39.9	5.8	Y4b	40-70	88.0	*4.9*
Y2a	0-40	43.1	12.6	Y4c	0-10	40.1	9.5
Y2a	40-70	59.7	5.6	Y4c	10-40	74.0	14.1
Y2b	0-45	52.6	12.4	Y4c	40-70	59.2	37.0
Y2b	45-70	73.3	8.4	Y5	0-70	80.7	7.0
Y2c	0-40	45.7	11.6	Y6	0-35	51.4	10.6
Y2c	40-60	67.2	10.4	Y6	35-70	73.3	5.9
Y3a	0-35	44.0	10.2	Y7	0-10	42.2	14.1
Y3a	35-60	75.7	6.1	Y7	10-100	35.0	7.1
Y3b	0-35	60.7	6.9	Y8	0-5	40.8	*3.5*
Y3b	35-50	56.0	11.4	Y8	5-100	46.9	10.5
Y3c	0-40	45.4	9.3	Y9	0-60	49.4	14.6
Y3c	40-70	83.3	7.2	Y10	0-70	59.6	11.1
Y4a	0-40	80.5	11.2	Y11	0-70	-	-
Y4a	40-70	80.8	17.2				

Only at Y3b (6.0%), the humus content was >4% in a depth of more than 40 cm. In the planting pits Y7 and Y8, the humus contents were 1.0% and 2.3%. Therefore, the substrate in Y8 exceeded the recommended 2% for overbuilt pits, but fitted in the range for not overbuilt pits. The only planting pits with too low values in 40-70 cm depth were Y4a and Y4b. Here, the humus contents of 0.3% and 0.6% were lower than the recommended 1% in the lower planting pit substrates. In 53.4% of the upper planting pit substrates of the two-layer-planting pits, the recommended values were exceeded. In two (Y9 (10.5%) and Y10 (4.9%)) of the four single substrate planting pits (Y5, Y9, Y10 and Y11), the humus contents exceeded the recommended 4% for not overbuilt pits. According to the FLL (2012), too high organic matter contents can cause problems with anaerobic decomposition and settling. Therefore, high organic matter contents should be avoided, even if a higher humus content can increase the nutrient situation and can increase the water holding capacity (FLL 2012). Nevertheless, Krieter & Malkus (1996) observed very low rooting in planting pit substrates with only low organic matter, which were used as the bottom layer of two-layer planting pits. In those pits, the main rooting zones were concentrated in the uppermost humus richer substrate, which can lead for example to a destabilization of the tree (Krieter & Malkus 1996). Consequently, it is important to hold the balance between too low and too high organic matter contents in the substrates, because both can cause growth problems of the trees.

In contrast to the planting pit substrates, 9.7% of the analyzed layers of the urban soils around the planting pits had a humus content >4% and 45.2% a humus content smaller than 1% (data not shown). That means that in the urban soils around the planting pits a shortage of humus content occurred more often than an oversupply. Trees planted planting pits in areas, where the surrounding urban soils have very low humus contents, can depend on the nutrient availability in the planting substrates.

The general recommendation of the FLL (2012) of a pH value between pH 5.0 and pH 8.5 was fulfilled in all planting pit substrates (see chapter 6.1.2.2 and Appendix III: Table 22). The pH value was exactly 5 in the uppermost planting pit substrate at the planting pit Y4b. Therefore, this site should be regularly observed, so that a decrease of the pH can be early detected.

Salt contents should be lower than 150 mg/ 100 g soil, measured in water extract (FLL 2012). The mainly used salt is NaCl (BSU 2012). In this study, the amount of Cl and Na were measured at five sites. At these sites, the values were much lower (see Appendix III: Table 23).

Table 14: Humus content in relation to the soil substrates including the skeleton content. Data of the planting pit substrates of Y1 to Y11. Percentages of the humus content >4% are marked in bold and <1% in italics.

Profile no.	Depth of planting substrate [cm]	Humus content in relation to the soil with skeleton content [%]	Profile no.	Depth of planting substrate [cm]	Humus content in relation to the soil with skeleton content [%]
Y1	0-25	3.6	Y4b	0-40	2.0
Y1	25-55	3.1	Y4b	40-70	*0.6*
Y2a	0-40	**11.2**	Y4c	0-10	**10.8**
Y2a	40-70	2.3	Y4c	10-40	3.8
Y2b	0-45	**9.9**	Y4c	40-70	1.0
Y2b	45-70	1.0	Y5	0-70	2.0
Y2c	0-40	**9.7**	Y6	0-35	**8.0**
Y2c	40-60	3.1	Y6	35-70	1.9
Y3a	0-35	**11.4**	Y7	0-10	**6.3**
Y3a	35-60	1.7	Y7	10-100	1.0
Y3b	0-35	3.4	Y8	0-5	*0.2*
Y3b	35-50	**6.0**	Y8	5-100	2.3
Y3c	0-40	**8.0**	Y9	0-60	**10.5**
Y3c	40-70	1.4	Y10	0-70	**4.9**
Y4a	0-40	2.4	Y11	0-70	*0.7*
Y4a	40-70	*0.3*			

Based on the sampling method without undisturbed sample taking, further recommendations by the FLL (2012) like water capacity, air capacity, and water permeability could not be checked. All together, the organic matter was often higher in the upper planting pit layers, but possible negative effects like too high water storage or settling were not observed.

It is known that urban soils can be very heterogeneous (e.g. Craul & Klein 1980, Craul 1985, Pouyart et al. 2010, Greinert 2015), which was demonstrated in this study for soils at established roadside trees in chapter 4, too. Other studies like Chau & Chan (2000) showed that planter soils show large heterogeneities between different sites in a city and within sites, too. They pointed out, that in Hong Kong the planter soils had high variabilities in pH, soil organic matter, nitrate, total and available phosphorus and exchangeable potassium, while texture, total Kjeldahl Nitrogen, ammonium and exchangeable calcium did not differ that much. In this study, the sand, silt and clay contents of the planting substrates showed a slightly lower standard deviation than the different urban substrates around them, which means, that their variability is smaller. In contrast to that, the standard deviation of 17.0% of the skeleton content was higher in comparison to the standard deviation of the skeleton content of urban soil layers (8.4%). The standard deviation of the humus content was high in the planting substrates, too (standard deviation of humus content of planting substrates: 6.7%; of urban soil layers: 2.6). Therefore, the degrees of soil heterogeneity of planting pit substrates and of their surrounding urban soil variate, when different soil characteristics were considered.

Interesting were the differences between the planting substrates in the same streets (Y2, Y3, Y4). At these sites, the planting pits were filled with the same substrates from the same company at each street at the same time. Nevertheless, differences between the planting substrate were found, especially at the sites Y3 and Y4. For instance, in the planting pit Y4c three planting substrates were used instead of two as in Y4a and Y4b. The additional layer in Y4c was reaching from the surface to 10 cm depth. It contained a higher clay content, a higher humus content and a much higher skeleton content, which was 50.3%, while it was around 8.2% in the top layers of the other two planting pits. In addition to that, the clay content in the planting substrate of 40-70 cm depth contained with 14.4% clay content more clay than the substrates in the other two planting pits (4.9%, 2.5% clay content). Further, Y4b had planting substrates with lower pH values (pH 5.0 and 5.3) than Y4a and Y4b (range: pH 6.1-6.9). This indicates a not homogenous mixture of the substrates, which can led to different substrate properties in adjacent planting pits.

Overall, most of the substrates fulfill the requirements of texture, pH value and salt content, which are given in the FLL (2012). Therefore, the substrates were comparable with substrates used in other areas, which were planted according to these or similar recommendations. In other countries like Switzerland, Sweden or USA, planting pit substrates with high percentages of skeleton content were used, too (Schönfeld 2017). For instance, Jim (1998d) found that the planting pits at roadsides in Hong Kong have a mean of 42.9% stone content. That is around 10% more than the average of this study found in Hamburg. He measured a mean values of 81.1% sand, 12.2% silt and 6.7% clay content in the planting pits. These contents were similar to the data of this study (mean values: 84.7%

sand, 9.7% silt and 5.6% clay content). Other properties at his soils were very different, as well as the climate, which affects the suitable substrate properties for the location. For example, the mean pH of 8.65 in the study of Jim (1998d) was much higher than the mean pH of 6.6 in the planting pit substrates in Hamburg, found at the study sites of young trees in this study. The pH values were also lower than the pH of planting pit substrates used in for the project “Stadtgrün 2021” in Würzburg, Kempten and Hof/ Müncheberg, which had a pH of about 7.5 in 2010 (Klemisch 2017). There, the pH was decreasing in the following years to pH 7.1 or 7.2 in 2016. Most of the trees, planted in central Europe prefer neutral or slightly acid pH-values below pH 8 or 7.5, depending on the tree species (Goss and Schönfeld 2014). Therefore, the pH values of the planting pits of this study were suitable for the most common species. In addition to that, the pH of the planting pit substrates were similar to the surrounding soil. Thus, difficulties of root growth caused by pH differences, when the tree roots grow from the planting pits into the urban soils, are nor expected.

Few recommendations for nutrient situations in soils for young oaks and maple were found in literature. Hence, the nutrient situation could not be evaluated in this study. Nevertheless, the medians of the nitrogen content of 0.21% in the planting substrates and of 0.12% in the surrounding urban soil were higher than the mean nitrogen contents used in planting pit substrates for the project “Stadtgrün 2021” in Würzburg, Kempten and Hof/Müncheberg. They were ranging between 0.02% and 0.06% in 2010 and between 0.03% and 0.07% in 2016 (Klemisch 2017), whereas the increase is a result of addition of fertilizers in 2013 and 2014, because of the nutrient status, which values were assumed to be low despite mainly normal nitrogen contents in the leafs of the trees (Klemisch 2017).

6.2.2 Soil water tension and consequences of given water availability at young roadside trees in Hamburg

Soil drought can not only occur at established roadside tree sites (see chapter 5), but also at sites of young roadside trees (see chapter 6.1.3). The soil water tension (SWT) measurement is a well-established measure for soil water availability for plants and is used for example in agriculture to manage irrigation (Shock & Wang 2011). During the last years, it is tested and used for controlling the water tension of young urban trees in different cities of Germany. For instance, the water tension measurements were tested in Hamburg (Wohlers, district office Hamburg-Mitte, personal communication, 2016), used for controlling of inflow of precipitations and effects of irrigations in Berlin (Balder & Borgmann 2017, Borgmann et al. 2017) or used for scheduling of irrigations in Leopoldshöhe (Borgmann et al. 2017).

The measurements of this study show that the SWT in the three different substrate types at young trees (root ball substrate, planting pit substrate and urban soil) reached the highest values in summer and autumn 2016 and 2017, while the SWT were low in winter and spring (chapter 6.1.3). In general, this is caused by higher evapotranspiration rates during summer and fall, because of higher air and soil temperatures as well as higher radiation. In addition to that, the young trees and the vegetation on the ground (if existing) uses more water in the vegetation period than in winter, so that the soils tend to dry at the upper soil layers during these seasons (Blume et al. 2010).

At all but one tree moderately dry phases of soils (SWT ≥750 hPa) occurred. These conditions can lead to reduced growth of trees, which was shown by Shock et al. (2002). They demonstrated that young poplar trees with irrigation criteria of 750 hPa had a reduced growth in comparison to trees with irrigation criteria of 250 hPa. They found that an irrigation criterion of 500 hPa leads to reduced growth, too. Based on the different tree species analyzed in this study, which were expected to be more drought resistant than poplar trees, a soil water tension of 750 hPa as threshold for moderately dry phases, which had the potential to restrict tree growth, was decided to use here.

The data of this study show, that the root balls substrates had longer dry phases than the planting pit substrates. In the root ball substrates, the SWT were higher than 750 hPa at 80% of the measured tree sites in fall 2016 (n= 10) and at 88% of the sites (n= 17) in summer and fall 2017 (Table 11). The urban soils were moister than the planting pit substrates and had mainly dry phases only in 30 cm depth, while deeper areas stayed moist. That the space near the root ball had longer dry phases in the year of planting can be explained by the root distribution. When the trees were planted, they had roots only in the root ball, which start to grow into the planting pit substrates of the planting pits during the first vegetation period. In the following years, the root systems are increasing and grow further into the planting pit substrates and are expected to grow into the surrounding urban soil, if the soil quality is suitable. Krieter & Malkus (1996) showed with excavations of young trees (*Tilia pallida*) in 14 German cities, that roots of nearly all analyzed young trees reached the lateral planting pit boarders in the second year after planting. That means that the trees extract soil water mostly from the soil of the root ball and the planting pit substrate during the first two vegetation periods. Schönfeld (2017) confirmed the fast and intensive rooting of trees in planting pit substrates, which were mixed according to the recommendations of the FLL (2010), ZTV – Vegtra – Mü (Landeshauptstadt München Baureferat Gartenbau 2016) and substrates used in the project "Stadtgrün 2021" (Schönfeld 2017), during the first years after planting; all these mixtures were based on the findings of Krieter & Malkus (1996). Therefore, it is expected, that the roots of the young trees of this study, which were planted in 2016 had in the first vegetation period a rooting system, which was mainly located in the root ball, but was expanding into the planting pit substrate for 2017. In contrast, it was expected, that the rooting space of those trees, which were planted earlier (sites Y7, Y8, Y9 and Y10), were larger and at least growing in the complete planting pit.

This study shows that the intensities of drying of the three different soil substrate types around young urban trees increased in the second year after planting (Table 11) even with higher precipitation rates in the second year (Table 6). It is assumed that the roots were growing further into the planting substrate in the second year and use water from the surrounding of the root ball, too, which led to a more intensive drying in the area around the root ball. In addition to that, the young trees were growing and so they increased their water demand from year to year, especially in the first years after planting. This could have led to the longer soil drought phases in the second year. In 2017, dry phases occurred in deeper soil layers than in the first year of measurement, too, which can be an evidence for extension of the root system into the depth. Furthermore, the tree crowns were getting bigger and denser with the aging. Nielsen et al. (2007) indicated that large parts of precipitation do not enter the soil matrix of planting pits because of extensive interception by buildings, bark mulch and tree crown. Therefore, the growing tree crowns could have increased the interception and could have reduced the water reaching the soil after precipitations to a higher amount in the second vegetation period.

In comparison to urban soils in 20 cm and 40 cm depth at established roadside trees, where dry phases occurred (see chapter 5.1.3), planting pit substrates in 30 cm depth at young urban trees in Hamburg had longer moderately dry phases (SWT ≥750 hPa) in summer 2017 and similar long dry phases in fall 2017 (around 38% of the days in fall). Further, the urban soils at established trees often had longer dry phases in the depth, while the urban soils below the planting pits in 100 cm depth stayed mainly moist. These differences can be explained by the differences of the rooting system, which is much bigger at established trees, but still small and limited in the planting pit at the young trees.

The differences in the course of measured SWT between the sites of the young roadside trees can be caused by differences of the site conditions, whereby single factors interact with each other. For instance, differences between the local climate (e.g. Kjelgren & Clark 1992), soil properties and sealing (e.g. Kjelgren & Montague 1998) affect the water availability in the soils and the growth of trees. The soil water content can also be affected by the trees itself (e.g. Clark & Kjelgren 1990, Kjelgren & Montague 1998), for example by root distribution, water demand or tree species specific water usage patterns. Lu et al. (2010) found that the survival of young street trees dependent on the location of the tree planting. They detected that street trees have better survival rates, when their tree pit is located in lawn stripes (78.1% survival rate) and not in sidewalk cutouts (72.9% survival rate). Trees at curbs had a higher survival rate (76.1%) than trees planted in street medians (53.1%). A high traffic volume effects the survival rate negatively (60.3%) compared to location of moderate (68.4%) or light traffic volumes (78.6%). The size of the tree pit had no significant effect on the survival rate during the first years, but the authors assume that it will affect the rate in later years, when the tree is growing and using more space. Bühler et al. (2007) had shown for planting pits in Copenhagen that increased rooting space in the depth in combination with larger unsealed surfaces lead to higher growth rates of the trees.

In this study, it was observed that soils at tree sites exposed to the sun like at open squares or traffic islands without shading (Y5, Y3) were warmer than soils in areas with more shading (Y1, Y4). The average temperature differences in summer (June to August 2017) was up to 6°C in 30 cm depth. Those temperature differences can affect the growth of roots. Too low or too warm temperatures slow the growth of roots, the optimal temperature is depending on the species (e.g. Lyr & Hoffmann 1967, Henninger & White 1974, Teskey & Hinckley 1981, Pregitzer et al. 2000). Higher temperatures can raise the evapotranspiration and decrease the water availability in the soil. At the site Y4, which had the lowest soil temperatures because of low sealing and high shading, the lowest SWT during the measurement period were measured. In contrast to that, the two sites with the highest soil temperatures (Y5 and Y3), because of high soil sealing between 70% and 90% and low shading by other vegetation or buildings, exhibited high SWT during summer and fall 2017. That is in accordance with the findings of Kjelgren & Clark (1992) and Kjelgren & Montague (1998). Kjelgren & Clark (1992) indicated that plaza trees had lower growth, measured with leaf area, shoot elongation and diameter increment, than mature street trees in urban parks and street canyon sites in Seattle. Kjelgren & Montague (1998) showed for isolated trees, that they intercept more long-wave radiation because of higher surface temperatures over paved asphalt surfaces in comparison to trees over a cooler turf surface. At sites with mixed surfaces with paved and vegetated parts, this effect varies with the amount of sealing. Further, they showed by using a model that the amount of water, which loses the trees over asphalt, is dependent on the degree of stomatal closure. The effect of surface sealing was reported by Sand et al. (2018). They found that trees have reduced shoot and stem growth, when there is only a small fraction of permeable surface in the tree crown area. Duthweiler et al. (2017) had shown, that sealed surfaces reduce the cooling effect of the trees in comparison to unsealed surfaces.

Nevertheless, in this study the SWT were not systematically lower at all sites, which had higher shading, lower soil temperatures and lower sealing, than at exposed sites. For example, the site Y1 was shaded by other trees and had low soil temperatures, but the SWT were high in summer and fall 2017. That shows that the shading and the soil temperature alone were not enough for estimating phases of dry soil and that the urban tree sites are complex systems, where many factors influence the soil water availability and the potential soil drought.

At the site Y4, the three soils at the three trees showed differences of their soil water availabilities in 2016 and 2017. Therefore, it become apparent that the SWT can vary to a high extend within small areas. Here, the variabilities were probably not caused by differences of the microclimate (e.g. precipitation rates), because the trees were not more than 100 m apart from each other planted next to the same sidewalk. In addition to that, the surrounding of the trees was very similar. Nevertheless, the differences might be caused by different growth of the three trees or the heterogeneity of the sites. The degree of soil sealing was very low at all three trees sites, so that effects by differences of the sealing could be excluded. It is assumed that other site conditions had affected the soil water tensions to a higher degree. At first, there was a gradient of the groundwater level. Y4a had the greatest distance of about 3 m to the groundwater, while the surface at Y4c were only about 1 m over the groundwater table (BUE, 2015a), so that the analyzed soil at Y4c could be stronger affected by capillary rise of groundwater. Another aspect, which influences the water budget in the soils of Y4, was the different distance to a noise protection embankment. Y4c is direct adjacent to the noise protection embankment. That might have caused additional water inflow from runoff from the embankment. In addition to that, the tree at Y4c is slightly closer located to shrubbery, so that more shading of the tree and the planting pit surface was expected. Furthermore, the planting pit substrates were slightly different. At 4c, the clay and silt contents in the bottom layer of this planting pit were higher and the skeleton content were lower than the recommended values of the FLL (2012). Therefore, the substrate in the bottom of the planting pit at Y4c has probably a lower pore volume and a higher water holding capacity. All these factors might have contributed to the low SWT, which did not reach 750 hPa in the measurement period from summer 2016 to December 2017. This was the only analyzed young urban tree of this study, where no phases with soil drought occurred. Therefore, no drought stress was expected for this tree, but further measurements are needed to detect, if stagnant moisture is a problem of this site and if the texture of the deepest planting pit substrate layer is responsible for it, which is not fitting in the recommended particle size distribution of the FLL (2012).

Not only the described differences of the local site conditions can have small-scale effects on the SWT. Differences of the growth and differences of the vitalities of the trees can affect their water demand, which changes the soil water content and the SWT, too. The BUE and the district offices of Hamburg conducted growth measurements at the trees. Some trees were part of the GALK-test (GALK e.V. 2015), while the others were monitored by the district offices as part of the normal rating for the Straßenbaumkataster (street tree cadaster) (BUE 2015f). In further studies, the results of tree growth and vitality will be analyzed in context of the results of this study. Additional analyses of carbon isotopes, which are a measure for drought stress, were done at some of the trees by Reisdorff (2018, personal communication).

