Significance of soil water availability for growth and vitality of recently planted urban street trees

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Content

Abstract

Growth conditions at urban street-tree sites can be unfavorable and in northern Europe temperate climates tree vitality will be increasingly threatened by water scarcity due to a changing climate. Nursery grown and recently planted trees in urban areas have a barely developed root system. Therefore, particularly in the first years after planting, young trees along streets might suffer from limited soil water availability and poor site conditions. As soil water is mainly determining tree growth, vitality and mortality, knowledge about root zone soil-water dynamics, hydrological properties of artificial urban planting soils and water stress responses of different urban tree species is crucial, but still lacking.

Therefore, this thesis aims to answer to what extent recently planted street-trees were exposed to critical soil water availability and which external parameters are most important for soil drought to occur. Further, investigations were conducted to test if technically mixed structural soil and artificial urban soil were suitable as urban planting media in terms of soil hydrological properties and growth responses of different urban tree species. Finally, research addressed on how and to which extent recently planted street trees respond physiologically to limited soil water availability and if species specific water stress can be explained by growth and vitality parameters. To answer the research questions, three different study approaches were applied and structured in three individual manuscripts. The studies field data were thereby collected on basis of two independent experimental approaches that differ strongly in terms of extent, location and study design: (i) A long-term *in situ* soil water monitoring in the urban environment and (ii) a large-scale experimental field study in a complete block design with different soil substrates, representative for young urban street tree sites, and commonly used urban street tree species.

First, a soil water monitoring network containing 17 young urban street-tree sites in the city of Hamburg, Germany was established. Over four years (2016–2019) the soil water potential and the soil temperature were measured under *in situ* conditions. Based on a plausible soil water potential (SWP) threshold derived from literature, beyond which tree growth and vitality is likely to be critically affected (SWP; < -1200 hPa), the extent of SWP below was quantified for the soil compartments root ball, planting pit, and surrounding urban soil. During 2018 and 2019, average critical soil water availability in the root ball and planting pit occurred between three to five months per year. Thus, the trees were exposed prolonged periods of potential water stress for two consecutive years. To assess the tree site sensitivity towards meteorological variables, tree- and site characteristics, a data driven *randomForest* model was adapted and trained by the quantified critical soil water availability data.

After planting, critical soil water availability increasingly shifted year wise from the root ball into the entire planting pit as a consequence of root development and increasing water demand of the trees. Considering less usable water within the surrounding sandy soils, indicated by lower water stress intensity, soil water in the planting pit may be depleted earlier and more rapidly with increasing tree age. This finding can likewise be interpreted from the *randomForest* modelling result that identified tree age as an important predictor. However, long-term (10-day) precipitation was the most important variable predicting the occurrence of critical soil water availability, suggesting a further extension of periods with critical soil water availability as rainy summer days are projected to decrease with climate change. Additionally, soil temperature was identified being a more important predictor than air temperature as it reflects site specific characteristics affecting water- an energy balance. Water infiltration capacity and soil sealing were of medium importance for the occurrence of critical soil water availability in planting pits and urban soils. However, the influence of soil properties was not pronounced in this model approach, likely due to the separated consideration of the soil compartments, their low variability in composition and the thus represented very narrow range of data. The plausible conclusions drawn from the analysis demonstrated the capability of a data-driven method to predict the occurrence of critical soil water availability with high accuracy.

In the second study approach, a large-scale experimental field study was established to investigate the response of nine tree species (135 individuals in total) to two common urban planting soils (‘Sand’ and ‘FLL’) and a ‘Loamy Silt’ reference over a three-year period. Therefore, soil hydrological parameters were determined and tree growth and -vitality were measured and monitored regularly. The results revealed for the sandy-textured urban planting soils low plant available water capacities of 6% v/v in the ‘Sand’ and 10% v/v in the ‘FLL’ and also a low unsaturated hydraulic conductivity, that likely limits water resupply to the roots during phases of high demand. Tree growth was restricted in both urban planting soils, but evidently stronger in the ’Sand’ than in ‘FLL’ compared to the reference soil. However, for single tree species different patterns have been identified: e.g. *Ostrya carpinifolia* with least growth restrictions in ‘FLL’, *Liquidambar styraciflua* with restricted growth but simultaneously high vitality in ‘Sand’, *Amelanchier lamarkii* that was weakest in ‘Sand’ and vigorous in ‘FLL’ and *Koelreuteria paniculata* with no differences in growth between the substrates and however, overall poor vitality. On average, tree growth was most limited in ‘Sand’ (-64% compared to ‘Loamy Silt’) with strongest effect for *Quercus palustris* and *Amelanchier lamarkii*. The results suggest that commonly used urban street tree species react differently to water limitations and thus have both, different genetic fixed and actually developed strategies to cope with soil drought. I hypothesize, that tree species which invest resources in fine root growth and exploration to extract water from dry soils with low conductivities might be more successful in urban roadside settings than trees that are only able to lower their root water potential. Thus, as a consequence of low water availability, the use of unfavorable planting soils can cause severe, species-specific growth deficits reflecting limited above-ground carbon uptake or a redistribution of assimilates to plant organs of higher demand (i.e. roots).

In the third study approach I intended to investigate the impact of decreased soil water availability on stomatal limitation of assimilation to quantitatively estimate the stress incidences for recently planted urban tree species. Therefore, SWP data of 14 of the 17 *in situ* soil water monitoring sites in the City of Hamburg, Germany were used over a four years record (2018 – 2021). Thereby, stomatal conductivity (g_S) was measured over a two years period. Recorded maximum g_S was strongly different in specific *species and site combinations*. Decreasing SWP significantly decreased g_S of most species with differently shaped correlation functions. The individual *species x site combination* g_S response on SWP was highly sensitive to the soil compartment. Adapting a widely used photosynthesis model considering measured stomatal and literature based enzyme kinetic parameters, revealed their high relevance for assimilation. Furthermore, the stomatal limited assimilation depends again strongly on the interplay of the temperature dependent assimilation and the modelled range of stomatal conductivity. Species with lower stomatal regulative ranges and medium ranged values of enzyme kinetic parameters were limited in carbon assimilation due to stomatal regulation earlier and already at low temperatures. Species with higher stomatal regulative ranges were less limited in assimilation and lead to a lower stress incidence during the four years record compared to the species of lower stomatal regulative ranges. Therefore, and as the results correlate significantly with parameters such as isotopic signature ($\delta^{13}C$) and relative growth, the generic assumption that broadly ranged stomatal regulation be coupled with higher incidences of stomatal limitation of assimilation can be questioned. Particularly $\delta^{13}C$ data, comparatively easy to gather, has proven to approximate these stress incidences and thus might be an applicable parameter for future investigations at urban tree sites. Based on a set of seven tree species this study approach showed complex interactions of soil water availability and physiological responses, however only valid for the respective sites. To assess future favored plant selection, follow-up studies need to further clarify the benefits of identified patterns (e.g., stomatal regulatory width, temperature sensitivity of assimilation) for urban cooling or death avoidance under increasing climate extremes and at sites with varying soil conditions.

Taken together, in addition to protecting and preserving mature, established trees , the results of this study clearly indicate the need of adequate soil conditions at yet to be planted tree sites to increase their water supply and thus the trees resilience and longevity towards climate extremes in an even denser urban environment than their predecessors faced.

Zusammenfassung

Wachstumsbedingungen für städtische Straßenbäume können unvorteilhaft sein, und in den gemäßigten Klimazonen Nordeuropas kann das Gedeihen von Bäumen zukünftig zunehmend durch Wasserknappheit aufgrund des Klimawandels gefährdet sein. In Baumschulen kultivierte und kürzlich gepflanzte Bäume in städtischer Umgebung haben ein wenig entwickeltes Wurzelsystem. Daher können junge Bäume entlang von Straßen, vor allem in den ersten Jahren nach der Pflanzung, unter der begrenzten Verfügbarkeit von Bodenwasser und schlechten Standortbedingungen leiden. Da das Bodenwasser das Wachstum, die Vitalität und die Sterblichkeit von Bäumen maßgeblich bestimmt, ist das Wissen über die Boden-Wasser-Dynamik in der Wurzelzone, die hydrologischen Eigenschaften von künstlichen städtischen Pflanzböden und die Reaktion verschiedener städtischer Baumarten auf begrenzte Wasserverfügbarkeit von hoher Bedeutung, aber noch nicht ausreichend erforscht. In dieser Arbeit soll daher geklärt werden, inwieweit kürzlich gepflanzte Straßenbäume einer kritischen Wasserverfügbarkeit im Boden ausgesetzt sind und welche externen Parameter für das Auftreten von Bodentrockenheit am bedeutendsten sind. Des Weiteren wurde untersucht, ob sich technisch gemischte Strukturböden und künstliche Stadtböden im Hinblick auf die hydrologischen Bodeneigenschaften und die Wachstumsreaktionen verschiedener Stadtbaumarten eignen. Abschließend wurde untersucht, wie und in welchem Ausmaß neu gepflanzte Straßenbäume physiologisch auf die begrenzte Wasserverfügbarkeit im Boden reagieren und ob der artspezifische Wasserstress durch Wachstums- und Vitalitätsparameter erklärt werden kann. Zur Beantwortung der Forschungsfragen wurden drei unterschiedliche Studienansätze angewandt und in drei einzelne Manuskripten gegliedert. Die Felddaten der Studie wurden dabei auf der Grundlage von zwei voneinander unabhängigen experimentellen Ansätzen erhoben, die sich hinsichtlich Studiendesign, Standort und Umfang stark unterschieden: (i) ein langfristiges *in situ* Bodenwasser-Monitoring im städtischen Umfeld und (ii) eine groß angelegte experimentelle Feldstudie in einem Blockdesign mit verschiedenen repräsentativen Bodensubstraten und für den Einsatz in Städten empfohlenen Straßenbaumarten.