The first results of carbon isotopes analyses of leafs by Reisdorff (2018, not published data) gave hints for drought stress at sites of young roadside trees. The accumulation of $^{13}CO_2$ in leafs can be a sign that the tree has closed its stomata and therefore reduced his water usage because of stress. These reactions are tree species specific. In tests, Reisdorff (2018, unpublished data) found that *Quercus cerris* reacts to drought with closing of stomata. With this reaction, it loses less water, but also receives less CO_2. Therefore, this species is accumulating $^{13}CO_2$ in its leafs to a higher amount, when the soil is dry. At the sites Y2 and Y4, $^{13}CO_2$-analyses were done at the same tree species (*Q. cerris*) in September 2016. Reisdorff (2018, unpublished data) detected significant higher amounts of ^{13}C and therefore lower $\delta^{13}C$ (whereas $\delta^{13}C= (((^{13}C/^{12}C)_{Sample}/(^{13}C/^{12}C)_{Standard})-1)*1000$ [‰]) in the leafs of the trees at the site Y4 in comparison to site Y2 (Figure 51). This is consistent with the results of the SWT measurements of this study, which showed higher SWT at Y2 and accordingly higher potential drought for the trees. The results of Reisdorff (unpublished data, 2018) confirmed that the drought of soil substrates in the planting pits led to stomata closure and therefore affects the trees.

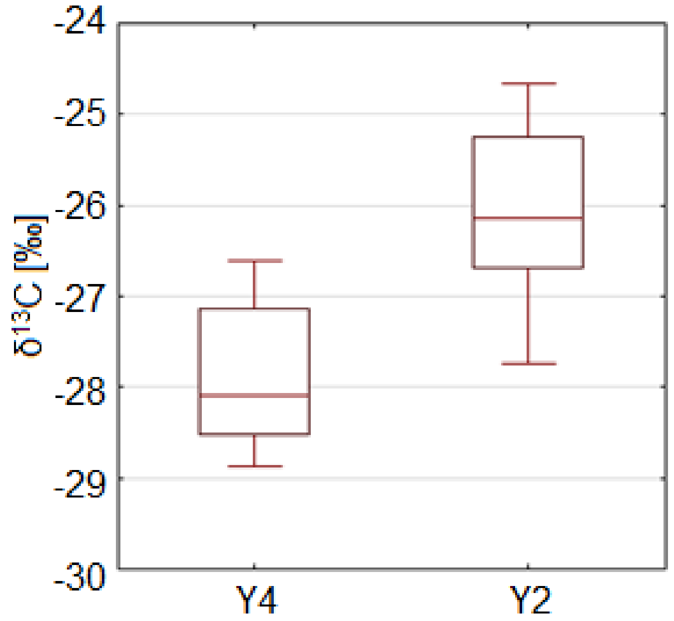

Figure 51: δ^{13}C in leafs of *Q. cerris* at the sites Y4 and Y2. Source: Reisdorff (2018, unpublished), changed.

It is known, that drought can decrease the vitality of young trees. According to this, young trees are irrigated during their first years after planting. Plietzsch (2017) highlighted that a sufficient irrigation is the most important factor for the establishment of young trees after planting at a new location. Young street trees in Hamburg are also irrigated during their first three years at the new planting sites (Doobe (BUE, personal communication) 2015, Herrmann and Schlote (district office Altona, personal communication) 2015). The analyzed young trees of this study were irrigated too (Strachwitz 2017). Nevertheless phases of dry soil with SWT ≥750 hPa occurred. The irrigations led only to decreases of SWT for a few days This means that the irrigated water could not be stored in the planting pits for a longer period, but was infiltrating into deeper layers (see also Strachwitz 2017), which means that the irrigations were not sufficient over longer time periods. The water removal by tree root uptake and evapotranspiration may have contributed to the fast drying after irrigations. Therefore, the effect of irrigations were only short-time effects. That highlights that the substrates had a suboptimal texture for water retention during dry periods with low precipitations. Their high skeleton and sand content (see chapter 6.1.2.1) is likely to increase the water flow into deeper soil layers and is responsible for the low water holding capacity. It is possible, that substrates with a higher percentage of finer texture can increase the water retention. A more frequent irrigation may also help to avoid longer phases of dry soil and so prevent water shortages for the young urban trees. Dreßler et al. (2017) found, that different tree species show different reactions to varied irrigation settings. Therefore, species related reactions to drought and irrigations should be considered.

In the year 2017, the soil got dry even in the rainy summer and autumn, which shows, that the precipitation alone is not enough to moisture the soil and that irrigation was needed to keep the soils moist. At Y7, Y8, Y9 and Y10, the trees were planted in 2013 or earlier, so that less or no irrigation were conducted in the monitoring years. Based on the root analyses of Krieter & Malkus (1996) and Schönfeld (2017), it is assumed that the tree roots already reached the boarders of the planting pit and were using water from larger volumes than the trees, which were planted in 2016. In summer and fall 2017, the planting pit substrates became dry at the sites Y7, Y8, Y9 and Y10 – often dryer (higher SWT and longer drought phases) than the soils at sites with one- and two-year old trees. An exception was the site Y10. Here, the phases with SWT ≥750 hPa were shorter (less than 30% of summer and 10% of the days in fall in 2017) than at most of the other sites (see Table 11). This can be caused by the location, which is closely to buildings so that higher shading and therefore less water demand is expected. Other factors like soil properties or tree vitality may also have led to the lower and shorter phases with dry soil. Nevertheless, phases with high SWT (≥750 hPa) occurred here, too. This means that older trees would benefit from irrigating, too. Tree species, which react fast to soil drought, would probably have a better growing performance, when these dryer phases with water shortages near the root balls were reduced.

That practiced irrigation were not always sufficient to keep the soils moist, were shown by Borgmann et al. (2017), who found for instance that five irrigations each with 70 l water during late summers did not reach deeper soil layers (60 cm and 90 cm) in soil substrates at young trees in Leopoldshöhe in 2016. Therefore, in this case, the amount of water was too small. This showed that the problem of dry soils can occur at sites with irrigations and are common problems in other cities, too. Nielsen et al. (2007) found that irrigation increased the water content for a limited time and helped tree growth in planting pits in Copenhagen, but the irrigation (7 times from May to August) did not prevent the depletion of soil water resources. This study can confirm that irrigations decrease the SWT for a short time at the young urban trees in Hamburg. Nevertheless, phases with dry soils occurred here, too. The normal conducted irrigations in addition to the precipitation were not sufficient to prevent dry phases for the young trees in the planting pits in Hamburg. Therefore, a controlling of irrigations is necessary as well as an adapted irrigation management system to guaranty moist soils without phases of drought, which will support the growth of young urban trees.

6.3 Summary

The young roadside trees were planted in planting pits with special substrates, which should optimize their growth. This study showed that the substrates used in the 17 studied planting pits in Hamburg had a high skeleton content (median= 34.7%) and were mainly sandy. All of them fulfilled the recent recommendations regarding the sand content (≥30%) by the FLL guideline (FLL 2012). Other specifications regarding the texture were no criterions of exclusion as a planting pit substrate, because the resulting physical soil properties like the water holding capacity were the critical parameters. Additionally the studied substrates had pH values, which were in the given range of pH 5 to 8.5 (FLL 2012). The humus content was higher than the recommended 4% (FLL 2012) at 64% of the studied planting pits in at least one of the used planting pit substrates. In three substrates, the humus content was lower than 1%. Therefore, the humus content was the most critical parameter of the recommendations of the substrate quality, recommended by the FLL (2012), which could be checked in this study.

The monitoring of the SWT showed that phases of moderately dry soils occurred - even in years, when the trees were irrigated and the precipitation rates were higher than the 30-year-average precipitation rates. The root ball dried at first, then the planting pit substrates and later the surrounding soil. The soil near the surface reacted faster than deeper layers to drought. At most of the sites, the soil substrates became dryer in the second year after planting. Especially, the planting substrates experienced a stronger drought. That can be explained by the growth of trees, their developing root systems, their higher water demand and possible higher interception rates caused by their thicker crowns. Therefore, the increased water use led to more intensive drought phases of the soils, whereas effects of the higher precipitation rates during the second observed vegetation period were not visible.

Most of the young trees of this study got additional water by irrigation during summer. These irrigations increased the soil water availability in the soil substrates. Nevertheless, the SWT increased shortly after the irrigations, so that the SWT were again reaching high levels (≥750 hPa and ≥2000 hPa), even in moist years. The effect of the fast drying of soils might be increased by the texture of the planting pit substrates with their high content of sand and skeleton. The observed dry phases of the planting substrates during summer and fall 2017 might have caused reduced growth of the young trees, because young trees with small root systems dependent on the water availability in the planting pits.

Thus, controlling of irrigations would be necessary as well as an adapted irrigation management system to guaranty moist soils in planting pit substrates without phases of drought, so that the possible drought stress for young urban roadside trees will be reduced.

7. Synthesis

This study was conducted to analyze the potential soil affected drought stress of roadside trees in the city of Hamburg. For this objective, different methodological approaches have been applied. As part of the study consisted of analyses of field moisture and gas exchange dynamics, the presented results were not only restricted by the number of profiles studied but also by the weather situation in the two analyzed years 2016 and 2017. Thus, some of the results may be revised by future investigations. Additionally, this study did not include the results of the measurements on the sap-flow dynamics of the trees at the intensively studied sites. Thus, the conclusions focus on potential drought stress and do not correlate these findings with actual drought stress within the trees.

Within this and the following chapter, the findings of this study were synthesized in the answers of the research questions and conclusions were drawn regarding future research questions as well as the management of soils at sites of roadside trees.

(1) Which properties of urban soils increase the stress probability for urban roadside trees in Hamburg?

a) Which site characteristics and physical soil properties (e.g. texture, compaction) relevant for increasing the potential risk of soil drought?

This study confirms that soils at sites of urban road trees are typically influenced by human activities down to at least 1 m depth. The construction of buildings, streets, pathways as well as the underground installation of pipes and cables results in a change of the naturally occurring soils. The soils show features of the excavation or mixing of the natural materials and in most cases the coverage with other, predominantly sandy soil materials. The soils thus have to be characterized as young formations and are classified as Terric Anthrosols and Transportic Arenosols. The suitability of these anthropogenic influenced soils and their given properties for tree growth is not well known. Because of climate change, the soil water availability at urban street tree sites and the risk of soil drought is of special interest in order to assess and safeguard the vitality of urban trees for future.

Despite of climatic factors, the ability of the soils to reduce drought stress is controlled by their ability of infiltration and their potential to store plant available water in the rooting space. In general, the investigated soils were quiet similar in their overall properties. However, by comparing soil profiles located close to each other (within 5 m distance) a small-scale variability was apparent. In general, the soils were mainly composed of sand-rich (42.1% loamy sands) and pure sandy materials (54.3%); the studied soil layers had in average a sand content of 86.3%. In the uppermost 100 cm depth, the soils had mainly a low (60 to <140 mm) or medium (14 to <22 mm) available water capacity according to Ad-hoc-Arbeitsgruppe Boden (2005). This soil characteristic effects a potential risk of soil drought. This was reflecting in the positive correlation of the available water capacity with the root density (Pearson: r=0.658, p<0.001).

The water storage capacity of the soil is partly set out of function, if the soil is sealed with sorts of pavement or if the soils infiltrability is so low, that part of the rainfall is lost by run-off. The percentages of surface sealing of the studied sites at established roadside trees were ranging between 16% and 92%. The sealing reduces not only the water infiltration into the soil below them, but also it can reduce the evaporation and aeration. At sites, which had only low vegetation or bare soil at the unsealed parts of the surface, the average effective bulk density of the uppermost soil layer of 1.39 g/cm³ was higher than the average effective bulk density of 1.27 g/cm³ at vegetated sites. Accordingly, the infiltration was especially low at sites with low or no vegetation. At these study sites, the measured infiltrability was “low” or “low to medium” according to the classification of Wolff (1993). Therefore, it is assumed that at sites with high sealing and low infiltration rates, the runoff is an important factor, which reduces the soil moisture.

In summary, the sandy texture, which leads to the low available water capacities of the soils, seems to be the main cause for an increase of the risk of potential drought of urban soils in Hamburg. Only one of the 36 study sites had a “high” available water capacity according to Ad-hoc Arbeitsgruppe Boden (2005), while 47% profiles had a “low” available water capacity. In addition to that, the high percentages of surface sealing at many sites can reduce the infiltration of precipitations into the soils.

b) Are chemical soil properties (e.g. deicing salts, pH) relevant for increasing the potential stress for trees in Hamburg?

It is known, that trees, which have stress, react stronger to additional stress factors. Accordingly, disadvantageous chemical properties can bear a stress potential for trees and increase their reactions to drought stress in general. However, at the study sites of this study, the concentrations of deicing salts were mainly low (median of Cl: 4.1 mg/kg DM, median of Na: 8.5 mg/kg DM). The pH of the soils were in the range of pH values, which are recommended for common roadside tree species in Germany (“acidic to slightly acidic” to a maximum between 7 and 8.2 depending on the tree species (Goss & Schönfeld 2014)). Therefore, no stress by deicing salts or by the pH values of the soils were expected at the study sites.

In contrast to these two chemical properties, the humus content was very low (<1%) according to Ad-hoc-Arbeitsgruppe Boden (2005) in 41.1% of the soil layers. Few recommendations for nutrient situations in soils for established or young oaks and maple were found in literature. Hence, the nutrient situation could not be evaluated in this study.

Overall, the chemical soil properties “deicing salts” and “pH value” seem to have at the analyzed roadside tree sites in Hamburg a smaller effect on the potential stress for trees in comparison to the physical properties, which might increase the risk of soil drought. The next question is about further stress for the tree, which can be affected by the physical properties of the soil, namely the soil gas composition.

c) Does the aeration of the roadside soils has the potential to reduce tree growth?

It is known that the soil gas composition is influenced by the biological activity like root respiration in the soil and the gas exchange with the atmosphere. The exchange processes were effected by soil properties like pore volume, pore size distribution, which were affected by soil compaction, soil water conditions and by surface sealing. (e.g. Blume et al. 2010)

The soils of the study sites were mainly sandy soils, which had in average “low” bulk densities according to Ad-hoc-Arbeitsgruppe Boden (2005) and “high” air capacities. The mean air capacities of the studied layers (19.8 vol.-%) as well as the mean air capacities of the profiles (19.4 vol.-%) are in the category “high” according to Ad-hoc-Arbeitsgruppe Boden (2005). Thus, based on these soil properties, a sufficient aeration of the soils seemed possible. However, the measurement of the CO_2- and O_2-content in the soil at six sites with established roadside trees showed that the CO_2-contents were often relatively high. At five of six sites, the CO_2-contents were exceeding 5%, which is a threshold for root growth according to Horn (1992), in a depth of 100 cm in summer and fall in both years.

As described above, the surface sealing is often very high at the roadside tree sites, where sealing over 70% was not unusual. The sealing affects not only the infiltration of water, but also reduces the gas exchange of the soil gas with the atmospheric gas. This can cause an accumulation of CO_2 in the soil. In this study, no gas measurements were conducted under surface sealing, therefore further studies are needed to prove the intensity of the effect of sealing of pavements and roads on the soil aeration of typical roadside tree sites.

In summary, one of the problems for the aeration seems to be the high percentages of surface sealing at roadside sites, but also in potential good soils for aeration like the sandy soils of the studied sites, the CO_2-concentrations reached high levels, which have the potential to restrict root growth.

After getting to know that the physical properties of roadside soils can increase the probability stress for trees by decreasing the aeration and increasing the risk of soil drought, it is important to find out, whether the soils were really getting dry during the investigation time. Therefore, the second question, this study will answer is:

(2) Does soil drought occur at roadside tree locations in Hamburg?

To answer this question in more detail, four sub-questions were answered.

a) When and how long did drought occur in the studied years?

Hamburg as a northern German city has a humid climate with a longtime precipitation average of 793 mm at the weather station in Fuhlsbüttel (DWD 2018). Nevertheless, the monitoring of the water tension and water content demonstrated that water shortage in the soil occurred at some urban roadside tree sites in Hamburg during summer and fall in the years of investigation (2016 and 2017). However, precipitation rates were comparable high in summer 2016 (285 mm) and in summer (301 mm) and fall 2017 (284 mm) to the 30-year averages (summer: 235 mm, fall: 204 mm), while the precipitation sum of 105 mm was lower in fall 2016 than the 30-year average.

Here, soil drought was defined as a water availability below a water tension of 750 hPa (pF 2.9) according to Shock et al. (2002) (see chapter 2.1) and a more intensive drought of 2000 hPa (pF 3.3) measured in soil in at least one depth between 20 cm and 100 cm depth.

At one of the six monitoring sites at established roadside trees (E5), nearly no drying within the soil profile with a soil depth of 100 cm appeared, probably because of water logging layers below the profiles. At this and one other study site (E2), the soil water tensions were always less than 2000 hPa (pF <3.3). A plausible explanation of the uninterrupted moist soil conditions is that the soil densities, which were slightly higher at to the other sites, might have reduced the aeration. This reduced aeration might have caused the restricted growth of fine roots mainly to the uppermost soil layers and thus decreased the water uptake from deeper layers. The measurements of soil water tensions additionally indicate that water logging within the subsoil (depth > 100 cm) is possible at site E5.

At the other four sites, the soil had dry phases with soil water tensions ≥2000 hPa mainly between August and December 2016. In contrast to that, 2017 was a year with more rain in spring and fall. That leads to two shorter drought periods of the soils at established trees: The first one was a short phase in June and the second was between August and October. In comparison to 2016, the intensity of drought was lower, too. Therefore, the length of dry soils at established trees varied from year to year, depending to a high extend on the precipitation patterns.

This was supported by the modeling of the potential length of drought phases in the last 36 years, which showed a high variation of the number of days with low water tensions in 20 cm depth during the vegetation period. The number of days varied from site to site, too, but the number of days were in the same years high or low, which is reflecting the influence of the weather conditions.

At 15 of 17 study sites at young roadside trees, phases with dry soils occurred. Here, in 2016 the duration of dry phases were similar to the ones at established trees in the same year. However, despite of higher rain amounts in 2017, the dry phases of the soil substrates started in June and ended between September and November at sites of young trees. This period with restricted water supply was interrupted by several short phase of lower water tensions, caused by precipitations and irrigations. In accordance to the likely root distribution of young trees, the duration and intensity of drought was more pronounced in the root ball substrates than in the planting pit substrates and was least developed in the outer urban soil substrates. Additionally, the substrates at young tree sites were dryer near the surface.

Results of both measuring approaches indicate, that drought in roadside tree soils is possible even in comparatively moist summers and that the intensity and duration of drought corresponds to the root distribution. For recently planted trees with still restricted root development, soil drought concentrates on the inner canopy area, whereas for established trees the soils within the open canopy area may become dry.

b) What is the effect of surface sealing on soil drought?

In urban areas, a high surface sealing in the area of roadside trees is common. Streets, pavements and buildings cause these high percentages of sealing close to the trees. In this study, soil sealing between 0% and more than 90% was determined, reflecting the large variability of surface sealing. Especially at tree sites with grass strips or single tree pits, the sealing of the surface was high. At some of these sites, the only unsealed areas were below the tree crowns. Mainly, it was not clear, where the tree root were exactly located and whether the tree roots had access to the adjacent unsealed soils, which were separated from the green strip by pavements. Roadside trees often face the problem of underground constructed pipes and cables, which may cause a blocking of tree root growth (e.g. by line protections, for roots unsuitable fill sands) or a cutting of the roots during excavations and construction works), so that adjacent unsealed areas could not be reached (e.g. Endlicher 2012, Roloff 2013a).

It was expected that the sealing of the surfaces lead to a smaller or to no infiltration of precipitation into the soils below the sealed surfaces and to higher inflow in adjacent unsealed areas caused by runoff (e.g. Ragab 2003, Flöter 2006). In this study, the soil water content measurements showed no hints for additional inflow. Nevertheless, it was shown by detailed site investigations, that the unsealed parts of the soil surfaces were often dense and without vegetation at sites with high percentage of sealing in the surrounding of the trees, especially at sites with established trees. Infiltration tests revealed that these compacted surfaces offer in average lower infiltration rates than the sites with grass vegetation and lower bulk densities. This is consistent with the findings of Wolff 1993 and Yang & Zhang 2011, who found correlations between the infiltration rates and the bulk density. The lower infiltration rates on compacted soils might induce higher runoff of strong rainfalls and might cause a loss of water by drainage into the canalization.

Further, the sealing can effect differences of small-scale soil and air temperatures, which might lead to a higher water demand of the trees (e.g. Kjelgren & Montague 1998). In this study, the amount of six sites with monitoring at established trees was too low and the site heterogeneity too large to estimate the effects of the surface sealing on the water availability at established tree sites. Here, the two sites with the highest surface sealing were the two sites without phases with water tensions ≥2000 hPa in 2016. However, it is not likely that this is an effect of the soil sealing, but caused by further conditions of the soil and site conditions. For instance, these two sites with high sealing were located in narrow streets with buildings close to the trees, so that it was expected, that the radiation was lower. Additionally, the soils had at one of the two sites a slightly lower sand content, a higher bulk density and the water content measurement at one of the sites showed high water contents of more than 30% in 1 m depth, which was probably caused by perched water below the analyzed profiles. In comparison to the sealed sites at established trees, buildings or other vegetation did not shade the young trees with high sealing, so that they were exposed to higher solar radiation, so that the site properties were different. Here, the sites with high percentage of sealing had longer dry phases than sites with very low sealing. For example, the site with the lowest soil sealing below 10% at the three young trees had lower water tensions and shorter phases with water tensions ≥750 hPa than sites with a sealing of more than 70% in 2017.

In conclusion, single effects of the surface sealing could not be evaluated in this study, because of the heterogeneities between the different sites in the city. However, it shows that young trees at sites with high sealing and low shading have a higher risk of soil drought than trees in areas with low sealing and shading. All location factors like sealing, surface structure, vegetation, shading, inclination, groundwater depth, radiation and wind velocity interact with each other and influence the water availability in the soils. Altogether, the complex surrounding of the roadside trees has to be considered individually at each site as well as their effects on the water demand of trees to estimate the potential for soil drought.

c) How did the potential soil drought differ between sites from 1959 to 2016?

Modeling of the water tension of sites, where established trees had been felled, shows high variations of the water content in the soils from year to year, which leads to very different length of dry phases of the soil. Because of the high interannual variability, there was no significant trend over the modeled period starting between 1950 and 1980 and ending 2016. Nevertheless, large spatial variability between the single sites were measured. The average number of drought days (with mean water tensions ≥750 hPa in 20 cm depth) was 88 days per year during the vegetation period (April to October) of the years from 1980 to 2016. However, this mean value ranged from 68 days (F20) to 120 days (F12), which is nearly a factor of two. This result demonstrated, how important the soil properties of the different roadside tree sites are for the potential drought risk.

The last research question refers to the different living conditions for established and young trees:

(3) What are the differences between sites with established trees and young trees according to drought stress?

The third part of this thesis illustrates that the drought problem is more distinct at sites of young trees, even if this study shows, that at sites with established trees, drought phases occurred as well.

In comparison to established trees, young trees have a small rooting system. After planting, the roots start to leave the root ball and spread into the surrounding planting substrate before they leave the planting pit and use the urban soil in their surroundings to archive needed water and nutrient supplies. In the first years, the roots are very close to the root ball. That means that the trees are dependent on the water and nutrients in this area of the planting pit. It is not possible for them to use water from deeper layers. For this reason the preparation of the planting pits are of high relevance. Existing guidelines (e.g. FLL 2012, 2015) recommend planting pit substrates with certain properties to enhance the water capacity, and at the same time a high degree of sands to fulfill requirements to avoid restrictions of the aeration and high rates of soil skeleton for stabilization and protection against compaction. The size and depth of the planting pits are given as well as their preparation and the planting process itself are described. Nowadays, plantings of young trees in urban areas are often realized according to these or similar recommendations. In comparison to that, the analyzed established trees were planted directly in the urban soils, because planting pits were at that time not common.

The planting pits of the study sites of this study can be divided in two types: The first type has two different layers of substrates. Whereas the upper substrate contains in most cases a higher humus content and higher skeleton content than the deeper layer. The second planting pit type has just one substrate. Influences of the planting pit type on the water tensions could not be estimated because of the low number of planting pits with one substrate. In general, the analyzed planting pit substrates had a very high skeleton content (median of 34.7%) and contained a high sand and humus content. All studied planting pits fulfilled the substrate recommendations for texture (only sand content was evaluated, because the other recommendations were no criterion of exclusion as a planting pit substrate, if the other physical properties like water capacity are reached) and pH value of the FLL guideline (FLL 2012). The humus content was higher than 4% at 64% in at least one planting pit substrate of the 17 studied planting pits. In three substrates, the humus content was lower than 1%. Therefore, the humus content was the most critical parameter of the recommendations of the substrate quality, recommended by the FLL (2012), which was checked in this study.

At sites with young trees, the dry phases occurred in the main rooting zone, which is in the root ball and the surrounding planting pit substrates, during summer and fall of 2016 and 2017. The rooting zone of young trees in their first years is expected to be small, so they cannot take water from areas with larger distance to the stem during the first years after planting. This means that a soil drought in the root ball and in the planting pit affects the young trees and may reduce their growth performance and their vitality. The first results of carbon isotopes analyses of leafs by Reisdorff (not published data, 2018) showed a higher accumulation of $^{13}CO_2$ in the leafs at a site, where in average more than two times longer phases of soil drought (water tensions ≥750 hPa) occurred in in the rooting balls in fall 2016, than at the second site. These accumulations gave first hints for drought stress of young trees caused by soil drought.

In both years, the dry phases in the substrates at young roadside trees were interrupted by short phases of low water tensions caused not only by precipitations, but also by irrigations. Irrigations were carried out only at young trees, while the established trees were not irrigated. The water tensions were decreasing with the depth at planting pits of young trees, so that dry phases of the soils in 100 cm depth were rare, but in that depth, no or only few roots, which could use this water, were expected to reach that depth in the first two years after planting. In contrast to the sites at established trees, the water tensions in the planting pits of young trees is higher in the second year of monitoring – although the fall was rich of precipitation. In addition to that, the area, which got dry, increased, the intensity of drought was higher and the dry phase was longer in 2017. This can be caused by the growth of the roots and the trees themselves.

At sites with established trees, which have a well-established root system, the situation is different. There, the drought phases were mainly more intensive in 20 cm and 40 cm depth, but the depth with the longest dry phases variated from site to site. In addition to that, dry phases in 100 cm depth were measured more often at sites of established trees than at young trees. During the dry phases, often not all measured soil layers were to the same time dry at soils at established trees. That means that the tree can take water from the moist soil layers, if the tree is rooting there. Therefore, older trees have more possibilities to take water from different depth and distances to its locations than young trees, which lowers the risk of drought stress.

Altogether, this study confirms, that roadside trees have to live with difficult growing conditions. For example, their surrounding is affected by surface sealing, which can reach over 90% of the surrounding of the trees. In addition to that, the analyzed soil substrates of this study (urban soils as well as planting pit substrates) had a high sand content. These and other factors like a lack of shading or reduced rooting space can support the water shortage. This study showed that the soil water availability was reduced at many sites of roadside trees during summer and fall 2016 and 2017. These decreased water availabilities have the potential to decrease tree growth. That means, that the situation in regard to the soil water availability for roadside trees can be improved in Hamburg.

Therefore, the situation for urban roadside trees is difficult. In future, the aspect of the sealing can become a more urgent problem, because of the growing of cities. In addition to that, the supposed effects of climate change with higher temperatures and accordingly higher water demand of trees, will increase the problem of drought stress. Even if the living conditions are difficult for trees in cities, trees have many positive effects on the microclimate in urban areas, so that it is important to keep them in the urban areas and care for a high vitality of them. Consequently, it is necessary to increase the knowledge about the living conditions of urban trees and their needs for an adapted tree management.

8. Outlook

This study showed that dry phases occurred in the soil substrates during the measurement period from 2016 to 2017 at the urban roadside trees in Hamburg. In these years, the summers were wetter than the average. Here, it should be observed if the drying of the soil starts earlier in “normal” summers. That is especially important to take adapted measures like irrigation for young trees. Therefore, it is important to monitor the water availability in the soils at roadside tree sites over a longer time period. Only then, an average course of the year can be analyzed as well as the situation at extreme events like very wet years and very dry years like the year 2018. Another important aspect is the consideration of the sealed soil surfaces. This study showed that the surface sealing is very high in the surrounding of the roadside trees, but less is known about the plant water availability under these surfaces and the possibility for tree roots to use these areas, where problems of the aeration are likely. In general, more knowledge about the tree species, their water demand depending on weather and location as well as their reactions to water shortages in different seasons must be gained. A combination of site and plant measurement seems to be necessary for future research.

In addition to that, further research, which includes different climate and local planting and soil differences in cities, will make it possible to transfer the results of this study to other urban areas.

Due to the occurrence of dry phases in the soils, the situation of the trees can be improved. It is difficult to improve the situation for existing trees, because a change of soil material is expensive and difficult to realize without damaging the roots. At established trees, it is important not to worsen the location, but to improve it. For example, the changing of the surface from a compact soil to a looser surface material can improve the infiltration rates and can affect a better water supply as well as a better aeration. At young tree sites, the planting pits with suitable planting substrates can be enlarged, especially at sites with high sealing. For young trees, a slightly lower sand content and a corresponding higher percentage of finer textures in the planting pit substrates would improve the water holding capacities. At the same time, the aeration must be maintained and longer water logging prevented. Here further research is needed to analyze and valuate the effects of soil mixtures with a lower sand content to find an optimal balance of grain sizes, so that further compaction of the substrates do not happen after installation. At new planted sites, it would be helpful, if no underground cables or pipes will be installed in the area, which the young will tree use as rooting space in future, so that later damages of the roots or limitations of the rooting area will be avoided.

For the identification of stress of established and young roadside trees during phases of low soil water availability, direct stress measurements at the trees like sap flow analyses or isotope measurements or growth parameters (e.g. stem diameter) are necessary and would increase the knowledge about reactions of trees to the given water availabilities. With this knowledge, changes of the irrigation management can be conducted. For example, an increase of irrigations per year, the determination of the optimal point of time for the irrigations, the extension of young tree irrigations over longer time (more than three years) at planting pits with limited rooting area, or a controlling of the effects of the irrigations may help to keep the soils moist. An optimized soil moisture will help to prevent drought phases and supports the vitality of young trees, which will have better chances to develop a huge rooting system, with which they can overcome dry phases without irrigations. Therefore, further research at roadside trees will contribute to a green and healthy tree stock in urban areas.

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Appendix I: Site plans

All six site plans (originally drawn by Ruprecht (2018) and Kuqi (2017)) were changed according to the design of Strachwitz (2017) and further details were added.

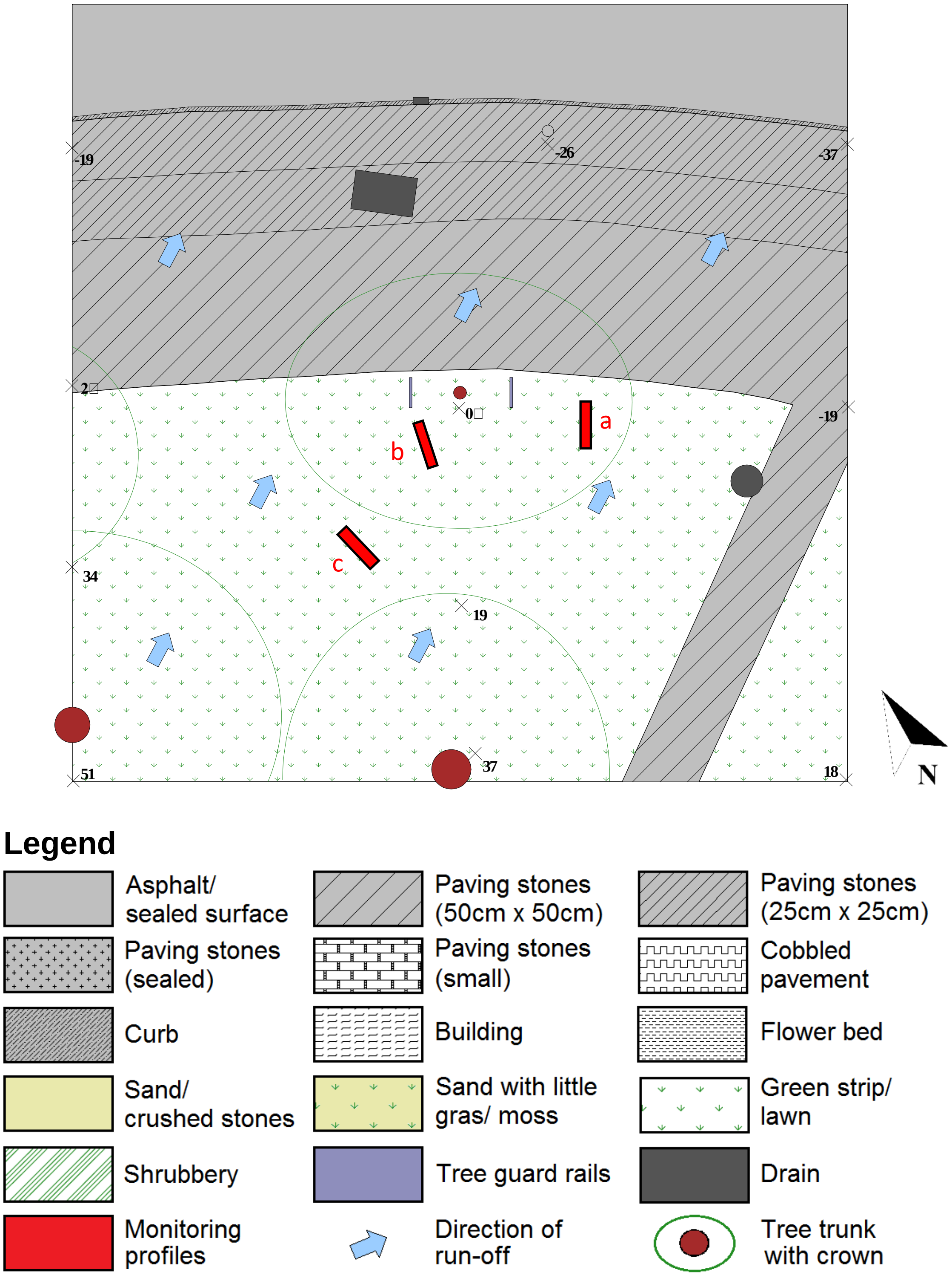

Figure 52: Site plan (20m x 20m) of the site E1 with the profiles a-c and legend. Numbers next to crosses show the relative height to the height of the surface of the tree in the middle.

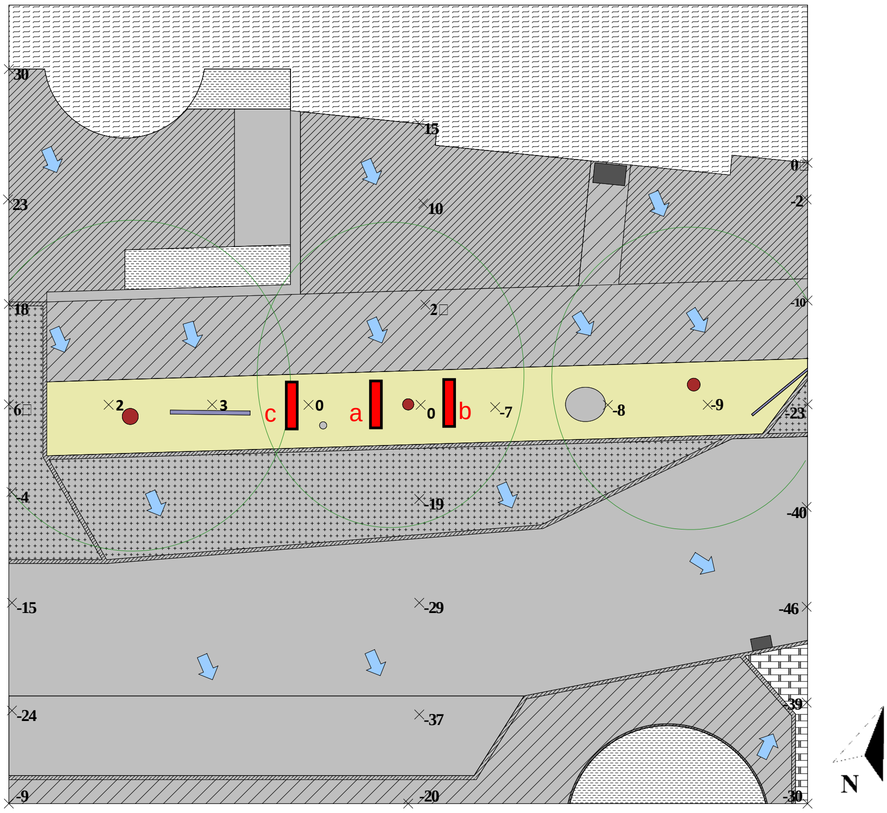

Figure 53: Site plan (20m x 20m) of E2 with the profiles a-c.

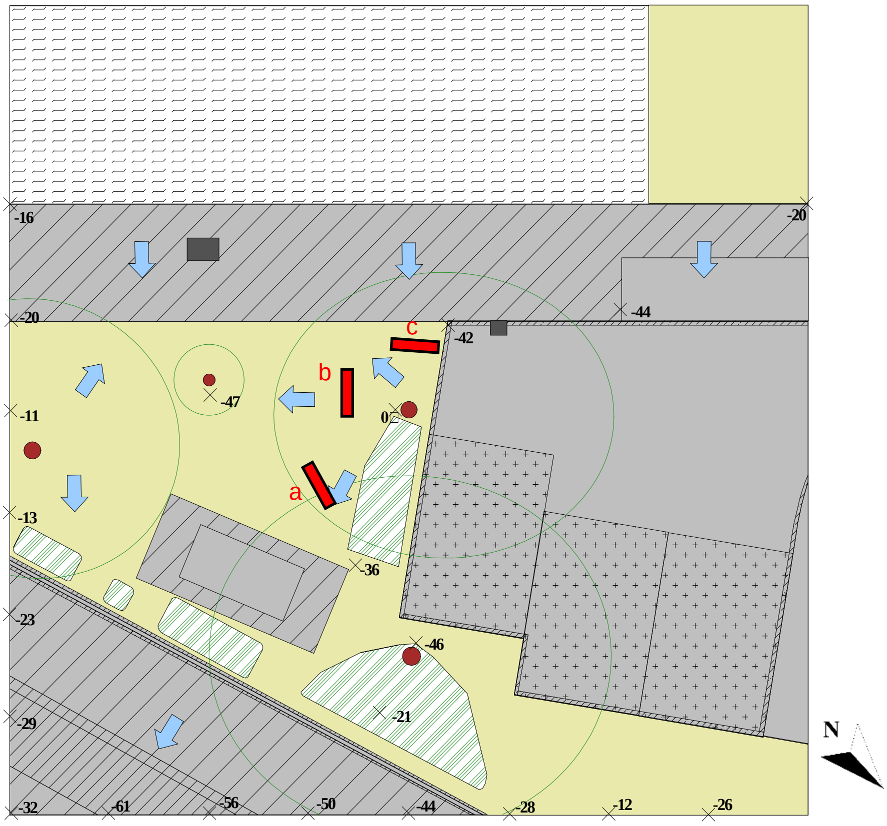

Figure 54: Site plan (20m x 20m) of E3 with the profiles a-c.

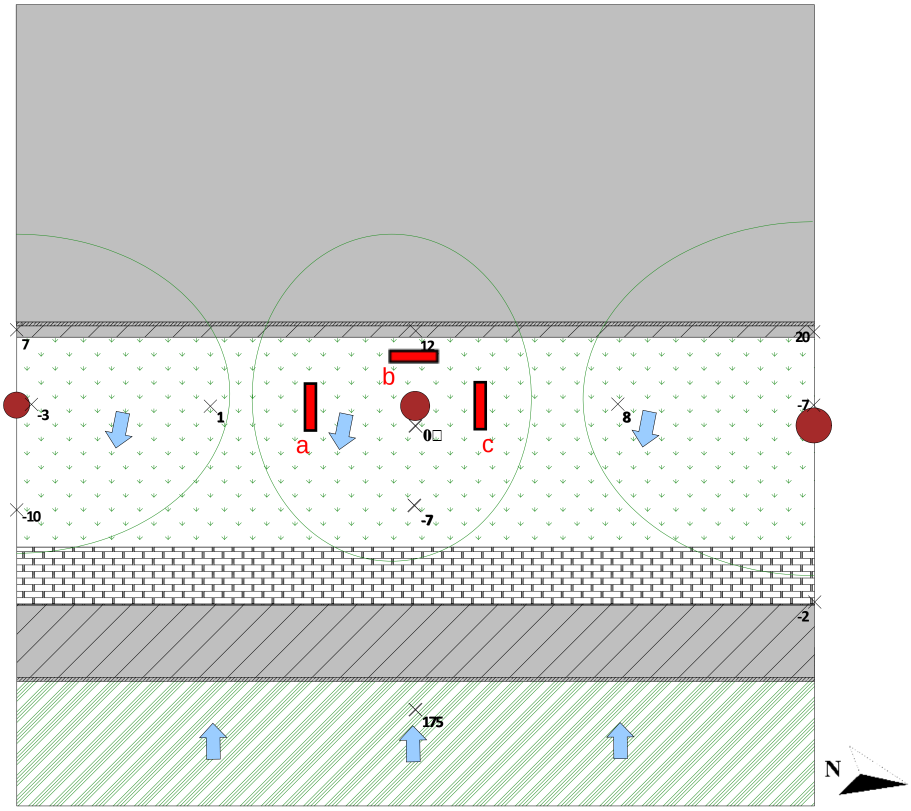

Figure 55: Site plan (20m x 20m) of E4 with the profiles a-c.