In einem ersten Ansatz wurde ein Bodenwasser-Monitoring mit 17 jungen städtischen Straßenbäumen in der Stadt Hamburg, Deutschland, aufgebaut. Über vier Jahre (2016-2019) wurden das Bodenwasserpotential (SWP) und die Bodentemperatur unter *in situ* Bedingungen gemessen. Auf der Grundlage eines aus der Literatur abgeleiteten plausiblen Schwellenwerts für das Bodenwasserpotential (< -1200 hPa), bei dessen Unterschreitung das Wachstum und die Vitalität von Bäumen wahrscheinlich kritisch beeinträchtigt werden, wurde das Ausmaß dieses Zustands für die Bodenkompartimente Wurzelballen, Pflanzgrube und umgebender Stadtboden quantifiziert. In den Jahren 2018 und 2019 lag die durchschnittliche kritische Bodenwasserverfügbarkeit im Wurzelballen und in der Pflanzgrube zwischen drei und fünf Monaten pro Jahr. Die Bäume waren demnach in zwei

aufeinanderfolgenden Jahren über längere Zeiträume hinweg potentiellem Wasserstress ausgesetzt. Um die Empfindlichkeit des Baumstandortes gegenüber meteorologischen Variablen, Baum- und Standortcharakteristika zu bewerten, wurde ein datengesteuertes *randomForest* Modell mit den quantifizierten Daten der kritischen Bodenwasserverfügbarkeit angepasst und damit "trainiert". Nach der Pflanzung verlagerte sich die Ausbildung kritischer Bodenwasserverfügbarkeit im Jahresverlauf zunehmend vom Wurzelballen in die gesamte Pflanzgrube. Somit könnte, vermutlich in Folge der Wurzelentwicklung und des steigenden Wasserbedarfs der Bäume und in Anbetracht des unvollständig ausgenutzten Bodenwassers in den umgebenden Sandböden, angedeutet durch eine geringere Wasserstressintensität, das Bodenwasser in der Pflanzgrube früher und schneller verbraucht sein. Dies lässt sich auch aus dem Ergebnis der *randomForest* Modellierung interpretieren, die das Baumalter als wichtigen Prädiktor identifiziert. Der langfristige (10-tägige) Niederschlag die wichtigste Variable zur Vorhersage des Auftretens kritischer Bodenwasserverfügbarkeit, was auf eine weitere Verlängerung der Zeiträume mit kritischer Bodenwasserverfügbarkeit hindeutet, da die Regentage im Sommer im Zuge des Klimawandels voraussichtlich abnehmen werden. Darüber hinaus erwies sich die Bodentemperatur als wichtigerer Prädiktor als die Lufttemperatur, da sie standortspezifische Merkmale widerspiegelt, die den Wasser- und Energiehaushalt der Standorte beeinflussen. Als einzelne Parameter betrachtet waren die Infiltrationskapazität und die Bodenversiegelung von mittlerer Bedeutung für das Auftreten kritischer Bodenwasserverfügbarkeit in Pflanzgruben und städtischen Böden. Der Einfluss der Bodeneigenschaften war in diesem Modellansatz nicht ausgeprägt, was wahrscheinlich auf die getrennte Betrachtung der Bodenkompartimente, ihre geringe Variabilität in der Zusammensetzung und die damit dargestellte sehr enge Bandbreite an Daten zurückzuführen ist. Die plausiblen Schlussfolgerungen, die aus der Analyse gezogen wurden, zeigen die Fähigkeit dieser datengesteuerten Methode, in einem nächsten Schritt, das Auftreten von kritischer Bodenwasserverfügbarkeit mit hoher Genauigkeit vorherzusagen.

Im Rahmen des zweiten Studienansatzes wurde eine groß angelegte experimentelle Feldstudie durchgeführt, um die Reaktion von neun Baumarten (135 Individuen insgesamt) auf zwei gängige städtische Pflanzböden ('Sand' und 'FLL' im Vergleich zu einer Referenz aus "lehmigem Schluff") über einen Zeitraum von drei Jahren zu untersuchen. Dazu wurden die hydrologischen Parameter der Böden bestimmt und das Wachstum und die Vitalität der Bäume regelmäßig gemessen und überwacht. Die Ergebnisse zeigten für die sandigen und strukturierten städtischen Pflanzböden eine niedrige pflanzenverfügbare Wasserkapazität von 6 % (v/v) im 'Sand' und 10 % (v/v) im 'FLL' sowie eine niedrige ungesättigte hydraulische Leitfähigkeit, die wahrscheinlich die Wasserzufuhr zu den Wurzeln in Phasen mit hohem Bedarf einschränkt. Das Wachstum der Bäume war in beiden städtischen Böden eingeschränkt, im Vergleich zum Referenzboden jedoch im 'Sand' deutlich stärker als im 'FLL'. Bei einzelnen Baumarten wurden dennoch unterschiedliche Muster festgestellt: z.B. bei *Ostrya carpinifolia* mit den geringsten Wachstumseinschränkungen im 'FLL', bei *Liquidambar styraciflua* mit eingeschränktem Wachstum, aber gleichzeitig hoher Vitalität im 'Sand', *Amelanchier lamarkii*, die im 'Sand' am schwächsten und im 'FLL' am vitalsten war, und *Koelreuteria paniculata* mit keinem Unterschied im Wachstum zwischen den Substraten, aber insgesamt schlechter Vitalität. Im Durchschnitt war das Baumwachstum im 'Sand' am stärksten limitiert (-64% im Vergleich zum 'Lehmigen Schluff'), mit dem stärksten Effekt für *Quercus palustris* und *Amelanchier lamarkii*. Die Ergebnisse deuten darauf hin, dass die häufig verwendeten städtischen Straßenbaumarten unterschiedlich auf Wassereinschränkungen reagieren und somit sowohl unterschiedliche genetisch fixierte als auch unter den Umständen entwickelte Strategien zur Bewältigung von Bodentrockenheit haben. Ich stelle die Hypothese auf, dass Baumarten, die Ressourcen in das Feinwurzelwachstum und die Erschließung des Wurzelraumes investieren, um trockenen Böden mit niedriger Leitfähigkeit die nötige Menge Wasser zu entziehen, an städtischen Straßenrändern erfolgreicher sein könnten als Bäume, die "nur" ihr Wurzelwasserpotenzial senken können. Als Folge der geringen Wasserverfügbarkeit kann die Verwendung ungünstiger Pflanzböden also zu schweren, artspezifischen Wachstumsdefiziten führen, die eine begrenzte oberirdische Kohlenstoffaufnahme oder eine Umverteilung von Assimilaten auf Pflanzenorgane mit höherem Bedarf (d. h. Wurzeln) widerspiegeln. Im dritten Studienansatz wollte ich die Auswirkungen von geringer Bodenwasserverfügbarkeit auf die stomatäre Assimilationslimitierung untersuchen, um die Stresshäufigkeit und -auswirkung für neu gepflanzte Stadtbaumarten quantitativ abschätzen zu können. Dazu wurden SWP-Daten von 14 der 17 *in situ* Bodenwassermessstellen in der Stadt Hamburg, Deutschland, über einen Zeitraum von vier Jahren (2018 - 2021) verwendet. Zudem wurde die stomatäre Leitfähigkeit (g_S) über einen Zeitraum von zwei Jahren gemessen. Die aufgezeichneten maximalen g_S Werte unterschieden sich stark zwischen den einzelnen Arten und Standortkombinationen. Mit abnehmender SWP verringerte sich die g_S bei den meisten Arten signifikant, mit unterschiedlichen Korrelationsfunktionen. Die g_S-Reaktion einzelner Arten und Standortkombinationen auf SWP war sehr empfindlich gegenüber dem Bodenkompartiment. Die Anwendung und Anpassung eines weit verbreiteten Photosynthese-Modells unter Berücksichtigung gemessener stomatärer und literaturbasierter enzymkinetischer Parameter zeigte deren hohe Relevanz für die Assimilation. Darüber hinaus hängt die stomatär limitierte Assimilation wiederum stark von der Wechselwirkung zwischen der Temperaturabhängigkeit der Assimilation und dem modellierten Bereich der stomatären Leitfähigkeit ab. Arten mit niedrigeren stomatären Regulierungsbereichen und mittleren enzymkinetischen Werten waren in der Kohlenstoffassimilation aufgrund stomatärer Regulierung früher und bereits bei niedrigen Temperaturen begrenzt. Arten mit höheren stomatären Regulierungsbereichen und mittleren bis hohen enzymkinetischen Werten waren in der Assimilation weniger eingeschränkt. Dies führte in den vier modellierten Jahren zu einer geringeren Stresshäufigkeit als bei den Arten mit niedrigeren stomatären Regulierungsbereichen. Da die Ergebnisse signifikant mit Parametern wie der Isotopensignatur ($\delta^{13}C$) und dem relativen Wachstum korrelieren, kann die allgemeine Annahme, dass ein breiter stomatärer Regulierungsbereich mit einer höheren Häufigkeit der stomatären Assimilationsbegrenzung einhergeht, in Frage gestellt werden. Insbesondere $\delta^{13}C$-Daten, die vergleichsweise einfach zu erheben sind, haben sich als Näherungswerte für diese Stresshäufigkeit erwiesen und könnten daher ein geeigneter Parameter für zukünftige Untersuchungen an städtischen Baumstandorten sein. Anhand einer Reihe von sieben Baumarten zeigte dieser Studienansatz komplexe Wechselwirkungen zwischen Bodenwasserverfügbarkeit und physiologischen Reaktionen, die jedoch nicht allgemeingültig, sondern nur für die jeweiligen Standorte gelten. Um die zukünftig zu bevorzugende Pflanzenauswahl ermitteln zu können, müssen Folgestudien den Nutzen der identifizierten Muster (z.B. stomatäre Regulationsbreite, Temperaturempfindlichkeit der Assimilation) für die Kühlfunktion oder die Vermeidung des Absterbens bei zunehmenden Klimaextremen und an Standorten mit unterschiedlichen Bodenbedingungen weiter klären.