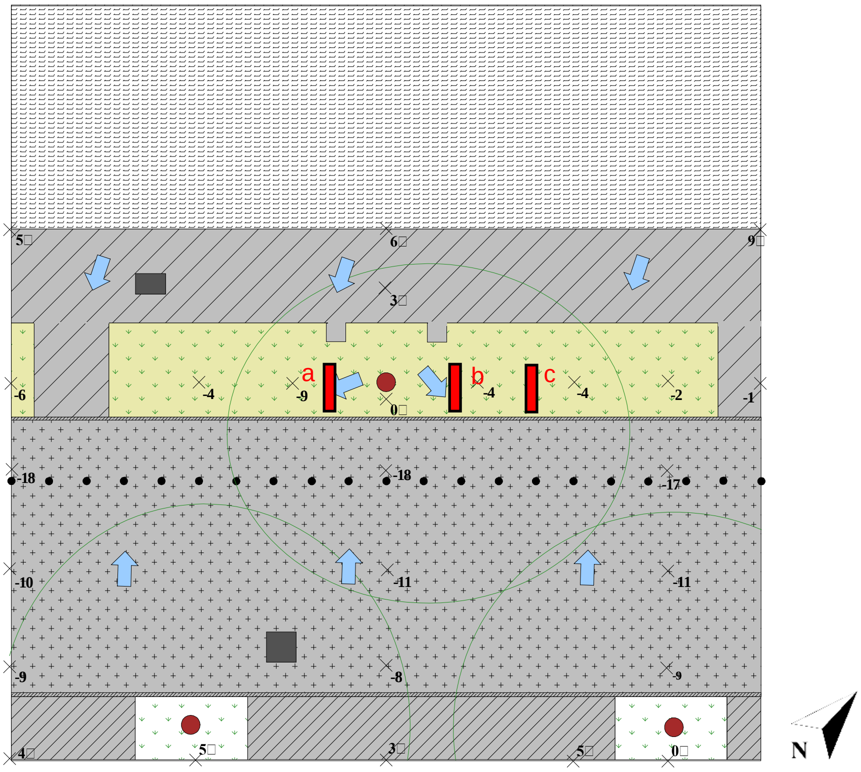

Figure 56: Site plan (20m x 20m) of E5 with the profiles a-c.

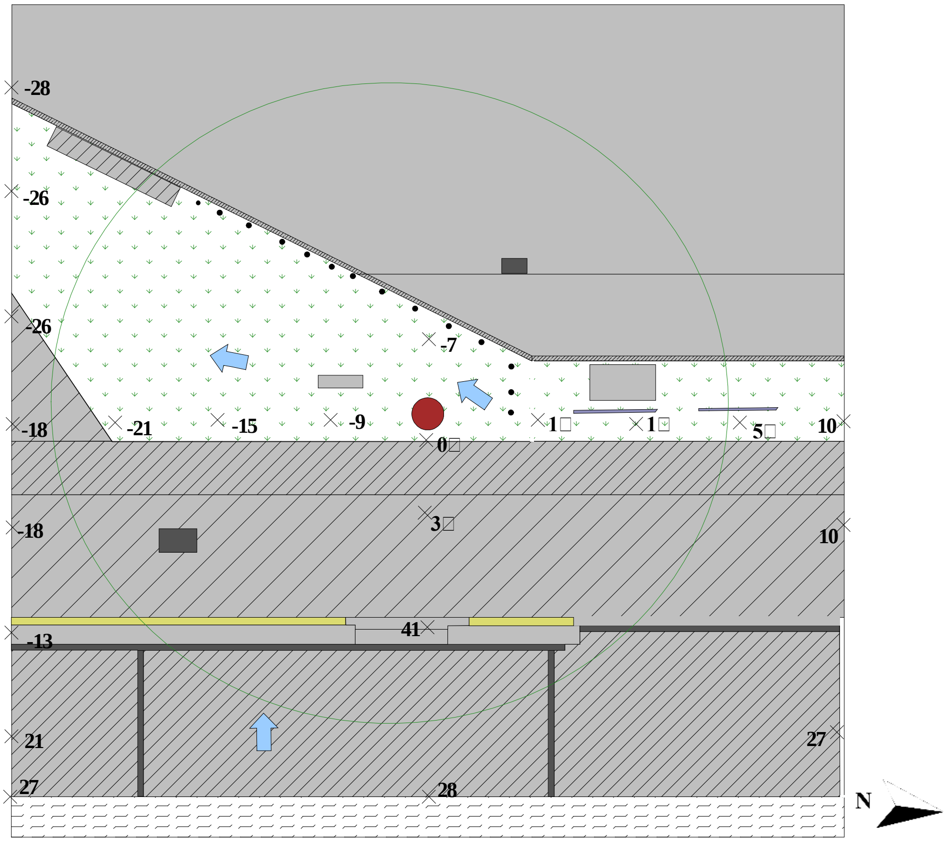

Figure 57: Site plan (20m x 20m) of E6 (profiles a-c are close to the tree in the middle).

Appendix II: Soil analyses at sites at established trees

Table 15: P, P_2O_5, K and K_2O in the soils at established trees (F1-20 and E1-6)**.**

Profile no.	Depth [cm]	P [mg/kg]	P_2O_5 [mg/100g]	K [mg/kg]	K_2O [mg/100g]
F1	0-4	34.6	7.9	94.5	11.4
F2	0-12	73.7	16.9	186.5	22.5
F2	74-100	172.6	39.5	283.0	34.1
F3.1	0-7	171.8	39.4	283.0	34.1
F3.2	0-7	145.8	33.4	324.9	39.1
F4	0-22	86.1	19.7	71.4	8.6
F5	0-11	53.9	12.3	79.4	9.6
F6	0-3	212.2	48.6	400.4	48.2
F7	0-12	50.8	11.6	147.5	17.8
F8	0-6	165.4	37.9	73.0	8.8
F9	0-22	85.5	19.6	101.5	12.2
F10	0-2	32.6	7.5	121.4	14.6
F11	0-10	161.3	36.9	92.9	11.2
F12	0-9	112.5	25.8	138.4	16.7
F13	0-19	113.9	26.1	151.9	18.3
F14	0-32	104.7	24.0	28.9	3.5
F15	0-18	27.4	6.3	178.4	21.5
F16	0-20	61.2	14.0	61.4	7.4
F17	0-8	118.7	27.2	188.5	22.7
F18	0-22	84.0	19.2	123.1	14.8
F19	0-9	81.1	18.6	115.7	13.9
F20	0-8	45.3	10.4	97.7	11.8
E1a	0-15	55.8	12.8	36.9	4.4
E1b	0-10	41.6	9.5	62.4	7.5
E1b	10-30	62.4	14.3	22.8	2.7
E1b	30-70	36.8	8.4	3.6	0.4
E1b	70-100	14.6	3.3	2.6	0.3
E1c	0-10	33.0	7.6	49.9	6.0
E2a	0-3	302.3	69.2	201.4	24.3
E2a	3-28	76.6	17.6	32.4	3.9
E2a	28-70	107.0	24.5	44.9	5.4
E2a	70-100	52.0	11.9	37.4	4.5
E2b	0-3	302.3	69.2	97.9	11.8
E2c	0-2	615.1	140.9	103.9	12.5
E3a	0-20	96.6	22.1	63.4	7.6
E3b	0-3	104.1	23.9	80.9	9.7
E3c	0-10	46.3	10.6	64.4	7.8
E3c	10-30	38.3	8.8	56.4	6.8
E3c	45-100	6.5	1.5	5.0	0.6
E4a	0-36	76.6	17.6	37.4	4.5
E4b	0-35	73.7	16.9	61.4	7.4
E4b	35-62	11.5	2.6	12.1	1.5
E4b	62-100	28.9	6.6	27.5	3.3
E4c	0-36	113.9	26.1	27.5	3.3
E5a	1-13	84.1	19.3	51.5	6.2
E5b	1-10	63.2	14.5	44.0	5.3
E5b	10-20	63.2	14.5	17.5	2.1
E5b	20-40	194.5	44.6	9.8	1.2
E5b	40-100	90.4	20.7	39.5	4.8
E5c	0-3	63.9	14.6	76.0	9.2

Table 16: Water-soluble ions (chloride (Cl), fluoride, bromide, nitrate, sulfate, calcium, sodium, magnesium (Mg), potassium (K)) in the soils at established trees (F1-20 and E1-6)**.**

Profile no.	Depth [cm]	Cl [mg/kg DM]	Fluoride [mg/kg DM]	Nitrite [mg/kg DM]	Bromide [mg/kg DM]	Nitrate [mg/kg DM]	Sulfate [mg/kg DM]	Calcium [mg/kg DM]	Sodium [mg/kg DM]	Mg [mg/kg DM]	K [mg/kg DM]
F1	0-4	3,1	0,1	0,2	<0,05	73,5	9,0	19,4	10,8	19,4	10,6
F2	0-12	7	0,3	16,4	<0,05	0,6	33,2	36,9	11,0	3,7	50,2
F3.1	0-7	5,4	0,4	18,6	<0,05	25,6	10,9	48,8	13,7	2,5	45,9
F3.2	0-7	8,3	0,3	15,3	<0,05	347,1	11,0	71,8	30,2	7,9	73,0
F4	0-22	14,7	0,6	0,1	<0,05	99,5	17,1	19,3	39,8	3,0	12,3
F5	0-11	20,2	1,5	5,1	<0,05	170,0	15,1	36,8	32,4	3,7	23,3
F6	0-3	11,4	0,4	2,6	<0,05	39,0	11,7	24,8	12,1	2,9	66,8
F7	0-12	7,9	0,3	8,7	<0,05	41,8	7,0	15,2	9,0	2,0	27,1
F8	0-6	2,4	0,2	0,2	<0,05	27,1	5,0	16,6	20,8	1,1	10,4
F9	0-22	2,7	0,3	<0,05	<0,05	6,7	6,2	11,3	7,3	2,8	13,3
F10	0-2	24,4	0,5	<0,05	<0,05	0,4	11,9	12,8	42,7	1,0	9,3
F11	0-10	7,2	0,3	0,6	<0,05	15,4	7,4	10,8	10,6	1,4	13,2
F12	0-9	6,3	0,3	3,1	<0,05	22,1	12,6	19,0	22,8	3,0	25,1
F13	0-19	2,2	0,6	0,1	<0,05	16,5	3,4	17,3	5,3	1,9	20,5
F14	0-32	4,8	0,4	<0,05	<0,05	<0,1	59,8	8,6	22,0	1,4	5,6
F15	0-18	7	0,3	4,9	<0,05	5,2	7,6	22,4	4,0	2,7	27,7
F16	0-20	12,6	0,4	<0,05	<0,05	<0,1	16,3	26,9	23,0	2,6	11,8
F17	0-8	3,3	0,3	<0,05	<0,05	3,0	5,5	22,1	16,1	3,6	24,8
F18	0-22	2,1	0,3	0,1	<0,05	9,5	4,2	19,5	5,0	1,2	11,4
F19	0-9	7,7	1,2	1,1	<0,05	1,6	14,2	25,7	9,4	2,7	23,8
F20	0-8	4,0	0,5	0,5	<0,05	21,6	7,3	21,4	3,1	1,3	12,6
E1a	0-15	4,9	0,3	13,3	<0,05	17,9	7,2	24,4	9,5	2,6	7,9
E1b*	0-10	7,7	0,2	1,9	<0,05	27,4	9,8	11,0	8,4	1,5	10,9
E1b*	10-30	3,3	0,2	3,2	<0,05	1,4	4,9	9,9	7,3	1,9	4,0
E1b*	30-70	1,9	0,5	<0,05	<0,05	1,0	2,4	8,0	3,8	0,6	1,0
E1b*	70-100	3,1	0,7	<0,05	<0,05	1,1	2,2	7,9	4,0	0,5	1,2
E1c	0-10	6,1	<0,1	0,1	<0,05	19,1	9,1	16,5	6,3	2,4	11,7
E2a*	0-3	21,8	0,1	9,6	<0,05	200,5	29,8	19,5	82,5	1,8	19,9
E2a*	3-28	2,4	0,2	<0,05	<0,05	3,6	3,6	3,4	9,6	1,4	5,3
E2a*	28-70	15,3	0,5	<0,05	<0,05	<0,1	3,4	10,8	21,4	3,3	10,1
E2a*	70-100	13,5	0,6	<0,05	<0,05	0,8	4,6	16,2	21,8	0,9	5,9
E2b	0-3	5	0,2	3,8	<0,05	169,3	16,0	385,8	8,5	5,6	20,7
E2c	0-2	5,4	0,1	2,3	<0,05	257,3	37,7	78,1	18,4	7,7	30,0
E3a	0-20	3	0,3	<0,05	0,1	4,2	4,4	125,2	4,5	1,6	8,6
E3b	0-3	1,5	0,3	0,7	<0,05	12,1	3,4	6,5	4,2	1,6	10,1
E3c*	0-10	2	0,4	0,3	<0,05	5,8	3,8	5,3	4,6	1,0	9,5
E3c*	10-30	2,1	0,4	0,3	<0,05	5,4	6,8	9,0	4,3	0,6	7,4
E3c*	45-100	1,1	0,3	0,1	<0,05	<0,1	1,7	10,1	2,0	2,5	6,0
E4a	0-36	2,5	0,5	<0,05	<0,05	9,0	6,1	18,5	3,6	2,3	6,1
E4b*	0-35	4,2	0,2	<0,05	<0,05	10,4	3,9	11,7	4,0	1,4	8,9
E4b*	35-62	0,7	0,5	<0,05	<0,05	<0,1	1,2	11,8	2,1	2,1	2,4
E4b*	62-100	1,1	0,7	<0,05	<0,05	<0,1	3,9	12,4	3,1	2,1	3,5
E4c	0-36	1,1	<0,1	<0,05	<0,05	7,4	5,2	18,7	4,0	1,9	3,7
E5a	1-13	0,6	0,4	<0,05	<0,05	<0,1	4,5	4,6	2,5	0,8	5,6
E5b*	1-10	3,6	0,2	<0,05	<0,05	<0,1	5,3	3,8	4,0	1,7	6,6
E5b*	10-20	4	0,3	<0,05	<0,05	1,0	3,2	8,3	5,6	2,8	4,4
E5b*	20-40	3,9	0,5	<0,05	<0,05	<0,1	1,8	8,6	8,6	5,2	2,8
E5b*	40-100	4,9	0,7	<0,05	<0,05	<0,1	3,6	13,5	13,9	9,1	6,4
E5c	0-3	1,4	0,2	0,1	<0,05	2,2	2,4	18,1	2,5	9,1	16,0
E6b*	0-5	25,6	0,2	4,5	<0,05	89,1	13,0	27,4	18,3	3,7	21,0
E6b*	5-10	4,2	0,5	0,1	<0,05	21,4	6,3	6,3	5,9	0,9	11,3
E6b*	10-20	4,3	0,6	<0,05	<0,05	22,2	6,0	7,8	7,6	0,8	10,1
E6b*	20-40	1,8	0,7	<0,05	1,0	9,7	6,0	10,2	5,5	13,1	14,8
E6b*	40-80	3,7	0,1	<0,05	<0,05	1,2	8,0	6,5	12,6	6,9	5,8

* Analyses by F. Zander (see Zander 2016).

Table 17: Nitrogen (N), carbon (C), C/N-value, humus content, C_{anorg}, $CaCO_3$, density of solid substance, pH-value and el. conductivity in the soil layers at established trees (F1-20 and E1-6)**.**

Profile no.	Depth [cm]	N [%]	C [%]	C/N [-]	Humus content [%]	C_{anorg} [%]	$CaCO_3$ [%]	Density of solid matter [g/cm³]	pH-value in H_2O [-]	pH-value in $CaCl_2$ [-]	Conduc-tivity in 1:2.5 [µS/cm]
F1	0-4	0.17	4.42	25.6	7.6	-	-	2.63	6.5	6.2	59
F1	4-10	0.03	0.38	12.1	0.6	-	-	2.63	6.6	6.3	17
F1	10-17	0.13	3.76	27.9	6.5	-	-	2.56	6.4	5.9	26
F1	17-22	0.10	1.24	13.0	2.1	-	-	2.60	6.3	5.9	25
F1	22-33	0.06	0.47	8.0	0.8	-	-	2.62	6.4	5.9	31
F1	33-68	0.04	0.30	7.8	0.5	-	-	2.67	6.4	6.1	29
F1	68-100	0.01	0.02	1.7	0.0	-	-	2.65	6.5	6.4	14
F2	0-12	0.40	5.98	15.0	10.3	0.06	0.52	2.47	7	6.7	151
F2	12-31	0.12	1.64	14.2	2.8	0.00	0.02	2.57	6.6	6.1	36
F2	31-40	0.13	3.73	29.1	6.4	-	-	2.49	6.5	6	45
F2	40-50	0.03	0.69	22.3	1.2	-	-	2.62	6.6	6.4	25
F2	50-60	0.02	0.09	4.7	0.2	-	-	2.64	6.6	6.3	28
F2	60-74	0.05	0.82	17.8	1.4	0.03	0.22	2.62	7.4	7.1	81
F2	74-100	0.02	0.08	3.4	0.1	0.02	0.15	2.64	7.3	7	52
F3.1	0-7	0.39	6.80	17.4	11.7	-	-	2.36	6.7	6.1	92
F3.1	7-15	0.15	4.25	28.9	7.3	-	-	2.59	6.6	6.1	52
F3.1	15-30	0.10	2.42	23.4	4.2	0.00	0.01	2.58	7.3	6.2	43
F3.1	30-70	0.04	0.33	8.3	0.6	0.00	0.00	2.63	7	6.5	56
F3.1	70-100	0.02	0.06	3.5	0.1	-	-	2.65	6.8	6.2	21
F3.2	0-7	0.61	8.92	14.7	15.3	-	-	2.32	6.4	5.9	148
F3.2	7-60	0.06	1.00	16.2	1.7	-	-	2.62	6.6	6.1	28
F3.2	60-100	0.04	0.56	13.0	1.0	-	-	2.63	6.6	6.4	33
F4	0-22	0.36	5.21	14.3	9.0	-	-	2.45	5.3	4.6	86
F4	22-30	0.05	0.96	18.2	1.7	-	-	2.62	5.9	5.1	26
F4	30-34	0.18	7.00	38.9	12.0	-	-	2.44	5.9	5.3	54
F4	34-57	0.08	1.38	16.4	2.4	-	-	2.63	5.9	5.5	51
F4	57-100	0.05	0.53	9.9	0.9	-	-	2.63	6.2	6	43
F5	0-11	0.31	4.33	13.9	7.5	-	-	2.48	5.3	4.9	145
F5	11-50	0.05	0.79	16.0	1.4	-	-	2.63	6.2	5.7	52
F5	50-100	0.04	0.60	14.0	1.0	-	-	2.63	6.6	6.3	53
F6	0-3	0.37	6.83	18.4	11.7	-	-	2.32	5.8	5.1	104
F6	3-18	0.22	3.33	15.1	5.7	-	-	2.54	6.1	5.6	57
F6	18-28	0.06	1.10	18.7	1.9	0.07	0.57	2.61	7.8	7.3	98
F6	28-50	0.12	2.23	18.8	3.8	0.11	0.89	2.60	7.4	7.1	85
F6	50-100	0.03	0.52	18.4	0.9	0.06	0.51	2.63	7.9	7.5	88
F7	0-12	0.20	2.61	13.7	4.5	-	-	2.53	6.1	5.7	64
F7	12-32	0.06	0.59	12.1	1.0	-	-	2.63	6.5	6.4	30
F7	32-85	0.07	0.83	12.8	1.4	-	-	2.64	6.5	6.4	34
F7	85-100	0.05	0.03	1.6	0.1	-	-	2.65	6.5	6.5	18
F8	0-6	0.33	4.14	12.5	7.1	-	-	2.48	6.5	6.2	50
F8	6-11	0.21	6.24	30.9	10.7	-	-	2.36	6.4	6	48
F8	11-53	0.08	1.13	15.6	1.9	-	-	2.61	6.3	5.8	29
F8	53-70	0.06	0.58	10.8	1.0	-	-	2.62	6.5	6.2	31
F9	0-22	0.28	7.32	33.5	12.6	-	-	2.47	6.6	6.3	38
F9	22-80	0.14	1.56	13.0	2.7	-	-	2.62	6.4	6	29
F10	0-2	0.04	1.04	24.6	1.8	0.55	4.59	2.64	7.8	7.3	110
F10	2-7	0.03	0.42	17.5	0.7	0.34	2.83	2.64	8.1	7.2	113
F10	7-15	0.07	1.79	20.1	3.1	-	-	2.56	7.2	6.6	138
F10	15-100	0.03	0.39	13.2	0.7	-	-	2.64	6.9	6.4	108
F11	0-10	0.27	4.06	15.0	7.0	-	-	2.61	6.38	5.56	48
F11	10-20	0.15	4.39	29.1	7.5	-	-	2.35	6.06	5.45	56
F11	20-40	0.04	1.40	31.3	2.4	-	-	2.63	6.44	6.51	31
F11	40-50	0.03	0.29	11.6	0.5	-	-	2.65	6.6	6.66	25
F11	50-100	0.05	1.17	21.6	2.0	-	-	2.61	6.53	6.69	37

Profile no.	Depth [cm]	N [%]	C [%]	C/N [-]	Humus content [%]	C_{anorg} [%]	$CaCO_3$ [%]	Density of solid matter [g/cm³]	pH-value in H_2O [-]	pH-value in $CaCl_2$ [-]	Conductivity in 1:2.5 [µS/cm]
F12	0-9	0.25	4.60	18.5	7.9	-	-	2.50	6.4	6.0	101
F12	9-20	0.09	2.15	23.3	3.7	-	-	2.61	6.3	6.3	43
F12	20-68	0.03	0.14	5.3	0.2	0.02	0.20	2.64	7	6.7	39
F12	68-90	0.02	0.07	2.7	0.1	0.00	0.00	2.65	7.1	6.8	32
F13	0-19	0.23	3.13	13.5	5.4	0.00	0.00	2.54	7.1	6.6	52
F13	19-50	0.07	1.88	27.4	3.2	0.01	0.08	2.61	8.1	7.4	101
F14	0-32	0.23	4.04	17.5	6.9	-	-	2.49	5.0	4.4	57
F14	32-50	0.13	2.28	16.4	3.9	-	-	2.63	6.6	5.5	28
F14	50-100	0.13	2.00	15.6	3.4	-	-	2.58	6.4	5.4	32
F15	0-18	0.24	2.71	11.4	4.7	-	-	2.53	6.7	6.1	54
F15	18-62	0.05	0.58	10.8	1.0	0.52	4.32	2.63	7.1	6.7	39
F15	62+	0.08	0.19	3.7	0.3	-	-	2.65	6.9	6.5	27
F16	0-20	0.35	4.37	13.8	7.5	0.00	0.00	2.48	7.3	5.9	48
F16	20-40	0.16	1.31	12.0	2.2	0.00	0.00	2.60	7.1	6.5	50
F16	40-100	0.14	0.60	9.8	1.0	-	-	2.63	6.8	6.7	48
F17	0-8	0.16	3.07	19.4	5.3	-	-	2.60	7	6.6	82
F17	8-70	0.21	0.45	4.9	0.8	-	-	2.63	6.2	6.3	27
F17	70-100	0.03	0.10	3.6	0.2	-	-	2.65	6.2	6.3	37
F18	0-22	0.20	3.18	15.6	5.5	-	-	2.52	6.4	6.3	54
F18	22-35	0.17	0.07	2.1	0.1	-	-	2.65	6.4	6.5	22
F18	35-100	0.02	0.03	2.4	0.1	-	-	2.65	6.4	6.5	18
F18	70-75	0.05	0.79	16.7	1.4	-	-	2.63	6.4	6.5	27
F19	0-9	0.17	2.87	16.8	4.9	-	-	2.59	6.3	6.1	87
F19	9-20	0.03	0.46	18.0	0.8	-	-	2.63	6.5	6.7	36
F19	20-24	0.03	0.30	11.1	0.5	-	-	2.63	7.6	7.2	93
F19	24-39	0.03	0.53	17.9	0.9	-	-	2.65	7.3	7.1	76
F19	39-70	0.02	0.10	5.1	0.2	-	-	2.65	6.7	6.9	31
F19	70-100	0.02	0.04	1.9	0.1	-	-	2.64	6.5	6.8	21
F20	0-8	0.04	0.69	17.1	1.2	-	-	2.68	7.4	7	87
F20	8-14	0.13	2.21	16.5	3.8	-	-	2.53	6.7	6.7	69
F20	14-58	0.03	0.20	7.6	0.3	-	-	2.64	6.5	6.7	19
F20	58-100	0.07	0.29	6.2	0.5	-	-	2.63	6.6	6.6	48
E1a	0-15	0.22	3.15	14.1	5.4	-	-	2.48	5.8	5.3	48
E1a	15-80	0.06	0.95	14.7	1.6	-	-	2.60	6.3	6	28
E1a	80-120	0.02	0.09	5.7	0.1	-	-	2.63	6.5	6.3	20
E1b	0-10	0.26	3.89	15.2	6.7	-	-	2.49	5.2	4.5	66,6
E1b	10-30	0.14	2.32	16.4	4.0	-	-	2.61	5.8	5.1	28,7
E1b	30-70	0.02	0.37	15.8	0.6	-	-	2.61	6.3	5.9	21,8
E1b	70-100	0.01	0.13	9.4	0.2	-	-	2.64	6.5	6.1	20,5
E1c	0-10	0.28	3.98	14.1	6.9	-	-	2.51	5.3	4.7	35
E1c	10-33	0.14	2.34	16.5	4.0	-	-	2.57	5.6	5.1	32
E1c	33-60	0.02	0.17	10.3	0.3	-	-	2.64	6.2	6.1	18
E1c	60-100	0.01	0.06	6.6	0.1	-	-	2.65	6.3	6.3	15
E2a	0-3	0.63	6.79	10.8	11.7	-	-	2.29	6.1	5.6	22,5
E2a	3-28	0.02	0.26	11.8	0.4	-	-	2.64	6.3	5.7	21,6
E2a	28-70	0.02	0.34	17.1	0.6	-	-	2.64	7.1	6.4	55,3
E2a	70-100	0.02	0.32	14.4	0.5	-	-	2.65	7.6	6.8	69,8
E2b	0-3	0.15	1.60	10.4	2.8	-	-	2.64	6.5	6.1	133
E2b	3-20	0.07	0.89	13.4	1.5	-	-	2.62	6.9	6.7	57
E2b	20-55	0.05	0.90	17.9	1.5	0.07	0.62	2.62	7.5	6.9	70
E2b	55-100	0.05	0.80	16.5	1.4	0.07	0.55	2.62	7.4	7.2	78
E2c	0-2	0.33	3.40	10.2	5.9	-	-	2.52	6.5	6.3	152
E2c	2-10	0.03	0.21	7.9	0.4	-	-	2.65	6.3	5.2	33
E2c	10-55	0.04	0.71	16.5	1.2	0.02	0.14	2.65	6.9	6.5	48
E2c	55-84	0.03	0.46	17.6	0.8	0.05	0.41	2.63	7.8	7.3	79
E2c	84-100	0.01	0.04	4.4	0.1	0.00	0.00	2.65	7	6.8	37
E3a	0-20	0.15	2.31	15.3	4.0	-	-	2.56	5.8	4.9	30
E3a	20-50	0.12	1.86	15.4	3.2	-	-	2.56	6.3	6	32
E3a	50-90	0.02	0.42	22.9	0.7	0.16	1.36	2.65	7.3	6.7	58

Profile no.	Depth [cm]	N [%]	C [%]	C/N [-]	Humus content [%]	C_{anorg} [%]	$CaCO_3$ [%]	Density of solid matter [g/cm^3]	pH-value in H_2O [-]	pH-value in $CaCl_2$ [-]	Conductivity in 1:2.5 [µS/cm]
E3a	90-100	0.03	0.98	31.1	1.7	0.82	6.82	2.64	8.1	7.3	99
E3b	0-3	0.11	1.52	13.3	2.6	-	-	2.59	5.8	5.2	33
E3b	3-20	0.06	0.87	14.4	1.5	0.03	0.28	2.61	7.2	6.7	71
E3b	20-60	0.07	1.10	15.4	1.9	0.11	0.94	2.62	7.8	7.3	102
E3b	60-100	0.07	1.30	17.8	2.2	0.24	2.04	2.60	7.9	7.4	108
E3c	0-10	0.11	1.59	14.6	2.7	-	-	2.59	5.7	5	26.1
E3c	10-30	0.11	1.76	15.9	3.0	-	-	2.59	6.2	5.7	28.4
E3c	45-100	0.01	0.03	4.8	0.1	-	-	2.65	6.7	6.3	18.6
E4a	0-36	0.26	4.67	18.2	8.0	-	-	2.64	5.7	5	39
E4a	36-45	0.02	0.30	12.5	0.5	-	-	2.63	6.7	5.9	18
E4a	45-90	0.03	0.41	12.8	0.7	-	-	2.63	6.7	6.1	20
E4a	90-100	0.03	0.33	11.3	0.6	-	-	2.66	6.4	6.5	27
E4b	0-35	0.26	4.49	17.5	7.7	-	-	2.47	5.5	5	26.1
E4b	35-62	0.01	0.15	11.7	0.3	-	-	2.64	6.3	6	23.5
E4b	62-100	0.07	1.30	18.8	2.2	-	-	2.54	6.5	6.1	32.5
E4c	0-36	0.22	3.71	17.0	6.4	-	-	2.50	5.6	5	30
E4c	36-55	0.01	0.14	11.0	0.2	-	-	2.66	6.2	6.1	21
E4c	55-80	0.06	0.96	15.1	1.6	-	-	2.61	6.2	6.1	28
E4c	80-90	0.08	1.05	13.7	1.8	-	-	2.61	6.5	6.4	34
E4c	90-100	0.04	0.39	10.3	0.7	-	-	2.63	6.4	6.3	21
E5a	1-13	0.35	8.80	34.7	15.1	-	-	2.36	6.3	6	18
E5a	13-17	0.03	0.11	6.8	0.2	-	-	2.65	6.3	6.4	14
E5a	17-46	0.11	1.88	20.6	3.2	0.07	0.56	2.58	7.7	7.1	75
E5a	46-60	0.08	0.41	7.3	0.7	0.03	0.22	2.64	7.5	7.1	62
E5a	60-100	0.06	0.16	3.8	0.3	-	-	2.65	6.4	6.3	29
E5b	1-10	0.29	6.46	31.6	8.6	-	-	2.35	6.3	5.6	17.4
E5b	10-20	0.10	0.69	12.1	1.2	-	-	2.64	6.1	5.6	19.8
E5b	20-40	0.15	0.91	8.1	1.6	-	-	2.61	6.3	5.8	24.1
E5b	40-100	0.06	0.26	5.4	0.4	-	-	2.64	6.3	5.8	25.7
E5c	0-3	0.09	0.59	8.5	1.0	-	-	2.33	6.3	6.1	30.2
E5c	3-12	0.17	9.02	53.2	15.5	-	-	2.31	6.3	6.3	30
E5c	12-45	0.06	0.78	13.0	1.3	-	-	2.63	6.4	6.4	35
E5c	45-100	0.03	0.25	7.8	0.4	-	-	2.63	6.5	6.3	37
E5c_2	12-35	0.02	0.26	12.8	0.4	-	-	2.64	6.3	6.3	20
E5c_3	3-100	0.01	0.02	2.6	0.0	-	-	2.66	6.2	6.3	12
E6a*	0-38	0.16	3.19	20.1	5.5	-	-	2.51	-	4.64	43
E6a*	38-48	0.02	0.17	7.8	0.3	-	-	2.65	-	5.23	32
E6a*	48-90	0.03	0.35	10.3	0.6	-	-	2.64	-	5.61	37
E6a*	90-100	0.03	0.22	8.6	0.4	-	-	-	-	5.53	26
E6a*	100-120	0.08	1.12	13.4	1.9	-	-	-	-	5.5	50
E6a*	120-135	0.04	0.52	12.5	0.9	-	-	-	-	6.04	33
E6a*	135-160	0.04	0.48	11.7	0.8	-	-	2.64	-	-	-
E6b*	0-5	0.18	3.43	19.1	5.9	-	-	-	5.1	4.6	110
E6b*	5-10	0.16	3.58	22.5	6.2	-	-	-	5.1	4.2	40
E6b*	10-20	0.16	3.48	22.1	6.0	-	-	-	5.1	4.3	39
E6b*	20-40	0.03	0.61	18.0	1.1	-	-	-	5.8	5.2	40
E6b*	40-80	0.04	0.42	10.4	0.7	-	-	-	5.9	5	26
E6c*	0-28	0.15	3.07	21.0	5.3	-	-	-	-	-	-
E6c*	28-31	0.02	0.18	8.6	0.3	-	-	-	-	-	-
E6c*	35-44	0.03	0.32	12.3	0.5	-	-	-	-	-	-
E6c*	44-60	0.04	0.78	22.0	1.3	-	-	-	-	-	-
E6c*	60-70	0.02	0.11	6.4	0.2	-	-	-	-	-	-
E6c*	70-82	0.03	0.23	7.2	0.4	-	-	-	-	-	-
E6c*	82-90	0.04	0.54	12.3	0.9	-	-	-	-	-	-
E6c*	90-110	0.02	0.28	11.6	0.5	-	-	-	-	-	-

* Analyses by S. Thomsen (see Thomsen 2018 and unpublished data).

Table 18: Soil texture and class according to Ad-hoc-Arbeitsgruppe Boden (2005) and color (Munsell Color Notation) of the soil layers of sites of established trees (F1-20 and E1-6).

Profile no.	Depth [cm]	Skeleton content [%]	Sand content [%]	Silt content [%]	Clay content [%]	Texture class	Color dry	Color wet
F1	0-4	36.5	81.6	14.0	4.4	Su2	10YR3/2	10YR2/1
F1	4-10	11.8	87.8	9.4	2.7	Ss	10YR5/3	10YR3/3
F1	10-17	27.1	87.1	9.2	3.7	Ss	10YR4/2	10YR2/2
F1	17-22	4.4	85.8	10.0	4.2	Su2	10YR4/2	10YR2/2
F1	22-33	1.0	83.5	11.8	4.7	Su2	10YR5/3	10YR3/3
F1	33-68	5.2	87.1	8.6	4.3	Ss	10YR5/6	10YR3/6
F1	68-100	0.4	95.7	3.4	0.9	Ss	10YR8/2	10YR6/4
F2	0-12	21.0	82.5	9.8	7.7	St2	10YR3/2	10YR2/1
F2	12-31	20.7	84.2	10.6	5.2	Sl2	10YR4/3	10YR2/2
F2	31-40	22.7	85.2	11.3	3.5	Su2	10YR4/2	10YR2/2
F2	40-50	18.1	97.9	1.5	0.6	Ss	10YR5/3	10YR3/3
F2	50-60	3.3	96.4	2.2	1.4	Ss	10YR6/6	10YR4/6
F2	60-74	28.2	93.3	4.4	2.3	Ss	10YR4/3	10YR2/2
F2	74-100	19.8	93.4	2.3	4.4	Ss	10YR5/4	10YR3/4
F3.1	0-7	13.2	87.9	6.5	5.7	St2	10YR3/2	10YR2/2
F3.1	7-15	69.8	86.7	10.0	3.4	Ss	10YR3/2	10YR2/2
F3.1	15-30	15.3	85.2	10.5	4.2	Su2	10YR4/2	10YR2/2
F3.1	30-70	11.6	85.5	10.3	4.2	Su2	10YR5/4	10YR3/4
F3.1	70-100	2.3	97.6	1.3	1.1	Ss	10YR6/4	10YR3/4
F3.2	0-7	8.0	81.9	9.4	8.7	St2	10YR3/2	10YR2/2
F3.2	7-60	11.2	93.0	4.5	2.6	Ss	10YR5/3	10YR3/3
F3.2	60-100	6.8	96.0	2.2	1.8	Ss	10YR5/3	10YR3/3
F4	0-22	7.0	82.5	12.1	5.4	Sl2	10YR3/1	10YR2/1
F4	22-30	3.7	93.3	4.0	2.6	Ss	10YR5/3	10YR3/3
F4	30-34	53.2	86.8	9.0	4.1	Ss	10YR4/2	10YR2/2
F4	34-57	30.1	78.7	13.2	8.1	Sl3	10YR4/2	10YR2/2
F4	57-100	15.4	74.2	16.6	9.2	Sl3	10YR5/3	10YR3/3
F5	0-11	6.3	90.2	5.5	4.3	Ss	10YR4/2	10YR2/2
F5	11-50	5.9	93.0	4.4	2.6	Ss	10YR5/3	10YR3/2
F5	50-100	10.0	92.7	4.7	2.6	Ss	10YR5/3	10YR3/2
F6	0-3	22.6	82.3	11.6	6.1	Su3	10YR3/2	10YR2/2
F6	3-18	9.6	82.6	11.3	6.1	Su4	10YR3/2	10YR2/2
F6	18-28	14.2	89.2	8.5	2.3	Ss	2.5Y4/2	10YR2/2
F6	28-50	18.5	83.3	13.9	2.8	Su2	10YR3/2	10YR2/1
F6	50-100	13.6	90.0	7.4	2.6	Ss	10YR5/3	10YR3/3
F7	0-12	9.0	87.1	7.3	5.6	St2	10YR4/2	10YR2/2
F7	12-32	11.9	96.1	2.0	1.8	Ss	10YR5/3	10YR3/3
F7	32-85	12.4	96.4	1.7	1.9	Ss	10YR4/3	10YR2/2
F7	85-100	0.3	98.3	0.6	1.1	Ss	2.5Y6/4	2.5Y4/4
F8	0-6	13.7	88.1	8.1	3.8	Ss	10YR4/2	10YR2/2
F8	6-11	40.6	86.3	11.0	2.7	Su2	10YR3/1	10YR2/1
F8	11-53	6.8	93.2	5.1	1.7	Ss	10YR4/2	10YR2/2
F8	53-70	15.4	94.6	3.9	1.5	Ss	10YR4/3	10YR2/2
F9	0-22	41.5	84.0	12.3	3.7	Su2	10YR4/1	10YR2/1
F9	22-80	5.7	65.7	25.4	8.9	Sl3	10YR5/2	10YR2/2
F10	0-2	37.3	83.0	13.6	3.4	Su2	10YR5/2	10YR3/2
F10	2-7	45.9	70.5	21.4	8.1	Sl3	10YR6/2	10YR4/2
F10	7-15	29.1	83.7	12.3	4.0	Su2	10YR3/2	10YR2/1
F10	15-100	9.8	94.1	3.9	2.0	Ss	10YR5/3	10YR4/2
F11	0-10	19.8	83.6	10.7	5.8	Sl2	10YR4/2	10YR2/2
F11	10-20	29.4	77.2	17.7	5.1	Sl2	10YR3/1	10YR2/1
F11	20-40	15.5	94.5	3.4	2.0	Ss	10YR4/2	10YR2/2
F11	40-50	4.5	97.0	1.8	1.2	Ss	10YR5/3	10YR3/3
F11	50-100	19.3	95.1	3.0	1.8	Ss	10YR5/2	10YR3/2

* Analyses by F. Zander (see Zander 2016).