Insgesamt gilt, neben der Notwendigkeit des Schutzes und der Erhaltung reifer, etablierter Bäume, zeigen die Ergebnisse dieser Studie eindeutig die Wichtigkeit angemessener Bodenbedingungen an Baumstandorten an. Es muss das Ziel sein die Wasserversorgung und damit die Widerstandsfähigkeit und Langlebigkeit an heute bepflanzten und zu bepflanzenden Baumstandorten gegenüber Klimaextremen in einer sehr viel dichter bebauten und entwickelten städtischen Umgebung zu erhöhen, als dies noch in der Vergangenheit der Fall war.

List of Publications and practical Co-Supervisions

Parts of this thesis have been published in peer-reviewed journals and were presented at national and international conferences. The relevant publications and conference contributions are listed below. In addition, thesis of students supervised practically during the doctoral studies are listed.

Publication I

Soil water stress at young urban street-tree sites in response to meteorology and site parameters

Alexander Schütt[1], Joscha N. Becker[1], Alexander Gröngröft[1], Selina Schaaf-Titel[1], Annette Eschenbach[1]

Contributions: Alexander Schütt: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. Joscha N. Becker: Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing, Supervision. Alexander Gröngröft: Methodology, Resources, Data curation, Writing – review & editing, Supervision. Selina Schaaf-Titel: Conceptualization; Investigation, Data curation. Annette Eschenbach: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Journal: Urban Forestry & Urban Greening

Publication II

Growth Response of Nine Tree Species to Water Supply in Planting Soils Representative for Urban Street Tree Sites

Alexander Schütt[1], Joscha N. Becker[1], Christoph Reisdorff[2] and Annette Eschenbach[1]

Contributions: Alexander Schütt: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Writing - original draft, Visualization. Joscha N. Becker: Validation, Data curation, Writing: review and editing, Christoph Reisdorff: Conceptualization, Validation, Writing:

review and editing, Supervision. Annette Eschenbach: Conceptualization, Methodology, Validation, Resources, Writing: review and editing, Supervision, Project administration, Funding acquisition.

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Journal: Forests

Publication III

Stomatal reaction patterns on soil water potential and temperature dependence of assimilation are decisive to carbon assimilation, stress incidences and growth – evidences from monitoring young urban street trees

Alexander Schütt[1], Joscha N. Becker[1], Annette Eschenbach[1], Christoph Reisdorff[2]

Contributions: Alexander Schütt: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Writing - original draft, Visualization. Joscha N. Becker: Validation, Data curation; Annette Eschenbach: Conceptualization, Methodology, Validation, Resources, Writing: review and editing, Supervision, Project administration, Funding acquisition; Christoph Reisdorff: Conceptualization, Methodology, Formal analysis, Resources, Writing - second draft, review and editing, Supervision.

Manuscript status: To be submitted to Trees (Springer)

Publication IV (Book chapter – not included in this thesis)

Urbane Böden – Leistungen und zukünftige Herausforderungen für Stadtbäume

Annette Eschenbach, Alexander Schütt, Joscha Becker

Yearbook of Arboriculture 2023; Dirk Dujesivken; p. 83-98; accepted in March 2023

ISBN: 978-3-87815-283-5

Publication V (Book chapter – not included in this thesis)

Urbanes Grün braucht Wurzelraum

Annette Eschenbach, Alexander Schütt, Joscha Becker

Book title: Blue-Green Cities; Susanne Böll; submitted and ready for publication

Practically co-supervised student thesis

Musal, S., (2019): Einfluss von Verdichtung, Versiegelung und Wassergehalt auf den Bodenlufthaushalt an Stadtbaumstandorten. Thesis in study program B.Sc. Geowissenschaften, Universität Hamburg.

Moll, F. (2020): Bilanzierung des Bodenwassers in Pflanzgruben von Jungbäumen eines Feldexperiments. Thesis in study program B.Sc. Geowissenschaften, Universität Hamburg.

Lisitano, L. (2021): Charakterisierung des Bodenlufthaushaltes an Standorten junger *Quercus cerris* Stadtbaum-Pflanzungen. Thesis in study program B.Sc. Geowissenschaften, Universität Hamburg.

Ocker, S., (2022): Einfluss von Baumart und Bodensubstrat auf die Feinwurzelbiomasse. Thesis in study program B.Sc. Geowissenschaften, Universität Hamburg.

Musal, S., (2022): Ausbreitung und Biomasse von Fein- und Grobwurzeln verschiedener Laubbaumarten in zwei Pflanzsubstraten. Thesis in study program M.Sc. Geowissenschaften, Universität Hamburg.

Abbreviations

SWP - Soil water potential
SWP$_C$ - Critical soil water potential below a threshold
VWC - Volumetric water content
REW% - Relative extractable water
FC - Field capacity
WP - Wilting point
PAWC - Plant available water content
pH - Measure of the acidic or basic character of an aqueous solution
OM - Organic matter content
IC - Infiltration capacity
BD - Bulk density
‘Sand‘ - Label of soil substrate pure sand (experimental study site)
‘FLL’ - Label of structural soil substrate mixed according FLL (experimental study site)
‘Loamy-Silt’ - Label of natural grown soil (experimental study site)
C - Carbon
CO$_2$ - Carbon dioxide
hPa/kPa - Hectopascal/Kilopascal [Pressure]

VPD - Vapor pressure deficit
VPD$_{max}$ d^{-1} - Daily maximum vapor pressure deficit
Y1-Y11 - Young tree sites No.
FLL - Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.
GALK - Deutsche Gartenamtsleiterkonferenz e.V.
KLAM - Climate adapted species matrix

DBH - Diameter at breast height
SDI - Stem diameter increment
(r)BAI - (relative) basal area increment
mds - Maximum daily shrinkage (stem)

TWD - Tree water deficit

g_S - Stomatal conductance

$g_{S\ mod}$ - Modelled stomatal conductance

$g_{S\ max}$ - Maximum stomatal conductance

A_c - CO_2 limited assimilation

A_j - Sugar ribulose-1,5-bisphosphat (RubP) limited assimilation

A_{lim} - Stomatal limitation of assimilation

RuBisCO - Ribulose-1,5-bisphosphat-carboxylase-oxygenase

ROS - Reactive oxygen species

V_{cmax} - Photosynthesis carboxylation capacity

J_{max} - Maximum electron transport rate

C_i/C_a - Intercellular partial pressure inside and outside the leaf

$\delta^{13}C$ - Carbon isotope composition

Al - *Amelanchier lamarkii*

Aps - *Acer pseudoplatanus*

Apl - *Acer platanoides* ‚Fairview‘

Cb - *Carpinus betulus* ‚Lucas‘

Gt - *Gleditsia traiacanthos* ‚Skyline‘

Kp - *Koelreuteria paniculata*

Ls - *Liquidambar styraciflua*

Oc - *Ostrya carpinifolia*

Ps - *Prunus serrulata*

Qc - *Quercus cerris*

Qp - *Quercus palustris*

Qr - *Quercus robur*

Tc - *Tilia cordata* ‚Greenspire‘

1 General Introduction & Objectives

1.1 Background

Until 2050 more than 65% of the global population is projected to live in cities and mega-cities (United Nations 2019). Urbanization strengthens the urban heat island effect and intensifies the human induced warming locally. Since the last eight years (2015 – 2022) were globally the warmest eight on record (C3S 2022), further urbanization along with the implications of climate change will increase the severity of heatwaves for the urban population (IPCC 2021) and heat related human mortality rate might increase across European cities (Dimitriadou et al. 2022). Urban trees have the potential to contribute to urban microclimate mitigation by providing ecosystem services such as cooling by transpiration and shading (Armson et al. 2012; Zölch et al. 2016; Rahman et al. 2017a). Evidence suggests that planting trees in heat-exposed sites, e.g. along urban streets or public squares, is more effective at cooling than just aiming a high percentage of vegetation cover (Zölch et al. 2016). Since the focus by planning highly heat-exposed sites is most often on a functioning urban infrastructure and less on climatic aspects, which includes the integration of urban greenery and trees (Bassuk et al. 2015), these represent the opposite of natural tree habitats. Consequently, trees that are originally intended to cool down heat exposed urban sites, may themselves suffer from tighten urban micro-climate (e.g. higher temperatures, lower humidity, insolation compared to a continuous canopy (Clark & Kjelgren 1990)) and thus have witnessed a growing academic interest.

In addition to micro-climatic issues in the urban environment, belowground conditions at urban tree sites were, depending on the sites history, often strongly altered compared to naturally grown or respective original soils (Greinert 2015) (Figure 1.1). In contrast to undisturbed, naturally grown soils, horizons in urban soils may be mixed up, completely absent or exchanged (Greinert 2015), enriched with sand- and stone substrates or artificial technogenic rubbles (Wessolek et al. 2011; Jim & Ng 2018; Schickhoff & Eschenbach 2018). Due to regular construction of aboveground infrastructure and the increasing demand for belowground space, in particular soils along streets can compose of highly compacted horizons (Jim 1998), be restricted in their vertical and horizontal distribution (Cermák et al. 2000; Jim & Ng 2018) (Figure 1.1 and 1.2) and vary in their hydrologic properties on a small scale (Wiesner et al. 2016). As cities becoming more compact with ongoing urbanization (Jim & Ng 2018), the share of imperviously sealed soil surfaces increases. As a consequence, the infiltration capacity and the gas exchange rate lowers (Wessolek et al. 2011; Armson et al. 2013; Morgenroth et al. 2013; Jim 2019a), whereas the surface runoff of water increases (Murata & Kawai 2018). With decreasing amounts of summertime precipitation and a higher probability of occurring “hot droughts” i.e. high evaporative demand of the air (Schuldt et al. 2020) as predicted for northern Europe and Germany (Trusilova & Riecke 2015), hydrologic soil properties, already altered by ongoing urbanization, might have an increased potential to affect the success of establishment from recently planted trees. Thereby, soil properties such as grain size, pore volume and organic matter content mainly determine the availability of soil water which in turn mainly controls tree growth, vitality, and mortality (Konijnendijk et al. 2005; Bréda et al. 2006; Granier et al. 2007; Allen et al. 2010; Moser et al. 2016; Puhlmann et al. 2019). Thus, soil properties might have a considerable impact on the level of ecosystem services that can be provided by trees in the urban environment. To assess the risk of vitality losses and mortality for trees (Granier et al. 2007; McDowell et al. 2008), *in situ* studies that generate data on soil water availability in interaction with tree development at urban street tree sites are necessary but still lacking (Nielsen et al. 2007; Riikonen et al. 2011; Thomsen et al. 2020), as belowground infrastructure, soil sealing and vandalism make such studies in cities technically challenging.

Street trees account for a large amount of the total tree population of cities, e.g. in the city of Hamburg, Germany, 225,000 street trees account for one quarter of the total tree population (Freie und Hansestadt Hamburg 2022). Established street trees in turn (i.e. age class since planting > 30-40 years), account for more than half of Hamburg's total street tree population (Freie und Hansestadt Hamburg 2022). As those trees were planted mainly in times when the cities were only less densely urbanized, they had been able to develop extended root systems reaching deep and distant soil water sources and therefore may cope phases of limited soil water availability (Clark und Kjelgren 1990; Thomsen et al. 2020) (Figure 1.1a).

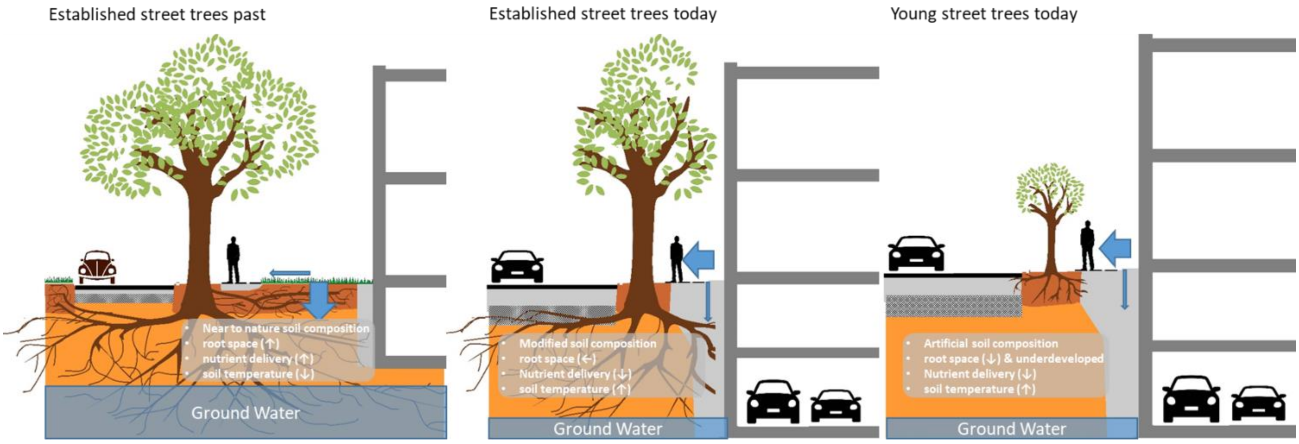

Figure 1.1: Historic development of urbanization on established and young urban street tree sites.

Moreover, the value of established trees with large canopies for the provision of ecosystem services had been part of few recent studies (Osone et al. 2014; Savi et al. 2015; Gillner et al. 2017a; Rahman et al. 2017a; Thomsen et al. 2020). Thus, the protection of established trees during ongoing urbanization (Figure 1.1b), is one very important element of preserving the urban tree population. As a consequence of urbanization and to preserve a balanced population-age structure, municipal agencies plant nursery grown trees (1) to replace established trees that died naturally (2) to replace felled established trees for reasons of traffic safety or for infrastructure-construction work, (3) to reach green infrastructure goals on the long-term. However, establishment of recently planted young trees (Gilbertson & Bradshaw 1990) that have to thrive and grow in a much more urbanized environment than their predecessors faced, is the other very important element of preserving and extending urban tree population (Marritz 2021) (actual challenges of young urban street trees: Figure 1.1c).

After planting, young trees suffering from transplanting shock, re-establishing a root:shoot ratio adequate to meet the above-ground demands (Watson 2005) and strongly depending on available soil water close to the root ball, as their root systems are initially only shallow. However, despite the roadsides are not by nature their ideal habitat and today's climatic and site-specific conditions are unprecedented, young street trees have to thrive to maturity, as the important ecosystem services can only then be provided on maximum levels. The improvement of young street tree sites prior to planting and the use of promising, i.e., drought-tolerant and "climate-adapted" tree species, may play an important preventive role to ensure their vitality, to minimize the risk of premature death and thus the loss of ecosystem services on the long-term (Nowak et al. 2004; Roman & Scatena 2011; Roman et al. 2014). Before planting, replacing of the prevailing, most often artificial and sandy soils (i.e. ‘urban soil’) (Wessolek et al. 2011; Jim & Ng 2018; Schickhoff & Eschenbach 2018) in exchange to backfilled technical soil-stone mixtures (structural soil substrates) (Figure 1.2.) is preferred over post-planting treatments to reduce compaction (Kozlowski 1999). Various substrates have been proposed or used as rooting media for young urban street trees e.g. ‘CU-structural soil’ ® (Bassuk et al. 2015), ‘Stockholm structural soils types A, B, C and D’ (Embrén et al. 2017), ‘Amsterdam soil’ (Rahman et al. 2011), overbuildable and non-overbuildable structural soils according to German recommendations (FLL 2015). Thereby, a load-bearing matrix of the stones/gravel should preserve site’s multifunctionality to ensure compaction stability for parking lots and pedestrian infra-structure, whereas the fine-soil fraction and the humus content in the voids of the matrix is intended to provide sufficient root growth and -aeration (Grabosky & Bassuk 1996; Smiley et al. 2006; Rahman et al. 2011; Grabosky 2015; Bühler et al. 2017). As the fine-soil fraction is mostly dominated by sandy textured soil particles (Grabosky 2015; Jim & Ng 2018), it is doubtful that these structural soil substrates can ensure sufficient water supply for young street trees (Jim 1998; Nielsen et al. 2007). Particularly under the changing climatic conditions towards hot and dry summers, there is a need to attach scientific relevance to soil substrates and tree pit surrounding soils these are intended to serve as water suppliers and water storage for young urban trees (Figure 1.2).

Figure 1.2: View on a future tree site within a pedestrian zone. The excavated planting pit with the backfilled, brownish structural planting soil is located in the center of the zone and is surrounded by the artificial urban soil containing of pure sands.