Profile no.	Depth [cm]	Skeleton content [%]	Sand content [%]	Silt content [%]	Clay content [%]	Texture class	Color dry	Color wet
F12	0-9	13.7	83.8	9.7	6.5	St2	10YR4/1	10YR2/1
F12	9-20	29.3	89.5	7.4	3.1	Ss	10YR4/2	10YR2/2
F12	20-68	3.9	95.0	3.1	1.9	Ss	10YR6/6	10YR4/6
F12	68-90	3.3	97.0	1.6	1.4	Ss	10YR6/4	10YR4/6
F13	0-19	2.2	81.2	13.5	5.3	Sl2	10YR3/2	10YR2/1
F13	19-50	29.0	84.6	10.3	5.0	Sl2	10YR5/2	10YR2/2
F14	0-32	8.7	79.6	13.6	6.8	Sl2	10YR3/2	10YR2/1
F14	32-50	13.3	78.3	14.2	7.5	Sl2	10YR5/3	10YR3/3
F14	50-100	6.7	83.4	10.7	5.9	Sl2	10YR4/2	10YR2/2
F15	0-18	7.2	71.7	16.8	11.6	Sl3	10YR4/2	10YR2/2
F15	18-62	1.7	70.9	18.7	10.4	Sl3	10YR5/3	10YR3/4
F15	62+	1.6	61.6	19.5	18.8	Ls4	10YR6/4	10YR4/6
F16	0-20	10.7	80.5	13.9	5.6	Sl2	10YR3/1	10YR2/1
F16	20-40	12.7	66.8	25.4	7.8	Su3	10YR5/2	10YR3/2
F16	40-100	9.5	87.9	8.5	3.6	Ss	10YR5/3	10YR3/3
F17	0-8	60.7	82.1	13.4	4.4	Su2	10YR4/4	10YR3/2
F17	8-70	11.3	72.4	20.3	7.3	Sl2	10YR5/3	10YR3/3
F17	70-100	7.3	70.9	23.0	6.1	Sl2	10YR5/6	10YR3/6
F18	0-22	4.1	82.6	10.6	6.9	Sl2	10YR4/2	10YR2/1
F18	22-35	12.3	98.1	1.4	0.5	Ss	10YR5/6	10YR4/6
F18	35-100	9.2	98.9	0.5	0.6	Ss	10YR6/6	10YR4/6
F18	70-75	10.6	68.4	26.3	5.2	Su3	10YR5/3	10YR3/3
F19	0-9	35.6	88.0	8.1	4.0	Ss	10YR3/2	10YR2/2
F19	9-20	18.5	90.2	8.2	1.6	Ss	10YR5/3	10YR3/3
F19	20-24	8.8	90.5	6.9	2.5	Ss	10YR4/4	10YR3/3
F19	24-39	12.7	92.3	5.3	2.4	Ss	10YR4/3	10YR2/2
F19	39-70	1.6	77.2	18.6	4.2	Su2	10YR5/6	10YR3/6
F19	70-100	3.0	97.6	0.6	1.8	Ss	10YR6/6	10YR5/6
F20	0-8	42.7	84.6	11.2	4.2	Su2	10YR6/1	10YR4/2
F20	8-14	12.9	82.9	9.8	7.3	St2	10YR4/2	10YR2/2
F20	14-58	1.2	96.4	1.7	1.9	Ss	10YR5/3	10YR3/3
F20	58-100	0.8	94.6	2.7	2.8	Ss	10YR5/2	10YR2/2
E1a	0-15	3.3	88.4	6.9	4.7	Ss	10YR4/1	10YR2/1
E1a	15-80	9.7	91.7	5.5	2.9	Ss	10YR4/2	10YR2/2
E1a	80-120	0.8	97.6	1.5	0.9	Ss	10YR7/3	10YR5/4
E1b	0-10	2.4	86.0	10.2	3.8	Su2	10YR4/1	10YR2/1
E1b	10-30	16.9	82.1	12.8	5.1	Sl2	10YR5/1	10YR3/1
E1b	30-70	7.6	93.8	3.7	2.5	Ss	10YR5/2	10YR3/2
E1b	70-100	1.6	97.4	1.4	1.4	Ss	10YR7/1	10YR5/3
E1c	0-10	3.1	81.1	12.7	6.1	Sl2	10YR3/2	10YR2/2
E1c	10-33	13.7	81.7	12.2	6.1	Sl2	10YR4/2	10YR2/2
E1c	33-60	0.4	96.0	2.3	1.7	Ss	10YR6/3	10YR4/3
E1c	60-100	0.2	98.7	0.7	0.6	Ss	10YR7/2	10YR5/3
E2a	0-3	13.8	80.7	13.2	6.1	Sl2	10YR4/1	10YR2/1
E2a	3-28	14.0	92.8	5.7	1.6	Ss	10YR7/2	10YR4/3
E2a	28-70	17.8	90.8	6.3	2.9	Ss	10YR5/3	10YR4/3
E2a	70-100	14.3	91.4	5.4	3.4	Ss	10YR6/3	10YR4/3
E2b	0-3	15.1	86.2	8.7	5.1	St2	10YR4/2	10YR2/2
E2b	3-20	20.2	86.7	9.1	4.3	Ss	10YR4/3	10YR2/2
E2b	20-55	12.2	88.4	8.9	2.7	Ss	10YR4/2	10YR2/2
E2b	55-100	13.0	89.6	8.2	2.3	Ss	10YR4/2	10YR2/2
E2c	0-2	20.9	87.9	8.3	3.8	Ss	10YR3/2	10YR2/1
E2c	2-10	23.7	87.2	8.4	4.4	Ss	10YR5/4	10YR3/4
E2c	10-55	23.1	90.7	7.6	1.7	Ss	10YR4/2	10YR2/2
E2c	55-84	16.5	90.6	6.2	3.1	Ss	10YR5/3	10YR3/3
E2c	84-100	13.0	98.2	0.7	1.1	Ss	2.5Y7/4	2.5Y5/4
E3a	0-20	5.7	85.7	9.5	4.8	Ss	10YR4/2	10YR2/2
E3a	20-50	4.6	84.6	11.5	3.9	Su2	10YR3/2	10YR2/1
E3a	50-90	15.6	95.7	2.3	2.0	Ss	10YR4/3	10YR2/2

* Analyses by F. Zander (see Zander 2016).

Profile no.	Depth [cm]	Skeleton content [%]	Sand content [%]	Silt content [%]	Clay content [%]	Texture class	Color dry	Color wet
E3a	90-100	1.7	64.7	20.0	15.3	Sl4	10YR5/3	10YR3/3
E3b	0-3	10.9	83.7	10.7	5.6	Sl2	10YR4/2	10YR2/2
E3b	3-20	9.0	89.7	6.2	4.1	Ss	10YR4/2	10YR2/2
E3b	20-60	8.5	87.2	8.1	4.8	Ss	10YR4/2	10YR2/2
E3b	60-100	12.1	76.9	15.1	8.1	Su2	10YR4/2	10YR2/2
E3c	0-10	7.7	85.8	10.7	3.6	Su2	10YR4/2	10YR2/2
E3c	10-30	4.4	87.0	9.0	4.0	Ss	10YR4/2	10YR2/2
E3c	45-100	5.0	98.4	0.6	1.0	Ss	10YR7/4	10YR5/4
E4a	0-36	4.1	74.3	17.0	8.7	Sl3	10YR3/2	10YR2/1
E4a	36-45	12.1	95.3	2.6	2.1	Ss	10YR5/3	10YR3/3
E4a	45-90	10.5	92.4	4.4	3.3	Ss	10YR5/3	10YR3/3
E4a	90-100	8.4	92.3	4.6	3.1	Ss	10YR5/3	10YR3/3
E4b	0-35	5.9	79.5	15.5	4.8	Su2	10YR4/2	10YR2/1
E4b	35-62	10.9	94.8	2.8	2.5	Ss	10YR7/4	10YR4/4
E4b	62-100	17.1	87.9	8.3	3.8	Ss	10YR5/2	10YR3/2
E4c	0-36	4.2	75.4	18.6	6.0	Sl2	10YR3/2	10YR2/1
E4c	36-55	8.1	94.1	3.6	2.3	Ss	10YR6/4	10YR3/4
E4c	55-80	4.4	86.6	9.5	3.8	Ss	10YR4/3	10YR2/2
E4c	80-90	3.7	87.8	8.5	3.8	Ss	10YR4/3	10YR2/2
E4c	90-100	1.1	87.2	8.6	4.2	Ss	10YR5/3	10YR3/3
E5a	1-13	43.7	85.1	13.4	1.5	Su2	10YR3/1	10YR2/1
E5a	13-17	2.3	97.5	1.4	1.1	Ss	2.5Y6/3	2.5Y4/3
E5a	17-46	37.7	83.0	13.6	3.4	Su2	10YR5/3	10YR3/3
E5a	46-60	19.6	74.3	18.7	7.0	Sl2	10YR6/3	10YR4/3
E5a	60-100	4.7	65.5	21.8	12.7	Sl4	10YR6/4	10YR4/4
E5b	1-10	44.3	85.0	13.2	1.7	Su2	10YR4/1	10YR2/1
E5b	10-20	33.2	83.5	12.2	4.3	Su2	10YR6/3	10YR3/3
E5b	20-40	5.3	70.2	20.6	9.1	Sl3	10YR6/2	10YR3/2
E5b	40-100	5.6	66.9	24.0	9.2	Sl3	10YR7/3	10YR5/4
E5c	0-3	15.1	85.9	8.1	5.9	St2	10YR6/3	10YR4/3
E5c	3-12	43.5	87.9	10.2	2.0	Su2	10YR3/1	10YR2/1
E5c	12-45	5.5	78.8	15.6	5.5	Su2	10YR5/3	10YR3/3
E5c	45-100	6.3	64.7	21.3	14.0	Sl4	10YR6/4	10YR4/4
E5c_2	12-35	25.3	91.0	5.7	3.3	Ss	10YR5/4	10YR3/4
E5c_3	3-100	0.1	98.6	0.3	1.1	Ss	10YR7/4	10YR5/4
E6a*	0-38	-	89.2	8.6	2.2	Ss	-	-
E6a*	38-48	-	94.8	3.8	1.5	Ss	-	-
E6a*	48-90	-	93.1	3.7	3.3	SS	-	-
E6a*	90-100	-	95.1	3.4	1.6	Ss	-	-
E6a*	100-120	-	73.5	18.9	7.6	Sl2	-	-
E6a*	120-135	-	98.4	0.6	1.0	Ss	-	-
E6a*	135-160	-	89.1	7.9	3.1	Ss	-	-
E6b*	0-5	-	88.5	8.6	2.8	Ss	-	-
E6b**	5-10	13.8	83.7	12.0	4.4	Su2	-	-
E6b**	10-20	10.3	84.1	11.8	4.2	Su2	-	-
E6b*	20-40	-	80.1	14.3	5.7	Sl2	-	-
E6b*	40-80	-	64.4	23.9	11.6	Sl3	-	-
E6c*	0-28	-	89.9	6.5	3.6	Ss	-	-
E6c*	31-35	-	91.8	4.9	3.3	Ss	-	-
E6c*	35-44	-	88.3	7.6	4.1	Ss	-	-
E6c*	44-60	-	83.9	10.4	5.7	Sl2	-	-
E6c*	60-70	-	95.2	3.1	1.7	Ss	-	-
E6c*	70-82	-	56.6	27.8	15.6	Sl4	-	-
E6c*	82-90	-	73.0	18.4	8.6	Sl3	-	-
E6c*	90-110	-	94.2	3.5	2.2	Ss	-	-

* Analyses by S. Thomsen (see Thomsen 2018 and unpublished data). ** Analyses by F. Zander (see Zander 2016)

Table 19: Root categories according to Ad-hoc-Arbeitsgruppe Boden (2005), effective bulk density, pore volume, air capacity, field capacity, available water capacity (AWC) and K_{sat} at sites with established trees (F1-20 and E1-6)**.**

Profile no.	Depth [cm]	Root category	eff. bulk density [g/cm³]	Pore volume [%]	Air capacity [%]	Field capacity [%]	AWC [%]	K_{sat}, normalized to 10°C [cm/day]
F1	4-10	Wf3	1,77	33,0	11,6	21,4	17,6	3,5
F1	10-17	W0	1,52	40,8	20,8	20,0	13,3	-
F1	17-22	W2	1,72	33,8	3,8	30,0	20,6	-
F1	33-68	W1	1,66	37,8	13,6	24,2	18,5	83,0
F1	68-100	W0-1	1,73	34,6	14,7	19,9	19,2	192,5
F2	0-12	W5	1,26	49,1	10,2	38,9	21,3	1270,0
F2	12-31	W5	1,35	47,5	10,2	37,4	30,0	-
F2	50-60	Wf1	1,63	38,4	27,7	10,7	8,8	-
F2	60-74	Wf1	1,59	39,4	18,0	21,4	16,0	-
F2	74-100	W0	1,60	39,5	27,2	12,3	8,1	-
F3.1	0-7	Wf5, Wg4	0,88	62,9	15,1	47,8	34,7	-
F3.1	15-30	Wf2, Wg2	1,56	39,6	14,0	25,6	18,5	-
F3.1	30-70	Wf3	1,57	40,1	19,8	20,3	14,1	-
F3.1	70-100	Wf2	1,58	40,2	20,1	20,1	18,5	-
F3.2	7-60	Wg3, Wf4	1,50	42,6	24,2	18,5	14,3	-
F4	0-22	Wf5, Wg5	0,92	62,7	14,9	47,8	39,8	-
F4	22-30	Wf3	1,54	41,3	19,9	21,5	18,7	-
F4	34-57	W2	1,64	50,4	10,2	27,4	15,9	-
F4	57-100	W2	1,74	41,3	7,1	26,7	15,7	-
F5	0-11	Wf3, Wg3	1,09	56,1	20,9	35,2	28,1	-
F5	11-50	Wf2, Wg2	1,57	40,3	26,2	14,1	11,4	755,0
F5	50-100	Wf2, Wg3	1,51	42,5	27,3	15,1	11,9	463,0
F6	3-18	Wf3, Wg2	1,18	53,6	21,4	32,3	21,5	-
F6	18-28	W1	1,47	43,6	20,5	23,1	16,3	291,8
F6	28-50	W2	1,23	52,8	27,4	25,4	15,5	636,7
F6	50-100	Wg1	1,54	41,5	27,8	13,6	7,8	771,8
F7	0-12	Wf3, Wg2	1,33	47,4	15,5	31,9	22,8	-
F7	12-32	W2	1,44	45,2	32,3	12,9	8,8	1060,0
F7	32-85	Wf1, Wg1	1,45	44,9	33,7	11,2	7,4	-
F7	85-100	W0	1,67	37,0	29,9	7,1	5,5	3984,2
F8	0-6	Wf3, Wg2	1,33	46,4	11,6	34,8	22,7	2162,7
F8	6-11	W1	1,02	57,2	32,1	25,0	17,1	546,8
F8	11-53	W1-W3	1,52	41,7	24,6	17,1	12,5	-
F8	53-70	W3	1,36	48,3	32,9	15,4	11,9	-
F9	0-22	W2	1,34	45,8	27,4	18,4	10,7	373,4
F9	22-80	W2	1,55	40,8	13,6	27,2	13,9	25,8
F10	0-2	W0	1,69	35,9	20,1	15,8	10,5	-
F10	2-7	W0	1,69	35,9	20,1	15,8	10,9	-
F10	7-15	W1	1,28	50,0	23,9	26,1	18,1	261,3
F10	15-100	W1	1,58	40,1	25,6	14,5	12,2	-
F11	0-10	Wf5, Wg1	1,03	58,5	21,9	36,6	27,1	-
F11	10-20	Wf5-6, Wg2-5	0,78	66,7	35,8	30,9	20,5	-
F11	20-40	W0	1,52	42,2	30,0	12,1	8,8	-
F11	40-50	W0	1,55	41,6	32,2	9,4	3,3	-
F11	50-100	W0	1,37	47,4	31,4	15,9	10,1	-
F12	0-9	Wf3, Wg1	1,43	42,9	8,8	34,2	21,8	-
F12	9-20	Wf3, Wg2	1,54	46,8	25,4	21,5	14,0	-
F12	20-68	W0	1,60	39,6	27,5	12,1	9,9	-
F12	68-90	W0	1,48	44,2	36,9	7,4	5,8	-
F13	0-19	Wf3, Wg1	1,13	55,4	20,9	34,5	25,5	-
F13	19-50	Wf2	1,48	43,3	19,1	24,2	15,6	-

Profile no.	Depth [cm]	Root category	eff. bulk density [g/cm³]	Pore volume [%]	Air capacity [%]	Field capacity [%]	AWC [%]	K_{sat}, normalized to 10°C [cm/day]
F14	0-32	Wf5, Wg3	1,50	40,0	5,8	34,2	20,0	-
F14	32-50	Wf2, Wg1	1,54	41,6	18,7	22,9	12,9	-
F14	50-100	Wf4, Wg3	1,26	51,3	28,3	23,0	17,5	-
F15	0-18	Wf5, Wg3	1,26	50,2	9,8	40,4	26,3	-
F15	18-62	Wf2, Wg1	1,65	37,5	11,2	26,3	14,1	-
F16	0-20	Wf5-6, Wg2-5	1,03	58,3	16,3	42,0	28,0	-
F16	20-40	Wf3, Wg2	1,46	44,0	11,6	32,5	21,4	-
F16	40-100	Wf1, Wg2	1,44	45,2	18,2	27,0	20,8	-
F17	0-8	Wf1	1,35	48,1	20,6	27,5	16,6	-
F17	8-70	Wg2	1,66	37,1	8,4	28,7	19,5	-
F17	70-100	Wg2	1,75	33,8	11,3	22,5	14,3	-
F18	0-22	Wf3, Wg3	1,20	52,4	20,6	31,8	21,7	-
F18	22-35	Wf1	1,59	39,8	33,0	6,8	5,3	-
F18	35-100	W0	1,62	38,7	33,5	5,3	3,6	-
F19	0-9	Wf3, Wg3	1,14	55,9	26,7	29,2	22,1	-
F19	9-20	Wf1	1,65	37,3	24,4	12,9	10,4	-
F19	20-24	W0	1,61	39,0	25,4	13,6	10,1	-
F19	24-39	Wf1	1,70	35,8	23,5	12,3	9,1	-
F19	39-70	W0	1,73	34,8	17,4	17,4	13,9	-
F19	70-100	W0	1,53	41,9	36,0	6,0	5,0	-
F20	0-8	W0	1,51	43,7	27,7	16,0	12,8	-
F20	8-14	Wf3, Wg2	1,19	53,0	24,2	28,8	21,8	-
F20	14-58	W0	1,64	38,0	27,7	10,3	8,2	-
E1a	0-15	Wf6, Wg2	1,23	50,4	10,5	39,8	28,1	365,2
E1a	15-80	Wf3, Wg3	1,53	41,3	18,3	23,0	15,9	540,7
E1a	80-120	Wf2	1,59	39,5	27,7	11,7	9,4	1240,0
E1b	0-10	Wf6, Wg4	1,10	55,7	12,2	43,5	28,6	-
E1b	10-30	Wf3, Wg3	1,45	44,6	16,0	28,6	17,0	559,2
E1b	30-70	Wf3	1,54	41,2	21,4	19,9	15,5	-
E1c	0-10	Wf6, Wg2	1,17	53,4	10,3	43,1	29,4	393,7
E1c	10-33	Wf5, Wg5	1,33	48,3	17,0	31,3	20,1	-
E1c	33-60	Wf2	1,61	38,8	14,8	24,1	21,0	-
E1c	60-100	Wf2	1,64	38,0	16,6	21,4	19,6	-
E2a	3-28	Wf2, Wg1	1,69	36,1	19,8	16,3	10,4	269,5
E2a	28-70	Wf0, Wg1	1,67	36,8	23,2	13,6	6,7	-
E2a	70-100	Wf0, Wg1	1,68	36,4	21,9	14,4	7,9	-
E2b	3-20	Wf6, Wg4	1,56	40,3	14,6	25,6	16,6	257,6
E2b	20-55	Wf2	1,67	36,4	13,5	22,8	15,0	325,2
E2b	55-100	W0	1,60	38,7	18,2	20,5	13,7	-
E2c	2-10	Wf2, Wg1	1,75	34,2	17,9	16,3	1,8	159,8
E2c	10-55	W6-W1	1,70	36,0	18,5	17,6	10,1	3308,3
E2c	55-84	W0	1,63	37,9	18,2	19,7	14,6	797,2
E2c	84-100	W0	1,61	39,2	30,9	8,3	5,5	1578,0
E3a	0-20	Wf4, Wg2	1,45	43,3	7,2	36,1	26,0	-
E3a	20-50	Wf2, Wg1	1,56	39,0	11,0	28,0	17,5	104,8
E3a	50-90	Wf1	1,69	36,1	26,0	10,1	1,6	97,8
E3b	3-20	W2	1,70	34,7	7,4	27,3	17,4	-
E3b	20-60	W2	1,65	37,1	14,8	22,3	11,6	-
E3b	60-100	W2	1,46	43,9	23,0	20,8	10,5	284,8
E3c	0-10	Wf1-4, Wg1	1,61	37,9	14,5	23,5	15,3	41,2
E3c	10-30	W2	1,52	41,3	15,2	26,0	18,0	307,8
E3c	45-100	W0	1,62	39,0	37,2	1,8	0,5	2505,0
E4a	0-36	W3	1,27	51,9	10,1	41,8	24,5	238,2
E4a	36-45	W1	1,71	34,9	21,7	13,3	9,8	288,3
E4a	45-90	W1	1,74	34,0	19,8	14,2	10,0	1016,2
E4a	90-100	W1	1,63	38,5	26,1	12,4	8,2	582,8
E4b	0-35	W3	1,16	53,1	10,1	43,0	30,2	42,8
E4b	35-62	W0	1,70	35,6	25,8	9,8	6,9	828,2
E4b	62-100	W2	1,48	41,9	25,0	16,9	10,3	304,6

Profile no.	Depth [cm]	Root category	eff. bulk density [g/cm³]	Pore volume [%]	Air capacity [%]	Field capacity [%]	AWC [%]	K_{sat}, normalized to 10°C [cm/day]
E4c	0-36	W2	1,26	49,9	7,4	42,5	29,9	257,9
E4c	36-55	W0	1,64	38,4	21,1	17,3	15,0	-
E4c	55-80	W1	1,76	32,5	9,4	23,1	15,5	72,8
E4c	90-100	W0	1,76	33,1	15,4	17,7	12,2	-
E5a	1-13	Wf2, Wg1	1,01	57,3	31,2	26,0	21,0	-
E5a	17-46	Wf3, Wg2	1,56	39,7	16,8	22,9	14,6	-
E5a	46-60	Wf1	1,76	33,3	12,8	20,5	10,2	-
E5a	60-100	W0	1,84	30,7	4,0	26,6	12,2	0,3
E5b	1-10	Wf2, Wg1	0,97	58,6	33,9	24,6	19,4	520,7
E5b	10-20	Wf3, Wg2	1,74	33,9	13,7	20,2	11,4	-
E5b	20-40	Wf3, Wg2	1,82	30,2	3,1	27,2	12,8	0,3
E5b	40-100	Wf1, Wg1	1,73	34,6	8,9	25,7	14,3	-
E5c	3-12	W0	0,89	61,6	39,0	22,6	17,8	572,7
E5c	12-45	W0	1,84	30,2	5,1	25,1	12,2	3,3
E5c	45-100	Wf1-2	1,84	30,1	4,4	25,7	7,1	1,8
E5c_2	12-35	W0	1,70	35,6	23,1	12,5	7,8	-
E5c_3	3-100	W0	1,66	37,5	18,5	19,1	17,9	-
E6a*	10 (0-38)	Wf4, Wg1	1,34	47,8	12,6	35,2	27,2	-
E6a*	20 (0-38)	Wf4, Wg1	1,27	50,5	25,4	25,2	17,5	-
E6a*	40 (38-48)	Wf1, Wg1	1,77	34,4	14,0	20,4	16,7	-
E6a*	80 (48-90)	Wf1	1,63	41,7	17,0	24,7	20,0	-
E6a*	160 (135-160)	Wf1, Wg3	1,42	47,3	24,1	23,2	14,3	-

* Analyses by S. Thomsen (see Thomsen 2018 and unpublished data).