Depending on the particular hydrological characteristics of their natural habitat, trees have in theory evolved multiple morphological and physiological strategies to counteract substantial vitality loss during phases of limited soil water availability. Sufficiently available soil water allows maximum stomatal conductance and hence high rates of CO_2 uptake. Thus, soil water availability is crucial for the trees' carbon balance, allocation pattern and hence, growth and vitality. When soil water availability lowers, trees initiate stomatal regulation to reduce the loss of water. As an inevitable consequence, the diffusion of CO_2 from the atmosphere into the leaf and therefore the supply of CO_2 for the carboxylation of ribulose-1,5-bisposphate in the Calvin Cycle becomes restricted. The consequence for the C-balance is not only a decline of assimilate gain proportional to the lowered CO_2 flux, since C must be invested in live saving stress reactions. Thus, when drought causes relevant stomatal limitation of carboxylation, it can be assumed that the C investments into stress reactions grow reciprocally with reduction of assimilation causing a progressively increasing C-deficit with decreasing stomatal conductance. However, even for trees grown under natural conditions i.e. trees that stick to the germination-location without regular pruning and roots being cut, yet, adaptation and surviving strategies as well as physiological mortality mechanisms under different water deficit conditions were still unresolved and results being discussed controversial (Mitchell et al. 2014; Adams et al. 2017; Trugman et al. 2018; Blackman et al. 2019; McDowell et al. 2022). Despite of inconsistency related to drought reactions, there is evidence about genetic adaptations of tree species originating from harsh, urban-like environments, which are likely better coping insufficient site conditions e.g. urban street tree sites streets, than most commonly- or traditionally used street tree species. However, the suitability of non-native tree species for urban street site plantings has so far been mainly determined by meta-studies, assessing the drought resistance of tree species based on the aridity of their natural habitat (Roloff et al. 2009).

To ensure establishment, persistency and long-term vitality of yet to be planted young urban street trees, knowledge about the availability and the distribution of soil water in the first years after planting is vital in face of ongoing urbanization, present planting practices and climate change. Furthermore, to gain insight into species-specific soil and water requirements, inter-specific tree species response in terms of short- and long-term morphologic and physiologic reactions has to be investigated not only towards drought (Stratópoulos et al. 2018; Stratópoulos et al. 2019b; Stratópoulos et al. 2019a) but also in interaction with differing belowground conditions (Pregitzer et al. 2016).

1.2 Objective of the Study

The conditions for urban trees to grow are severely challenged by climate change and urban heat island. Particularly along streets, where competing interests and thus rarely available above- and belowground space for growing trees, the conditions mentioned affect the urban water cycle directly and indirectly. Since soil water supply is known to mainly control tree vitality and -survival, this study aims to investigate the water supply of commonly used soil substrates for young trees and their morphological and physiological responses over several years. To do so, a broad range of typical site characteristics, soil properties and tree species were captured in two experimental approaches: a long-term *in situ* soil water monitoring in the urban environment and a large-scale experimental field study in a complete block design with different soil substrates, representative for young urban street tree sites. For both approaches the soil hydrological properties were characterized by laboratory analysis and monitored the soil water availability by installing soil water potential sensors during tree-establishment period (three years and longer). Data of both approaches were obtained from 2016 until 2021 (*in situ*) and from 2019 until 2021 (field experiment). In particular, I examined three main research questions that were answered in already published or submitted manuscripts. I intended to answer the following research questions:

- To what extent were young street-trees exposed to critically lowered soil water availability during perennial site establishment phase and which external factor variables were statistically most important to assess critical soil water availability?

- Are technically mixed structural soil and artificial urban soil suitable as urban planting media in terms of soil hydrological properties and growth responses of different tree species?
- To which extent are recently planted street trees physiologically affected by variable hydrological dynamics in the urban environment?

1.3 Chapter overview

The **results** of the different studies are presented in chapters 3, 4 and 5.

Chapter 2, "**Site description**", introduces the scientific need to establish two different experimental approaches that were both located in the city of Hamburg, Germany, and provides detailed information about the crucial differences of the research designs. The long-term *in situ* soil water monitoring in the urban environment of Hamburg covers a six years record of *in situ* measurements at 17 street tree sites that represents typical site conditions in combination with different tree species randomly. The large-scale experimental field study in a complete block design with different soil substrates and nine different tree species is located at the southern border of Hamburg in a tree nursery. The predominant soil type of the location is characterized as Loamy-Silt with high water- and nutrient storage capacity, which serves in the experimental field study as reference soil.

Chapter 3, "**Soil water stress at young urban street-tree sites in response to meteorology and site parameters**" provides a detailed insight into the first four years results of the long-term *in situ* soil water monitoring in the urban environment of Hamburg. The study was conducted during the establishment phase of young street trees under meteorological conditions that varied considerably from year to year. Based on measurements of the soil water availability, I quantified the development and the occurrence of critical soil water availability in three different soil compartments (root ball, planting pit and surrounding urban soil) by applying on a literature threshold value. Moreover, these data were analyzed using a data driven approach to assess the importance of various response variables for the occurrence of critical soil water availability at the investigated sites.

Chapter 4, "**Growth response of nine tree species to water supply in planting soils representative for urban street tree sites**", focuses on the analysis of hydrological soil properties of representative substrates commonly used for filling planting pits (FLL substrate), or commonly dominating soil conditions surrounding planting pits (pure sand). Furthermore I aimed to find out if different tree species are affected in growth and vitality when planted into those conditions and to what extent. Therefore a large-scale experimental field study in a tree nursery in Hamburg was applied where in total 135 trees consisting of nine different tree species were planted. Over a three years record I monitored the development of soil water availability, tree growth and tree vitality in the planting pit substrate condition and the surrounding urban soil condition in comparison to a naturally grown loamy-silt reference soil.

Chapter 5, “**Species specific stomatal reaction patterns on soil water availability are decisive for the carbon balance and growth of young urban street trees**” Integrates the soil water availability measurements from the last four years of the long-term *in situ* soil water monitoring into a tree physiological analysis of the tree species growing at the respective sites. I aimed to identify if and to which extent these young and recently planted trees were physiologically affected under decreasing soil water availability. Therefore I measured the leaf stomatal conductivity of each individual throughout two growing seasons. To estimate the stomatal limited assimilation, a photosynthesis model was applied integrating empirical regression models of species specific stomatal reaction on soil moisture and air humidity and temperature corrected diffusional and metabolic parameters. To check the plausibility of the model approach, I applied annually measured tree attributes such as growth and carbon isotopic composition of the biomass.

Chapter 6.1, “**Conclusions drawn from research results**”, provides a general discussion and integrates the results and conclusions of Chapter 3, 4 and 5.

Chapter 6.2 and 6.3, "**General conclusions, practical implications and Outlook**", develops recommendations for practical application at tree sites and in tree species selection based on the key findings of this study. In addition, open- and further developed questions that should be part of future research are discussed.

2 Site Description

All study sites were located in the city of Hamburg, northern Germany (53° 33′ N, 10° 0′ E), that covers an area of about 755 km^2. Hamburg is characterized by a temperate and perennial humid climate with a marine influence dominated by western winds (Koeppen & Geiger: Cfb). The mean long-term precipitation and temperatures (1981-2010), measured at the climate station in Hamburg, Fuhlsbüttel of the Deutscher Wetterdienst, were 793 mm and 9.4 °C, respectively (DWD 2022). On average, summer months are the wettest, the autumn and winter are slightly drier and spring is characterized by lowest precipitation. Natural soils, developed from glacial and fluvial deposits, are dominated by loamy Cambisols and sandy Podzols (Schickhoff & Eschenbach 2018) and were in recent times, particularly in the densely urbanized areas, strongly influenced by anthropogenic processes and artefacts (Greinert 2015). Due to processes of urbanization e.g. surface sealing for housings, industry and infrastructure and loss of natural soils, Hamburg's inner city is influenced by an urban heat island leading on average to 0.5 to 1.1 K higher temperatures compared to surrounding natural areas (Schlünzen et al. 2010; Wiesner et al. 2014)

With a 14% share of open green spaces and parks (106 km^2), with around 600.000 trees, Hamburg is the "greenest" German city. Along streets and squares, another 226.124 trees (26.11.2022) of various tree species are growing (Freie und Hansestadt Hamburg 2022). The main tree genera are *Tilia*, *Quercus*, *Acer* and *Carpinus*, accounting for more than 60% of the total street tree population. Despite of in total more than 320 different tree species that were planted all over the cities street sides, 14 tree species account for more than 75% of the total street tree population and two tree species (*Quercus robur* and *Tilia* x *europea*) account again for more than one third of the total street tree population (Freie und Hansestadt Hamburg 2022). Street trees, that were planted from 1990-2021, account thereby for approximately 33% of total street tree population. As in the same period Hamburg's number of residents and the per capita living space have both increased significantly (+235,000 residents and +7 m^2 living space per capita, respectively) (Statistikamt Nord 2021; Statistisches Bundesamt 28.07.2022), former available above- and belowground space for street side trees decreased. As important ecosystem services can only be provided on high levels when trees reach maturity, it is important to minimize the risk of premature death of the recent and yet to be planted street tree population. Therefore, the research of this study focusses on soil water availability for recently and freshly planted trees under *in situ* conditions and in an experimental field study set up specifically for this purpose.

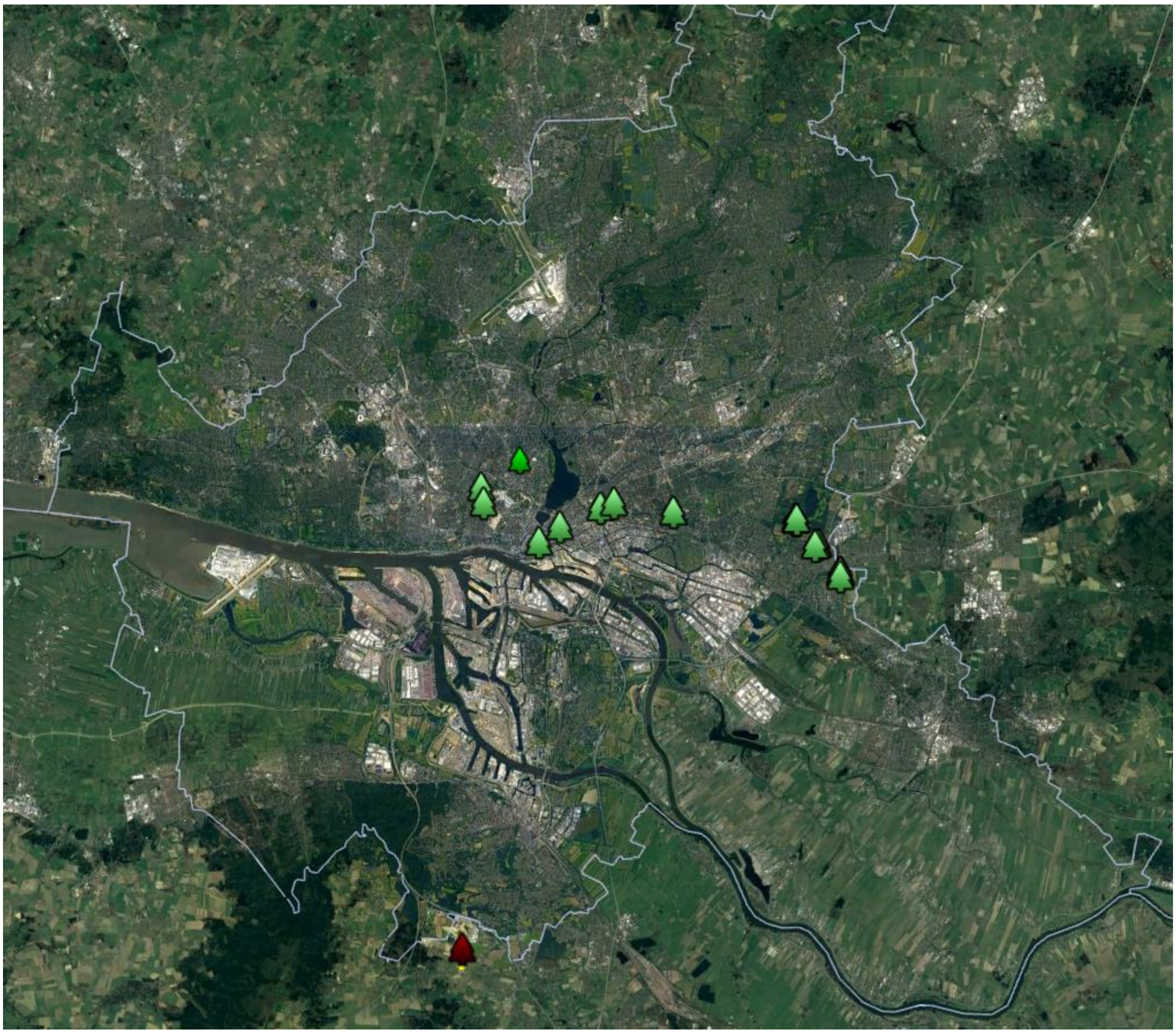

Figure 2.1: Locations of the two experimental sites: green trees indicate the 17 sub-sites of the long-term *in situ* soil water monitoring in the urban environment. The red tree indicates the location of the large-scale experimental field study in a complete block design with different soil substrates in the tree nursery Lorenz von Ehren Pflanzenproduktionsgesellschaft mbH & Co. KG. Aerial image by Google Earth 2023.

2.1 *In situ* monitoring sites

To evaluate and quantify the success of establishment from recently planted street trees under *in situ* conditions during the phase of establishment, measurements to analyze soil parameters in the laboratory and to monitor the soil water availability started from 2016. Additionally, I measured from 2018 on tree physiologic and morphologic parameters. In order to establish the long-term *in situ* soil water monitoring in the urban environment a selection of monitoring sites following a randomized design (to gain representative datasets within a broad range of each specific criteria) was developed. Following the criteria planting age, tree species and soil surface sealing, in total 17 trees along 11 streets or squares were selected (green trees in Figure 2.1) and labeled as follows:

Table 2.1: Basic site descriptions of the 17 sites within the long-term *in situ* soil water monitoring.

Site No.	Tree species	Planting year	Replicates No.	Latitude	Longitude
Y01	*Carpinus betulus* 'Lucas'	2016	1	53°34'5.04"N	9°59'1.38"E
Y02	*Quercus cerris*	2016	3	53°32'21.93"N	10° 8'35.65"E
Y03	*Acer platanoides* 'Fairview'	2016	3	53°31'44.52"N	10° 9'17.26"E
Y04	*Quercus cerris*	2016	3	53°32'50.31"N	10° 7'54.22"E
Y05	*Quercus robur*	2015	1	53°33'5.81"N	10° 1'36.22"E
Y06	*Quercus robur*	2014	1	53°33'0.22"N	10° 3'56.60"E
Y07	*Quercus palustris*	2012	1	53°32'26.78"N	9°59'36.88"E
Y08	*Quercus palustris*	2007	1	53°32'44.53"N	10° 0'17.62"E
Y09	*Acer pseudoplatanus*	2013	1	53°33'12.26"N	9°57'50.97"E
Y10	*Acer pseudoplatanus*	2011	1	53°33'11.29"N	10° 2'2.31"E
Y11	*Prunus serrulata*	2017	1	53°33'29.88"N	9°57'46.21"E

The tree sites represent a heterogeneous combination of criteria (i.e. tree ages (years after planting) from 0-10 years, seven tree species and sealed soil area around the tree ranging between 0-100%) and were arranged in a transect from the city center to the eastern sub-urbs (for detailed information see Table 3.1). All investigated trees were grown up and cultivated in tree-nurseries. When trees reached their propagated size (usually between 14-18 cm stem circumference for street side plantings) (Figure 2.2 left), they were excavated with a root-ball that composes of the nursery's top soil and contain high amounts of fine roots due to regular pruning of coarse roots and translocated to their intended and previously prepared street-side site. At all sites, except site Y4 (*Glinder Straße)*, the trees' root balls were embedded in a previously excavated planting pit, which was backfilled with a specific structural soil mixture (soil-substrate) in exchange for the prevailing urban soil. Around the planting pits, the prevailing urban soil conditions remained unchanged.

Figure 2.2: Tree-development at two of the 17 street sites between 2016 (left) and 2021 (right). Top: The site Y2a (*Oststeinbeker Weg*). Bottom: The site Y3c (*Große Holl*).

2.2 Experimental field study site

The chosen site (~ 6,000 m²) was located in an intensively, horticulturally used area on the ground of the tree nursery Lorenz von Ehren Pflanzenproduktionsgesellschaft mbH & Co. KG at the southern border of Hamburg (53°24’43’’N 9°57’01’’E) (red tree in Figure 2.1). The study area is located in the lower (southern) Geest in the northeastern Harburger Hills that were formed during the second last glaciation (Saale) and is characterized by alluvial deposited silts above glacio-fluviatile sands. The dominating soil type in the area of the tree nursery (400 ha) are Cambisols. Due to the agricultural and horticultural history of the site, the A horizon is characterized by a plowing horizon (Ap according to (AG Boden 2005)), followed by the characteristic Bv horizon (AG Boden 2005) (Figure 2.3). The altitude of the study site is ~ 34 m above sea level (Google Earth) and groundwater depth ranges between 20-25 m.

Figure 2.3: Excavation of the first six of the total 135 planting pits in the replication block I. Clearly visible is the brownish Ap horizon and the underlying lighter, but still silty Bv of the horticulturally used Cambisol.

The aim of this experimental approach was to investigate the extent to which hydrological properties of different soils substrates, representative for urban site conditions, affect the development of various freshly planted tree species. Therefore, the experimental setting was chosen as a large-scale experimental field study in a complete block design at one non-urbanized tree nursery site to minimize the impact of external variables (i.e. soil sealing, soil compaction, size of the planting pit) and to provide consistent environmental conditions for each individual. Nine different tree species and three different planting soils were selected. The field study was created during spring 2019 and measurements were conducted until spring 2022.

Planting pits, with dimensions of 2.5 m × 2.5 m × 1.2 m (7.5 m^3) were excavated to ensure that tree roots develop only in the designated planting soils during the three years of study. The planting pits were directly connected to the surrounding soil and were not structurally separated (Figure 2.3). The planting pits were arranged in a 4 × 35 grid with spacing from center to center of 3.5 m × 8 m (Figure 2.4). In total, five individuals of each tree species (Table 4.1) were planted in each of the three planting soils (Table 4.2). As the experiment was set up in a randomized complete block design, every species–substrate combination was replicated five times, one in each of five blocks, resulting in a total number of 135 trees (Figure 2.4). Two of the three planting soils were treatment soils representing urban artificial soil conditions typical for young street tree sites and one reference soil was supposed to represent optimal growing conditions. Thus, three soils of different origins and qualities were used as growing media:

(1) Pure ‘Sand’: represents the prevailing and artificial urban soil conditions surrounding street tree planting pits in strongly developed urban environments.