Table 20: Van Genuchten parameters of the sites F1, F3, F6, F8, F12, F19, F20 and E1-6.

Profile no.	Depth	θ_r	θ_s	α	n	Ks	l
	[cm]	[vol./vol.]	[vol./vol.]	[cm^{-1}]		[cm/day]	
F1	0-32.5	0.073	0.332	0.0198	2.375	24.0	3.564
F1	32.5-67.5	0.080	0.395	0.0172	3.458	11.2	4.502
F1	67.5-100	0.031	0.329	0.0164	4.417	19.9	4.156
F3.1	0-70	0.066	0.407	0.0663	1.649	59.7	1.485
F3.1	70-100	0.042	0.406	0.0479	4.843	12.4	-1.052
F3.2	0-100	0.074	0.446	0.0359	2.421	14.2	1.626
F6	0-18	0.010	0.531	0.1220	1.211	868.5	3.633
F6	18-28	0.106	0.403	0.0284	2.315	7.14	-1.428
F6	28-50	0.107	0.508	0.0599	1.519	12.6	2.790
F6	50-100	0.071	0.404	0.0510	2.180	21.5	12.487
F8	0-6	0.145	0.470	0.0264	1.770	7.61	2.929
F8	6-11	0.097	0.578	0.0929	1.802	2.85	3.180
F8	11-53	0.089	0.416	0.0285	2.932	3.38	-1.316
F8	53-100	0.067	0.392	0.0441	2.182	17.4	4.156
F12	0-20	0.060	0.470	0.0468	1.515	2.65	3.092
F12	20-68	0.044	0.395	0.0333	3.343	4.90	3.505
F12	68-90	0.047	0.449	0.0379	4.331	12.1	3.568
F19	0-20	0.035	0.382	0.0506	1.731	8.14	2.824
F19	20-24	0.038	0.390	0.0984	1.623	4.56	2.489
F19	24-39	0.051	0.367	0.0606	1.755	548.5	2.770
F19	39-70	0.011	0.343	0.0313	1.446	39.5	2.242
F19	70-100	0.051	0.367	0.0606	1.755	548.5	2.770
F20	1-100	0.067	0.396	0.0236	6.483	0.754	-1.511
E1a	0-15	0.030	0.501	0.0203	1.291	4.58	2.350
E1a	15-80	0.088	0.400	0.0261	1.500	47.2	4.949
E1a	80-100	0.050	0.356	0.0331	2.020	3.29	-1.388
E1b	0-10	0.048	0.424	0.0219	1.549	61.3	1.621
E1b	10-30	0.030	0.268	0.0862	1.256	172.4	1.820
E1b	30-70	0.038	0.361	0.0261	1.941	47.2	4.949
E1b	70-100	0.050	0.256	0.0331	2.020	3.29	-1.388
E1c	0-10	0.091	0.478	0.0196	1.527	9.26	0.942
E1c	10-33	0.030	0.368	0.0862	1.256	172.4	1.820
E1c	33-60	0.088	0.461	0.0261	1.941	47.2	4.949
E1c	60-100	0.008	0.360	0.0424	1.828	130.6	5.461
E2a	0-3	0.107	0.408	0.0318	1.832	41.9	2.327
E2a	3-28	0.077	0.369	0.0423	1.018	22.4	3.466
E2a	28-70	0.109	0.315	0.0317	2.743	19.3	4.192
E2a	70-100	0.079	0.361	0.0305	2.253	20.4	3.004
E2b	0-20	0.107	0.408	0.0318	1.832	41.9	2.327
E2b	20-55	0.006	0.373	0.0343	1.270	44.4	-0.932
E2b	55-100	0.068	0.386	0.0698	1.770	38.3	4.674
E2c	0-10	0.010	0.388	0.1632	1.315	2649.4	1.968
E2c	10-55	0.081	0.366	0.0298	1.855	26.5	3.406
E2c	55-84	0.043	0.376	0.0965	1.660	46.3	3.173
E2c	84-100	0.051	0.402	0.0480	4.489	0.814	-1.788
E3a	0-20	0.081	0.395	0.0208	1.586	44.2	1.476
E3a	20-50	0.01	0.364	0.0965	1.185	313.8	5.078
E3a	50-90	0.068	0.364	0.5000	1.508	114.5	3.324
E3a	90-100	0.124	0.433	0.0626	1.824	12.0	3.274

Profile no.	Depth [cm]	θ_r [vol./vol.]	θ_s [vol./vol.]	α [cm^{-1}]	n	Ks [cm/day]	l
E3b	0-20	0.081	0.366	0.0298	1.855	26.5	3.406
E3b	20-60	0.123	0.371	0.0376	1.874	12.6	-1.123
E3b	60-100	0.124	0.433	0.0626	1.824	12	3.274
E3c	0-10	0.031	0.329	0.0164	4.417	19.9	4.156
E3c	0-45	0.098	0.412	0.0355	1.648	28.4	2.419
E3c	45-100	0.032	0.425	0.0390	5.000	0.492	-1.562
E4a	0-36	0.202	0.495	0.0236	1.450	26.3	-0.939
E4a	36-45	0.067	0.35	0.0483	2.573	2.75	3.227
E4a	45-90	0.083	0.332	0.0208	2.821	4.31	5.234
E4a	90-100	0.06	0.376	0.0765	1.933	53.4	2.267
E4b	0-35	0.067	0.541	0.0347	1.251	40.0	0.797
E4b	35-62	0.036	0.349	0.1071	1.788	263.3	1.533
E4b	62-100	0.093	0.418	0.0455	1.993	39.4	-1.080
E4c	0-36	0.004	0.503	0.1513	1.199	312.8	1.380
E4c	36-55	0.061	0.379	0.0433	3.401	10.1	2.142
E4c	55-80	0.114	0.344	0.0181	2.527	15.3	4.452
E4c	80-100	0.075	0.306	0.0282	2.551	6.58	3.610
E5a	0-13	0.202	0.495	0.0236	1.45	26.3	-0.939
E5a	13-17	0.185	0.323	0.0280	1.815	2.07	3.573
E5a	17-46	0.075	0.313	0.0441	2.54	50.3	1.932
E5a	46-60	0.108	0.29	0.0063	1.457	9.29	2.551
E5a	60-100	0.094	0.351	0.0077	1.345	14.1	2.672
E5b	0-10	0.010	0.572	0.1852	1.351	10000	2.127
E5b	10-40	0.143	0.311	0.0118	1.742	0.296	-1.46
E5b	40-100	0.006	0.358	0.3176	1.144	483.4	3.833
E5c	0-12	0.010	0.664	0.4143	1.325	189.6	-1.311
E5c	12-45	0.113	0.305	0.0114	1.503	5.27	3.573
E5c	45-100	0.006	0.32	0.0392	1.089	13.4	-6.000
E5c_2	12-35	0.074	0.367	0.0414	3.091	14.6	3.431
E5c_3	3-100	0.185	0.323	0.0280	1.815	2.07	3.573
E6a	0-38	0.11	0.458	0.0228	1.894	13.9	-0.577
E6a	38-48	0.1	0.307	0.0274	2.285	1.56	-1.116
E6a	48-90	0.006	0.388	0.0574	1.323	50.9	-0.691
E6a	90-100	0.167	0.394	0.0225	2.796	0.752	-1.618

Appendix III: Soil analyses at sites of young trees

Table 21: Soil texture according to Ad-hoc-Arbeitsgruppe Boden (2005) and color (Munsell Color Notation) at sites of young trees. Planting substrates are marked in bold, others are the surrounding urban soil.

Profile no.	Depth [cm]	Skeleton content [%]	Sand content [%]	Silt content [%]	Clay content [%]	Texture class	Color dry	Color wet
Y1*	0-25	51.0	88.7	5.7	5.6	St2	10YR3/1	10YR2/1
Y1*	25-55	54.3	87.3	5.2	7.5	St2	10YR3/1	10YR2/1
Y1*	45-95	31.8	67.8	16.1	16.1	Sl4	7.5YR3/1	7.5YR2.5/1
Y1*	95-100	15.7	74.5	17.4	8.2	Sl3	10YR4/1	10YR2/2
Y1*	0-45	28.5	80.5	11.1	8.4	Sl3	10YR4/2	10YR3/1
Y2a	0-40	44.3	77.3	13.3	9.4	Sl3	10YR2/2	10YR2/1
Y2a	40-70	34.7	91.5	5.3	3.2	Ss	10YR4/2	10YR2/2
Y2a	0-35	18.4	77.3	15.1	7.6	Sl2	10YR4/2	10YR2/2
Y2a	35-60	7.9	90.9	5.5	3.6	Ss	10YR5/3	10YR3/3
Y2a	60-100	8.9	69.8	14.1	16.1	Sl4	10YR5/3	10YR3/3
Y2b	0-45	34.9	80.9	11.9	7.3	Sl2	10YR2/2	10YR2/1
Y2b	45-70	18.2	89.7	7.7	2.6	Ss	10YR4/3	10YR3/2
Y2b	0-40	13.3	72.9	16.6	10.5	Sl3	10YR4/2	10YR2/2
Y2b	40-60	14.8	92.3	5.6	2.1	Ss	10YR5/3	10YR3/3
Y2b	60-100	7.8	72.7	13.9	13.4	Sla	10YR5/3	10YR4/3
Y2c	0-40	42.8	79.8	12.6	7.6	Sl2	10YR2/2	10YR2/1
Y2c	40-60	22.4	86.6	8.7	4.7	St2	10YR4/2	10YR2/2
Y2c	0-30	26.1	87.2	9.4	3.4	Ss	10YR4/3	10YR2/2
Y2c	30+	7.9	89.6	7.8	2.5	Ss	10YR4/3	10YR2/2
Y3a	0-35	45.8	81.2	11.1	7.7	Sl2	10YR2/2	10YR2/1
Y3a	35-60	18.2	92.5	4.7	2.8	Ss	10YR4/2	10YR2/2
Y3a	60-65	19.4	89.6	7.5	3.0	Ss	10YR4/3	10YR2/2
Y3a	65-100	7.2	92.4	5.6	1.9	Ss	10YR5/4	10YR3/4
Y3a	0-60	17.1	93.6	3.7	2.7	Ss	10YR5/3	10YR4/3
Y3b	0-35	32.4	89.8	4.6	5.6	St2	10YR4/2	10YR2/2
Y3b	35-50	32.6	83.1	11.8	5.1	Sl2	10YR3/2	10YR2/1
Y3b	0-50	8.6	84.6	11.1	4.3	Su2	10YR4/2	10YR2/2
Y3b	50-80	18.2	95.2	2.9	1.8	Ss	10YR5/4	10YR3/4
Y3b	50-80	24.3	91.1	5.4	3.5	Ss	10YR5/3	10YR3/3
Y3c	0-40	45.3	82.9	9.7	7.4	St2	10YR2/2	10YR2/1
Y3c	40-70	9.5	92.1	5.5	2.4	Ss	10YR5/4	10YR3/4
Y3c	0-20	26.5	79.1	13.8	7.1	Sl2	10YR3/2	10YR2/1
Y3c	20-40	14.0	77.9	16.3	5.8	Sl2	10YR4/2	10YR2/2
Y3c	40-60	7.0	92.3	5.0	2.7	Ss	10YR5/4	10YR3/4
Y3c	60-80	9.0	73.9	14.5	11.6	Sl3	10YR5/3	10YR3/3
Y4a	0-40	8.3	87.8	8.8	3.4	Ss	10YR4/3	10YR2/2
Y4a	40-70	1.9	82.4	12.6	4.9	Su2	10YR6/3	10YR4/4
Y4a	0-5	4.2	85.9	9.8	4.4	Ss	10YR5/3	10YR3/3
Y4a	0-60	3.2	83.5	12.1	4.4	Su2	10YR4/2	10YR2/2
Y4a	60-100	2.7	79.2	13.9	6.9	Sl2	10YR6/4	10YR4/6
Y4b	0-40	8.2	86.8	8.9	4.3	Ss	10YR4/3	10YR2/2
Y4b	40-70	7.1	94.7	2.8	2.5	Ss	10YR4/4	10YR3/3
Y4b	0-60	8.6	86.3	9.7	4.0	Ss	10YR4/3	10YR2/2
Y4b	60-100	6.8	97.0	1.5	1.5	Ss	10YR5/4	10YR3/4

* Analyses by M. von Strachwitz (see Strachwitz 2017).

Profile no.	Depth [cm]	Skeleton content [%]	Sand content [%]	Silt content [%]	Clay content [%]	Texture class	Color dry	Color wet
Y4c	0-10	50.3	80.8	10.7	8.5	Sl3	10YR2/2	10YR2/1
Y4c	10-40+	11.9	84.0	12.1	3.9	Su2	10YR4/2	10YR2/2
Y4c	70	3.8	61.5	24.1	14.4	Sl4	10YR5/3	10YR3/3
Y4c	0-30	8.6	89.2	8.0	2.8	Ss	10YR4/3	10YR2/2
Y4c	30-80	12.7	85.6	9.4	4.9	Ss	10YR4/3	10YR2/2
Y4c	30-60	7.5	94.5	3.4	2.1	Ss	10YR5/4	10YR3/4
Y4c	80-100	2.1	77.3	12.9	9.7	Sl3	10YR6/6	10YR4/6
Y5*	0-70	12.3	92.0	4.9	3.1	Ss	10YR3/2	10YR2/1
Y5*	50-100	17.7	93.2	4.9	1.9	Ss	10YR5/1	10YR4/2
Y6*	0-35	38.0	82.9	10.4	6.7	Sl2	10YR3/1	10YR2/1
Y6*	35-70	20.8	92.6	4.2	3.2	Ss	10YR3/2	10YR2/1
Y6*	70-100	3.8	97.0	1.5	1.5	Ss	10YR5/3	10YR3/2
Y7*	0-10	43.7	74.9	21.2	3.9	Su2	7.5YR6/1	10YR4/1
Y7*	10-100	57.8	83.1	12.7	4.3	Su2	7.5YR4/3	7.5YR2.5/3
Y8*	0-5	55.8	92.2	4.4	3.4	Ss	10YR6/1	10YR4/1
Y8*	5-100	42.6	81.7	14.6	3.7	Su2	5YR4/4	5YR2.5/2
Y9	0-55	7.2	86.4	10.7	2.9	Su2	10YR4/2	10YR2/2
Y9	5-30	33.5	79.2	11.9	8.9	Sl3	10YR2/2	10YR2/1
Y9	55-80	2.5	85.4	9.9	4.8	Ss	10YR4/2	10YR2/2
Y9	80-100	0.1	93.7	5.4	0.9	Ss	10YR5/4	10YR3/4
Y9	0-60	36.0	77.2	11.7	11.1	Sl3	10YR3/1	10YR2/1
Y10	0-60	18.4	90.3	6.0	3.6	Ss	10YR4/2	10YR2/2
Y10	60-90	10.0	95.4	2.2	2.4	Ss	10YR4/3	10YR3/3
Y10	90-100	11.0	76.5	15.5	8.0	Sl2	10YR5/3	10YR3/3
Y10	0-70	29.4	84.3	9.0	6.7	St2	10YR3/1	10YR2/1
Y11	0-70	48	-	-	-	-	10YR2/2	10YR2/1
Y11	0-80	7.5	90.5	5.8	3.7	Ss	10YR4/3	10YR2/2
Y11	80-100	1.7	59.0	23.4	17.6	Ls4	10YR6/4	10YR4/4

* Analyses by M. von Strachwitz (see Strachwitz 2017).

Table 22: Nitrogen (N), carbon (C), C/N-value, humus content, C_{anorg}, $CaCO_3$, density of solid substance, pH-value and el. conductivity in the substrates at sites of young trees. Planting substrates are marked in bold, others are the surrounding urban soil.

Profile no.	Depth [cm]	N [%]	C [%]	C/N [-]	Humus content [%]	C_{anorg} [%]	$CaCO_3$ [%]	Density of solid matter [g/cm³]	pH-value in H_2O [-]	pH-value in $CaCl_2$ [-]	Conduc-tivity in 1:2.5 [µS/cm]
Y1*	0-25	0.32	4.3	13.3	7.4	-	-	2.71	6.6	6.4	74
Y1*	25-55	0.30	4.0	13.4	6.8	0.12	1.02	2.66	7.1	6.8	136
Y1*	45-95	0.15	1.9	12.7	3.2	0.16	1.33	2.64	7.5	7.1	355
Y1*	95-100	0.14	1.3	8.8	2.2	-	-	2.60	6.8	6.8	193
Y1*	0-45	0.12	1.7	13.8	2.9	-	-	2.59	6.7	6.6	33
Y2a	0-40	1.77	11.7	9.5	20.1	0.15	1.21	2.47	7.3	6.7	193
Y2a	40-70	0.32	2.1	9.2	3.5	0.01	0.12	2.63	7.0	6.5	101
Y2a	0-35	0.35	3.5	12.8	6.0	-	-	2.42	6.4	5.7	54
Y2a	35-60	0.23	0.3	6.2	0.6	0.00	0.03	2.63	7.0	6.6	50
Y2a	60-100	0.23	0.6	6.1	1.0	-	-	2.64	6.5	6.3	69
Y2b	0-45	0.62	8.8	14.2	15.2	0.14	1.16	2.47	7.4	6.8	325
Y2b	45-70	0.25	0.7	6.5	1.2	0.01	0.12	2.61	7.2	6.8	163
Y2b	0-40	0.34	2.3	9.5	4.0	-	-	2.48	6.4	5.6	67
Y2b	40-60	0.35	1.9	8.9	3.2	-	-	2.63	6.5	6.1	39
Y2b	60-100	0.50	0.4	4.6	0.7	-	-	2.62	6.7	6.5	47
Y2c	0-40	4.68	9.9	7.7	17.0	0.13	1.10	2.53	7.6	6.6	535
Y2c	40-60	0.16	2.3	14.8	4.0	0.06	0.49	-	8.0	6.9	167
Y2c	0-30	0.16	2.0	12.4	3.4	0.03	0.28	2.59	7.2	6.6	107
Y2c	30+	0.07	1.3	18.9	2.3	0.13	1.12	2.60	8.3	7.2	186
Y3a	0-35	0.83	12.2	14.8	20.9	0.16	1.35	2.44	7.2	6.6	249
Y3a	35-60	0.08	1.2	15.5	2.1	0.08	0.71	2.65	7.6	6.6	117
Y3a	60-65	0.05	0.7	12.9	1.1	0.03	0.24	-	7.4	6.7	107
Y3a	65-100	0.04	0.4	11.3	0.7	0.01	0.07	2.63	7.3	7.0	83
Y3a	0-60	1.26	2.3	8.4	4.0	0.55	4.58	2.64	8.0	7.2	98
Y3b	0-35	0.21	2.9	13.7	5.0	0.03	0.24	2.66	6.9	6.6	112
Y3b	35-50	0.35	5.2	14.7	8.9	0.05	0.44	2.55	7.5	6.5	173
Y3b	0-50	0.15	2.1	14.4	3.6	-	-	2.56	5.5	5.0	55
Y3b	50-80	0.04	0.5	12.4	0.8	-	-	2.63	6.8	6.4	51
Y3b	50-80	0.11	0.8	8.5	1.3	-	-	2.33	6.0	5.5	37
Y3c	0-40	0.58	8.5	14.8	14.7	0.12	1.02	2.59	7.3	6.6	228
Y3c	40-70	0.13	0.9	9.5	1.5	0.05	0.45	2.61	7.1	6.7	219
Y3c	0-20	0.35	4.7	13.6	8.1	-	-	2.50	6.4	5.9	230
Y3c	20-40	0.24	2.5	11.4	4.4	-	-	2.61	5.9	5.6	193
Y3c	40-60	0.15	0.4	6.9	0.8	-	-	2.62	6.7	6.3	135
Y3c	60-80	0.19	0.6	7.2	1.0	0.10	0.85	2.64	7.6	7.1	218
Y4a	0-40	0.12	1.5	12.1	2.6	0.01	0.07	2.61	7.1	6.3	83
Y4a	40-70	0.03	0.2	6.3	0.3	-	-	2.65	6.7	6.3	84
Y4a	0-5	0.06	0.5	8.3	0.8	-	-	2.64	6.7	6.0	64
Y4a	0-60	0.22	2.6	11.8	4.5	0.02	0.21	2.53	7.0	6.2	142
Y4a	60-100	0.02	0.1	5.7	0.2	-	-	2.64	6.7	6.3	31
Y4b	0-40	0.11	1.2	11.4	2.1	-	-	2.60	6.2	5	65
Y4b	40-70	0.04	0.4	9.5	0.6	-	-	-	6.0	5.3	35
Y4b	0-60	0.10	1.1	11.1	1.8	-	-	2.62	5.9	5.0	66
Y4b	60-100	0.03	0.2	8.0	0.4	-	-	2.63	6.7	5.5	34
Y4c	0-10	0.89	12.6	14.2	21.7	0.19	1.58	2.48	7.6	6.9	468
Y4c	10-40+	0.19	2.5	13.2	4.4	0.03	0.21	2.56	7.0	6.1	132
Y4c	70	0.07	0.6	8.4	1.0	0.00	0.00	2.54	7.0	6.3	56
Y4c	0-30	0.09	1.1	12.1	2.0	-	-	2.60	6.2	5.4	102
Y4c	30-80	0.06	0.7	11.9	1.2	-	-	-	6.7	5.8	77
Y4c	30-60	0.03	0.3	10.0	0.5	-	-	2.63	6.6	5.9	56
Y4c	80-100	0.03	0.2	6.8	0.3	-	-	2.64	6.9	6.0	53

* Analyses by M. von Strachwitz (see Strachwitz 2017).