(2) One-layer gravel–soil mixture (structural planting soil) (‘FLL‘): prepared according to German standardized guidelines ‘FLL‘ (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V – Empfehlungen für Baumpflanzungen) and represents the backfilling in exchange to prevailing urban soils.

(3) ‘Loamy-Silt’: the reference soil was supposed to represent optimal growing conditions that composed of a regional harvested natural topsoil similar to the naturally developed soil at the experimental site. This soil was considered to be suitable as a reference as it provided good yields and high quality for the commercial production of trees in the nursery for years.

Figure 2.4: Topview on the experimental setup of the field site on the ground of the tree nursery. The planting pits were depicted as colored and labeled boxes. The colors are divided into abbreviations of the nine tree species (top) and the planting soil type (bottom). Homogeneously colored boxes (orange and green) highlight planting pits with soil water sensor installations. The

orange dotted lines represent the borders of the five replication blocks labeled with the Roman numerals one to five. Aerial image by Google Earth (01.12.2022).

3 Soil water stress at young urban street-tree sites in response to meteorology and site parameters (Manuscript 1)

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3.1 Introduction

Urban street-trees provide important ecosystem services for the urban population and environment and become more and more important as population density in cities is constantly increasing (McCarthy et al. 2010). Vital street-trees can mitigate elevated summer temperatures caused by the urban heat island effect and climate change through shading and transpiration, if sufficient soil water is available (Bowler et al. 2010; Armson et al. 2013; Rahman et al. 2017c). However, urban soils were altered substantially through past and present anthropogenic activities and growing conditions were less favorable than in natural environments (Craul 1985; Greinert 2015). Along streets, soils were often composed of artificial sandy- and stony substrates (Wessolek et al. 2011; Jim & Ng 2018; Schickhoff & Eschenbach 2018), were highly compacted (Jim 1998) and were limited in vertical and horizontal distribution (Cermák et al. 2000; Jim & Ng 2018), which in total leads to small scale variability of hydrological properties (Wiesner et al. 2016). When the infiltration capacity is lowered due to top-soil compaction or inhibited due to impervious soil sealing, surface runoff is generally elevated and the recharge of soil water reservoir is reduced (Wessolek et al. 2011; Armson et al. 2013; Morgenroth et al. 2013; Jim 2019a). Climate change may cause additional threats for trees water supply. For northern Germany, air temperature is predicted to increase and summertime precipitation is predicted to decrease during the growing season (Schlünzen et al. 2010; Trusilova & Riecke 2015).

Mature, established street-trees had been able to develop extended root systems reaching deep and distant soil water sources to cope with phases of limited soil water availability (Clark & Kjelgren 1990; Thomsen et al. 2020). Young street-trees on the other hand depend strongly on the soil water availability in their closest surrounding soil compartments after planting, as their root systems are initially limited to the root ball (Clark & Kjelgren 1990; Konijnendijk et al. 2005). Overall, the mortality rate of young urban street trees within the first years after planting is high (Gilbertson & Bradshaw 1990; Lu et al. 2010; Roman et al. 2014). Therefore, the replacing of poor site soils (urban soil) by backfilling technical soil-stone mixtures (structural soil substrates) into a planting pit before planting is a common approach for multifunctional use of tree sites: to ensure compaction stability for infrastructure and to simultaneously enhance tree growth (Grabosky & Bassuk 1996; Smiley et al. 2006; Rahman et al. 2011; Grabosky 2015; Bühler et al. 2017). However, to provide sufficient air capacity after compaction, structural soil substrates contain coarse textured soils (Grabosky 2015; Jim & Ng 2018) resulting in lowered water retention capacities (Nielsen et al. 2007).

Consequently, the soil water supply - mainly controlling tree growth, tree vitality and tree mortality (Konijnendijk et al. 2005; Bréda et al. 2006; Granier et al. 2007; Allen et al. 2010; Moser et al. 2016; Puhlmann et al. 2019) - is likely insufficient at young street-tree sites. However, to provide important ecosystem services at high levels, young street-trees have to thrive to maturity and it is important to minimize the risk of premature death. To assess the risk of vitality losses and mortality for trees (Granier et al. 2007; McDowell et al. 2008), monitoring of soil water availability throughout the year is vital. Particularly, knowledge about the annual and seasonal duration and intensity of critical soil water availability, its development within different parts of the root zone and the sensitivity of planting sites towards critical soil water availability is crucial to develop adaptation and water-management strategies for young urban street tree sites in the future.

A common method to assess drought is the use of drought indices such as the Standardized-Precipitation-Evaporation-Index (SPEI) (Vicente-Serrano et al. 2010). However, SPEI already neglects local site characteristics in natural ecosystems (Schwarz et al. 2020). Because of generally very heterogeneous site characteristics at urban street-tree sites (Greinert 2015; Eschenbach & Gröngröft 2020), the resolution of SPEI and e.g. data provided by the German-drought-monitor (Zink et al. 2016) or remote sensed datasets were less suitable for assessing water stress conditions in the urban environment on single tree level (Moser et al. 2016; Paton et al. 2021). Therefore, critical soil water availability should be directly measured with high spatial and temporal resolution (Paton et al. 2021). Compared to forests, the availability of measurements with high spatial and temporal resolution on stands or on single trees for urban environments are very limited, especially for urban young tree settings (Nielsen et al. 2007; Wiesner et al. 2016; Gillner et al. 2017b; Thomsen et al. 2020). Recent studies on urban green, however, predominantly focus on above ground investigations such as the selection of climate adapted tree species (Roloff et al. 2009; Stratópoulos et al. 2018), the cooling potential and drought sensitivity of mature urban trees (Moser et al. 2017; Rahman et al. 2017b;

Thomsen et al. 2020), however, with limited temporal resolution and limited number of locations (Rahman et al. 2011; Gillner et al. 2017b).

To gain insight into soil water availability in interaction with meteorological variables, tree- and site characteristics at typical young urban street-tree sites, we implemented a long-term soil monitoring in 2016. Over the course of four years, the dynamic of soil water potential (SWP) within three root zone soil compartments (root ball, planting pit and surrounding urban soil (FLL 2015)) was investigated at 17 sites in the city of Hamburg, Germany.

The aim of this study was to characterize the availability of soil water in different soil compartments of the root zone during and after the initial growing phase of trees of different age. In order to evaluate growth and vitality reductions induced by inadequate soil water availability we quantified the duration and intensity of critical soil water availability. Critical soil water availability per definition was reached, when SWP fell below a critical threshold value of -1200 hPa (SWP_C), below which stomatal closure and as a consequence growth reductions and loss of vitality was reported (von Wilpert 1991; Blécourt et al. 2021). The studied years differed strongly in terms of meteorological conditions, the trees planted in different years and the sites chosen covered a broad variability of typical urban tree sites characteristics. Therefore, we integrated these as predictor variables (meteorological variables, tree- and site characteristics) into a data-driven model (*randomForest* model) to predict the occurrence of days below SWP_C and rank the predictor variables by importance for the prediction. With this study, we provide applied data for municipal authorities and urban planners by showing soil water distribution and limitation during development of young urban street trees, and we have tested an applied method that may be useful for future soil water management of tree sites. The main questions to be answered are:

- To what extent are young street-trees exposed to critical soil water availability under moderate and extreme meteorological conditions?
- Does the spatial distribution of water limitation in the root zone shift during the tree site adaptation process?
- Is it applicable to predict daily drought occurrence by using a *randomForest* approach and which variables are of most predictive importance?

3.2 Material and Methods

3.2.1 Study area and site selection

The study was carried out in the city of Hamburg, Germany (53° 33′ N, 10° 0′ E), covering an area of about 755 km^2. The climate shows a marine influence (Koeppen & Geiger: Cfb), with highest precipitation in summer, slightly dryer autumn and winter and low precipitation in spring season. The long-term annual means (1981-2010) of precipitation and air temperature are 793 mm and 9,4 °C, respectively (DWD 2022). Natural soils, developed from glacial and fluvial deposits, are dominated by loamy Cambisols and sandy Podzols (Schickhoff & Eschenbach 2018) and strongly influenced by anthropogenic processes and artefacts (Greinert 2015). At roadsides, however, soils were most often replaced or filled up by coarse textured sandy and technogenic substrates (Jim 1998; Schickhoff & Eschenbach 2018).