Profile no.	Depth [cm]	N [%]	C [%]	C/N [-]	Humus content [%]	C_{anorg} [%]	$CaCO_3$ [%]	Density of solid matter [g/cm³]	pH-value in H_2O [-]	pH-value in $CaCl_2$ [-]	Conduc-tivity in 1:2.5 [µS/cm]
Y5*	0-70	0.10	1.3	12.6	2.2	-	-	2.66	6.8	6.7	58
Y5*	50-100	0.05	0.6	13.2	1.1	0.18	1.54	2.64	7.7	7.3	73
Y6*	0-35	0.54	7.5	13.8	12.9	0.19	1.59	-	7.2	6.9	560
Y6*	35-70	0.12	1.4	11.6	2.3	0.09	0.72	2.69	7.0	6.8	17
Y6*	70-100	0.04	0.3	7.8	0.5	-	-	-	6.8	6.8	88
Y7*	0-10	0.05	6.5	138.1	11.2	5.34	44.48	-	7.8	7.3	95
Y7*	10-100	0.07	1.4	20.6	2.3	0.07	0.61	2.60	8.0	7.2	161
Y8*	0-5	0.04	0.2	5.2	0.4	0.30	2.48	2.66	7.3	7.1	35
Y8*	5-100+	0.09	2.4	27.2	4.1	0.12	0.96	2.68	7.5	7.2	97
Y9	0-55	0.12	1.8	14.8	3.1	-	-	2.56	6.6	6.4	65
Y9	5-30	0.59	8.6	14.6	14.8	-	-	-	6.6	6.4	241
Y9	55-80	0.06	0.8	13.3	1.4	-	-	2.62	6.6	6.4	69
Y9	80-100	0.02	0.2	6.9	0.3	-	-	-	6.5	6.5	44
Y9	0-60	0.60	9.6	15.9	16.5	-	-	2.57	6.6	6.4	293
Y10	0-60	0.05	0.9	18.3	1.5	0.13	1.09	2.66	7.7	7.0	114
Y10	60-90	0.03	0.5	18.2	0.8	0.11	0.89	2.64	7.6	7.1	93
Y10	90-100	0.04	1.4	36.4	2.4	0.71	5.94	-	8.1	7.2	143
Y10	0-70	0.29	4.0	14.0	6.9	-	-	2.63	7.2	6.8	116
Y11	0-70	12.33	0.8	14.9	1.4	-	-	-	7.6	7.0	918
Y11	0-80	0.88	0.0	17.8	0.1	-	-	-	7.9	7.2	152
Y11	80-100	1.16	0.0	30.0	0.1	-	-	-	8.3	7.5	132

* Analyses by M. von Strachwitz (see Strachwitz 2017).

Table 23: Water-soluble ions (chloride (Cl), fluoride, bromide, nitrate, sulfate, calcium, sodium, magnesium (Mg), potassium (K)) in the substrates at sites of young trees. Planting substrates are marked in bold, others are the surrounding urban soil.

Profile no.	Depth [cm]	Chloride [mg/kg DM]	Fluoride [mg/kg DM]	Nitrite [mg/kg DM]	Bromide [mg/kg DM]	Nitrate [mg/kg DM]	Sulfate [mg/kg DM]	Calcium [mg/kg DM]	Sodium [mg/kg DM]	Mg [mg/kg DM]	K [mg/kg DM]
Y1*	0-25	16.9	0.2	0.3	<0.05	359.0	33.6	91.9	22.2	8.7	51.0
Y1*	25-55	16.1	0.4	0.2	<0.05	290.6	37.7	70.8	22.9	9.9	84.1
Y1*	45-95	19.7	0.6	0.3	<0.05	473.8	121.6	142.2	26.9	16.7	75.6
Y1*	95-100	15.3	0.5	0.2	<0.05	340.1	112.8	127.8	24.9	10.9	23.3
Y1*	0-45	1.8	0.5	0.1	<0.05	64.1	5.3	34.5	5.5	8.3	29.0
Y5*	0-70	5.5	0.8	0.1	<0.05	155.1	36.8	36.2	14.9	6.2	43.7
Y5*	50-100	2.3	0.6	0.2	<0.05	9.0	70.5	31.8	5.2	2.3	22.4
Y6*	0-35	170.4	0.3	0.1	<0.05	225.7	293.0	57.3	83.8	10.7	347.0
Y6*	35-70	59.4	0.7	<0.05	<0.05	37.1	126.0	25.0	36.5	6.8	110.3
Y6*	70-100	25.7	0.3	<0.05	<0.05	10.5	40.6	9.3	16.2	2.3	42.4
Y7*	0-10	0.9	0.6	0.1	<0.05	33.0	6.3	24.8	5.5	2.3	11.7
Y7*	10-100	17.9	0.5	0.1	<0.05	14.5	189.1	82.4	18.3	4.5	9.7
Y8*	0-5	0.7	0.5	0.1	<0.05	9.7	34.3	20.2	2.5	1.0	6.1
Y8*	5-100	7.8	4.2	<0.05	<0.05	35.3	45.3	44.3	5.7	4.2	7.6

* Analyses by M. von Strachwitz (see Strachwitz 2017).

Table 24: P-, P_2O_5-, K- and K_2O-content in the substrates at sites of young trees. Planting substrates are marked in bold, others are the surrounding urban soil.

Profile no.	Depth [cm]	P [mg/kg]	P_2O_5 [mg/100g]	K [mg/kg]	K_2O [mg/100g]
Y1	0-25	191.2	43.8	200.9	24.2
Y1	0-45	69.4	15.9	101.4	12.2
Y2a	0-40	94.1	21.6	1115.5	134.4
Y2a	0-35	680.1	155.8	210.5	25.4
Y2b	0-45	69.3	15.9	840.5	101.3
Y2b	0-40	499.2	114.4	231.5	27.9
Y2c	0-40	369.5	84.7	621.4	74.9
Y2c	0-30	166.8	38.2	179.2	21.6
Y3a	0-35	83.1	19.0	795.5	95.9
Y3a	0-60	29.0	6.6	97.0	11.7
Y3b	0-35	1099.3	251.9	355.5	42.8
Y3b	0-50	180.6	41.4	80.0	9.6
Y3c	0-40	80.7	18.5	1050.5	126.6
Y3c	0-20	1087.3	249.1	495.5	59.7
Y4a	0-40	32.2	7.4	267.5	32.2
Y4a	0-5	13.2	3.0	43.5	5.2
Y4a	0-60	40.0	9.2	371.0	44.7
Y4b	0-40	45.0	10.3	233.5	28.1
Y4b	0-60	41.2	9.4	276.5	33.3
Y4c	0-10	109.4	25.1	1670.5	201.3
Y4c	0-30	121.6	27.9	103.5	12.5
Y5	0-70	111.5	25.6	122.9	14.8
Y6	0-35	301.6	69.1	886.4	106.8
Y7	0-10	23.9	5.5	67.4	8.1
Y8	0-5	22.8	5.2	44.4	5.4
Y9	0-55	244.5	56.0	116.7	14.1
Y9	0-60	361.9	82.9	312.2	37.6
Y10	0-60	148.0	33.9	159.0	19.2
Y10	0-70	224.5	51.4	210.2	25.3

Appendix IV: Modeled water tensions at sites of established roadside trees

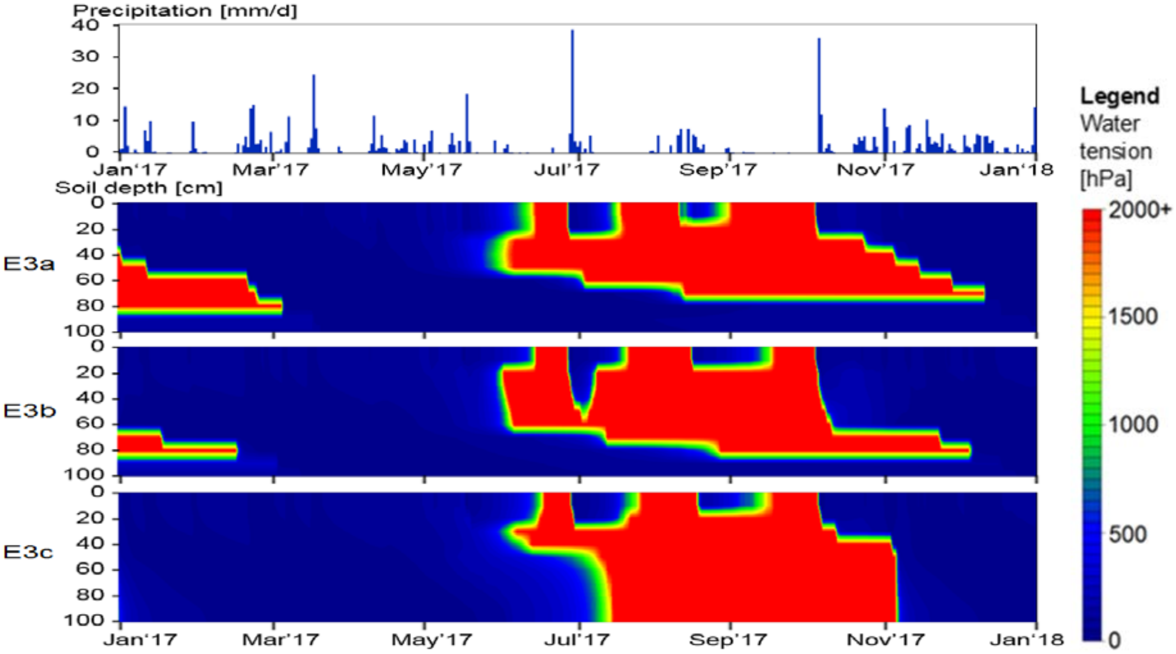

Figure 58: Precipitation [mm/d] of the climate station at E3 (data gaps filled with precipitation rates from Deutscher Wetterdienst) and modeled water tension [hPa] in the profiles E3a-c from 1st of January to 31st of December 2017.

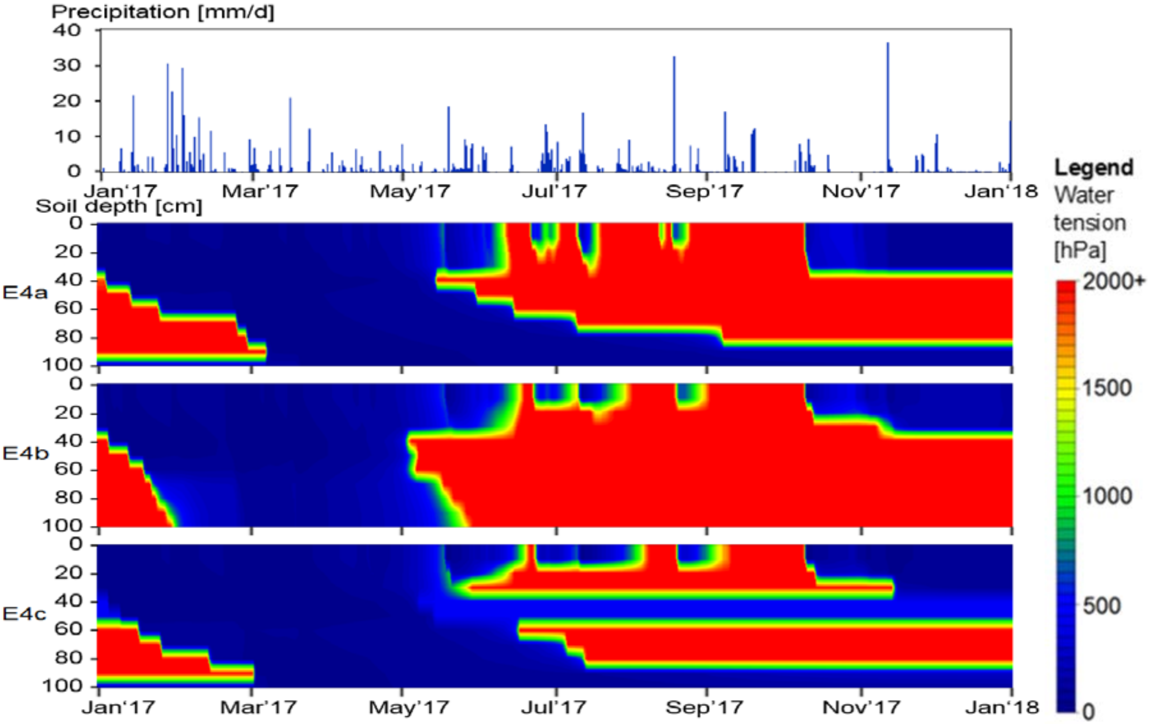

Figure 59: Precipitation [mm/d] of the climate station at E4 (data gaps filled with precipitation rates from Deutscher Wetterdienst) and modeled water tension [hPa] in the profiles E4a-c from 1st of January to 31st of December 2017.

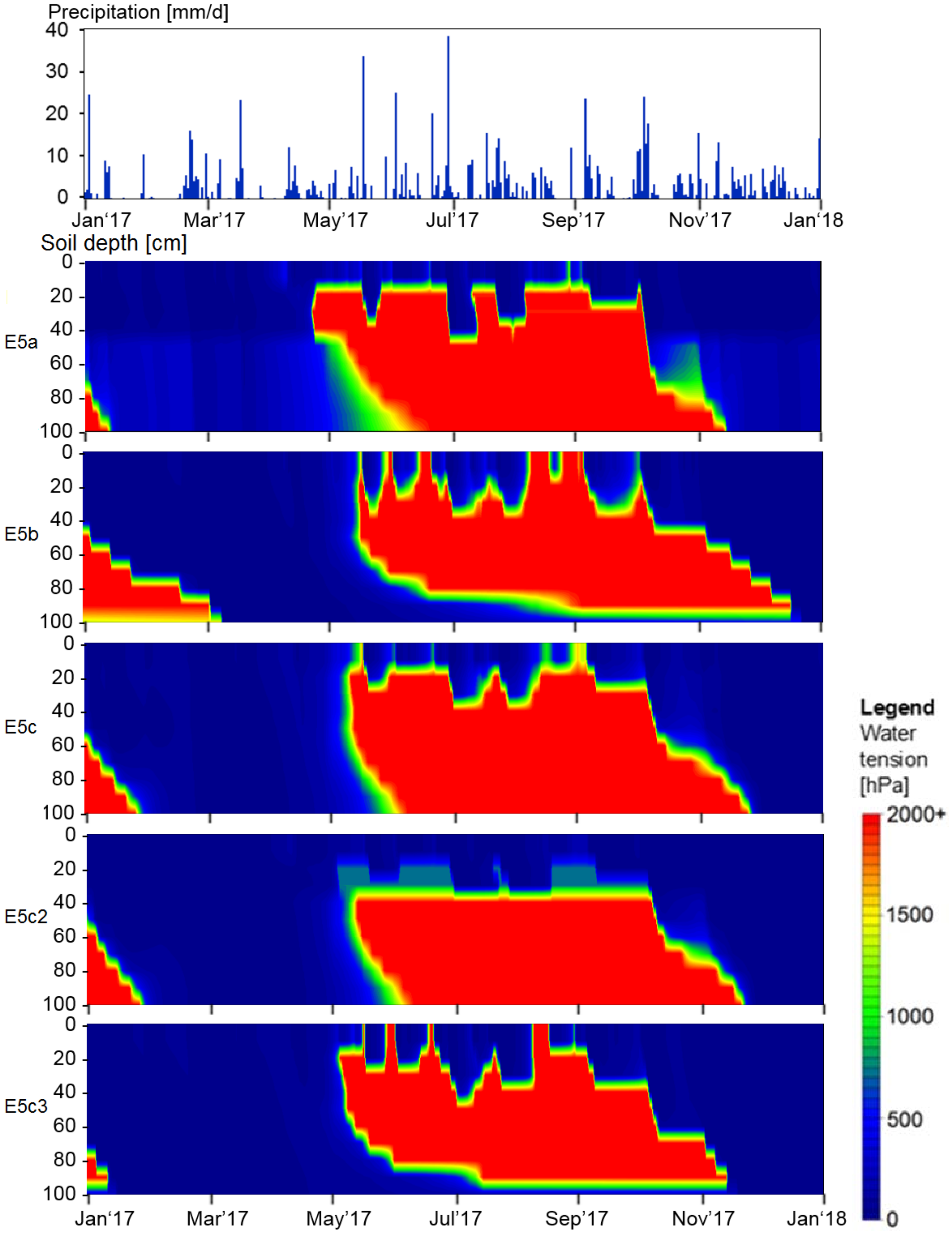

Figure 60: Precipitation [mm/d] of the climate station in Fuhlsbüttel (Deutscher Wetterdienst) and modeled water tension [hPa] in the profiles E5a-c from 1st of January to 31st of December 2017. Two additional profiles (E5c2 and E5c3) were modeled with data of soil profiles lying directly next to E5c.

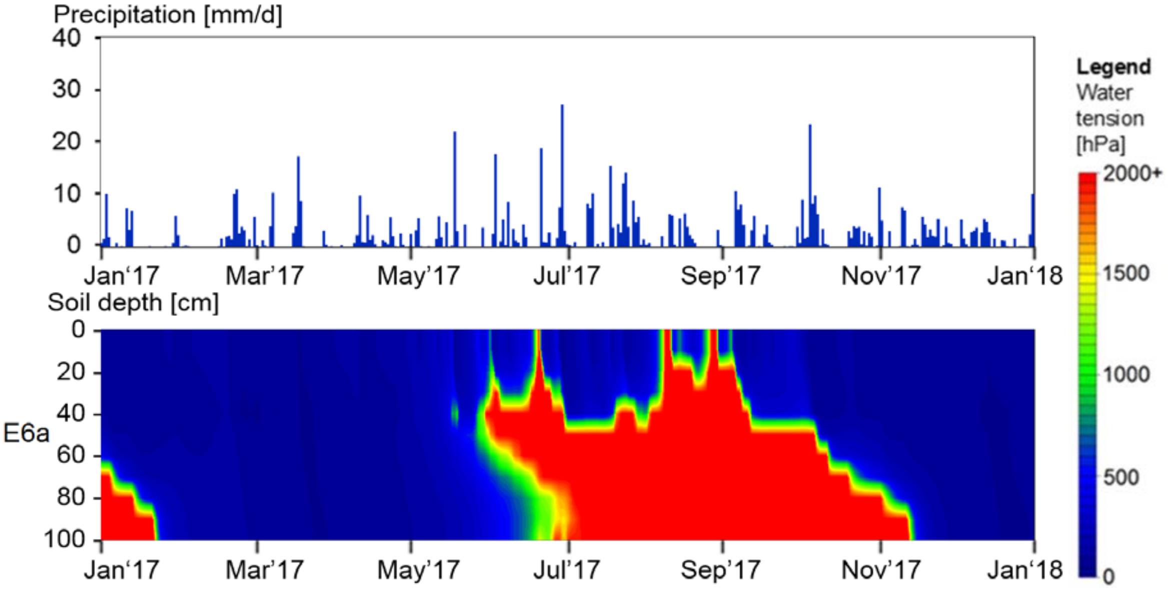

Figure 61: Precipitation [mm/d] of the climate station at E6 (data gaps filled with precipitation rates from Deutscher Wetterdienst) and modeled water tension [hPa] in the profile E6a from 1st of January to 31st of December 2017.