The study sites were arranged in a transect from the inner city to suburban areas. Between 2016 and 2017, we established 17 individual sites at eleven locations (Y1-Y11) (Table 3.1), which were listed in the Hamburger street-tree cadaster (Freie und Hansestadt Hamburg 2022). Study sites were located at streets (n=11), street banks (n=3) and public squares (n=3). The trees at the selected sites were planted from 2007 to 2015 (‘adapted’ young trees; n=6), in spring 2016 with beginning of the monitoring establishment (‘freshly planted’ young trees; n=10) and in autumn 2017 (n=1). The selected trees were grown in tree nurseries, were excavated with a root ball (Allen et al. 2017) and had an age of about 12 to 15 years and a DBH (diameter in breast height) of about 6 - 16 cm (median: 7.3 cm) at the moment of planting. The selected sites represented a broad variability of typical young urban tree site characteristics in Hamburg and comprised seven tree species varieties (Table 3.1). At three locations, the soil monitoring was replicated (n=3) to represent site specific heterogeneity.

Table 3.1: Site characteristics and soil physical parameters at the investigated young urban street-tree sites and as means for the replicated sites Y2-Y4. Soil samples were taken as non-volumetric, mixed samples separately for both, planting pit and urban soil. Means of soil texture, organic C content (OM) and pH for the soil compartments planting pit and urban soil were calculated depth weighted per site. IC = infiltration capacity; DBH = diameter in breast height (measured in 2019); FAO class. = texture class according to FAO with S = sand and L S = loamy sand.

Site	Tree species	Planting year	Monitoring started	DBH (2019)	Est. Type of Structural Soil	Planting Pit								Urban Soil								Sealed Soil Area	
						Soil texture (depth weighted)					pH	OM	IC	Soil texture (depth weighted)					pH	OM	IC		
Nr.				[cm]	acc. to FLL (2010)	[%]						[%]	[cm min^{-1}]	[%]						[%]	[cm min^{-1}]	[%]	[%]
						Sand	Silt	Clay	FAO Cl.	Stone				Sand	Silt	Clay	FAO Cl.	Stone				Grid 5x5 m	Grid 10x10 m
Y01	*Carpinus betulus 'Lucas'*	2016	2016	9.3	FLL- one layer	87.9	5.4	6.7	S	52.8	6.6	4.1	1.8	73.8	13.9	12.2	L S	29.5	6.9	1.8	0.4	16	41
Y02a	*Quercus cerris*	2016	2016	8.9	FLL- two layer	83.4	9.9	6.7	L S	40.2	6.6	7.9	1.1	77.7	12.3	10.0	L S	12.0	6.2	1.6	0.5	80	81
Y02 - Mean	*Quercus cerris*	2016	2016	9.4	FLL- two layer	83.2	10.5	6.3	L S	35.1	6.7	7.6	2.5	81.1	11.3	7.6	L S	12.3	6.4	1.5	0.7	58	64
Y02c	*Quercus cerris*	2016	2016	10.1	FLL- two layer	82.1	11.3	6.6	L S	36.0	6.7	9.2	3.4	88.9	8.3	2.8	S	13.4	7.0	1.5	1.2	52	73
Y03a	*Acer platanoides 'Fairview'*	2016	2016	10.2	FLL- two layer	86.9	7.9	5.3	S	29.9	6.6	5.2	2.4	80.8	12.4	6.8	L S	14.1	6.2	2.1	0.9	62	57
Y03 - Mean	*Acer platanoides 'Fairview'*	2016	2016	9.3	FLL- two layer	86.9	7.7	5.5	S	32.2	6.6	5.5	2.5	87.2	8.5	4.3	S	13.7	6.2	2.3	0.8	27	32
Y03c	*Acer platanoides 'Fairview'*	2016	2016	7.9	FLL- two layer	85.9	8.4	5.7	S	34.3	6.6	7.6	1.6	93.0	4.5	2.5	S	13.7	7.1	3.3	0.5	62	61
Y04a	*Quercus cerris*	2016	2016	8.0	Original soil	85.5	10.4	4.1	L S	5.6	6.3	0.9	1.8	81.9	12.7	5.4	L S	3.1	6.2	1.5	0.4	10	18
Y04 - Mean	*Quercus cerris*	2016	2016	7.9	Original soil	83.2	11.2	5.6	L S	9.1	5.9	1.6	3.1	86.7	9.0	4.3	S	6.3	5.7	0.9	0.4	33	51
Y04c	*Quercus cerris*	2016	2016	8.1	Original soil	73.9	17	9.1	L S	13.9	6.3	3.1	5.1	87.7	7.9	4.4	S	7.8	5.8	0.6	0.5	0	3
Y05	*Quercus robur*	2015	2017	8.2	FLL- one layer	92	4.9	3.1	S	12.3	6.7	1.3	2.4	93.2	4.9	1.9	S	17.7	7.3	0.6	1.7	59	81
Y06	*Quercus robur*	2014	2017	8.5	FLL- one layer	87.7	7.3	5	S	29.4	6.9	4.4	4.2	97.0	1.5	1.5	S	3.8	6.8	0.3	1.5	40	71
Y07	*Quercus palustris*	2012	2017	18.8	FLL - Vulkatec	82.2	13.5	4.2	L S	56.4	7.2	1.9	0.3	82.2	13.5	4.2	L S	56.4	7.2	1.9	0.3	100	100
Y08	*Quercus palustris*	2007	2017	20.5	FLL - Vulkatec	82.2	14.1	3.6	L S	43.2	7.2	2.3	0.9	82.2	14.1	3.6	L S	43.2	7.2	2.3	0.9	100	100
Y09	*Acer pseudoplatanus*	2013	2017	12.7	FLL- one layer	77.2	11.7	11.1	L S	36.0	6.4	9.6	0.6	87.6	9.4	3.0	S	4.6	6.4	1.2	1.6	71	93
Y10	*Acer pseudoplatanus*	2011	2017	14.0	FLL- one layer	84.3	9.0	6.7	L S	29.4	6.8	4.0	3.8	90.5	5.8	3.7	S	15.1	7.1	0.8	0.4	38	75
Y11	Prunus serrulata	2017	2018	7.1	FLL- one layer	NaN	NaN	NaN	NaN	48.0	NaN	0.8	0.8	84.2	9.3	6.4	NaN	6.3	7.3	0.0	0.1	20	45

3.2.2 Site characteristics and monitoring network

The monitoring setup at the young urban street-tree sites was structured in three soil compartments: root ball, planting pit and (surrounding-) urban soil (Figure 3.1). Thereby the root ball is the initial root zone which contains the clipped tree roots and the soil of the tree nursery. Prior to planting all study-trees were harvested with the B&B method (root ball-excavated and burlap wrapped (Allen et al. 2017)). The planting pits, except site Y4, were filled with structural soil substrates (Grabosky & Bassuk 1996; Bühler et al. 2017), mixed according to FLL (2015) recommendations (Table 3.1). The properties of the surrounding urban soil were not altered before and during planting and depended on the individual site history. During sensor installation at each site, non-volumetric soil samples were taken from up to three depths per soil compartment down to 100 cm depth using a 60 mm wide, low-invasive drilling equipment. The soil samples of the planting pit and the urban soil were analyzed in lab regarding soil texture, stone content, organic C content and soil pH ($CaCl_2$) and means were calculated subsequently per site and soil compartment (Table 3.1). To avoid root damage, the root ball was not sampled. The individual tree sites were mapped, and the degree of sealing was determined for a square grid of 5 x 5 m and 10 x 10 m around each tree (detailed site characteristics are listed in Table 3.1). Infiltration capacity of the unsealed planting pit and the urban soil were measured using a double-ring infiltrometer. Vegetation cover was classified as bare soil (n=3) and herbaceous/grass vegetation (n=14). Canopy openness was estimated by the length of time the tree-crown was shaded by surrounding trees or buildings between 8 am and 4 pm (April – September) and divided into three categories: free standing (no shadow) (n=7), partly shaded for up to four hours (n=5) and fully shaded for more than 4 hours (n=5). Irregular irrigation by municipal gardeners was subsequently estimated and categorized (two levels: irrigation provided; no irrigation provided) by screening the SWP data for substantially reductions at days with almost no precipitation (< 0.5 mm d^{-1}) (Appendix Table 3.1).

At each tree site, we installed a monitoring system consisting of 13 SWP-sensors (WATERMARK 200SS, Irrometer Inc., Riverside, CA, USA) and three soil temperature sensors (Irrometer Inc., Riverside, CA, USA) following a predefined scheme down to depths of approximately 105 cm (Figure 3.1). Soil temperature sensors were installed to allow correction for temperature effect on SWP measurements and to generate depth specific information about soil temperature dynamics between contrasting sites. The SWP and temperature sensors were installed on the sides parallel to the street and the spatial orientation was therefore variable between the sites. Sensors were installed using a 60 mm low-invasive drilling equipment. Data were automatically logged with 1-h measurement frequency using a WATERMARK M900 Monitor (Irrometer Inc., Riverside, CA, USA). To represent the respective soil compartment volume best (Appendix Table 3.2), two SWP-sensors were placed in the root ball, five in the planting pit and six in the urban soil (Figure 3.1). Except the sensor beneath the root ball (No. 9; 70-80 cm depth), the SWP-sensors were replicated twice, each in the opposing side of the tree.

Soil temperature sensors were installed in three depths (Figure 3.1). The monitoring at Y1-Y4 (n=10) started in June 2016, at Y5-Y10 (n=6) in April 2017 and at Y11 (n=1) in January 2018. Until the end of 2019, a total of only 15 of 272 sensors failed due to some sort of defect (< 5%).

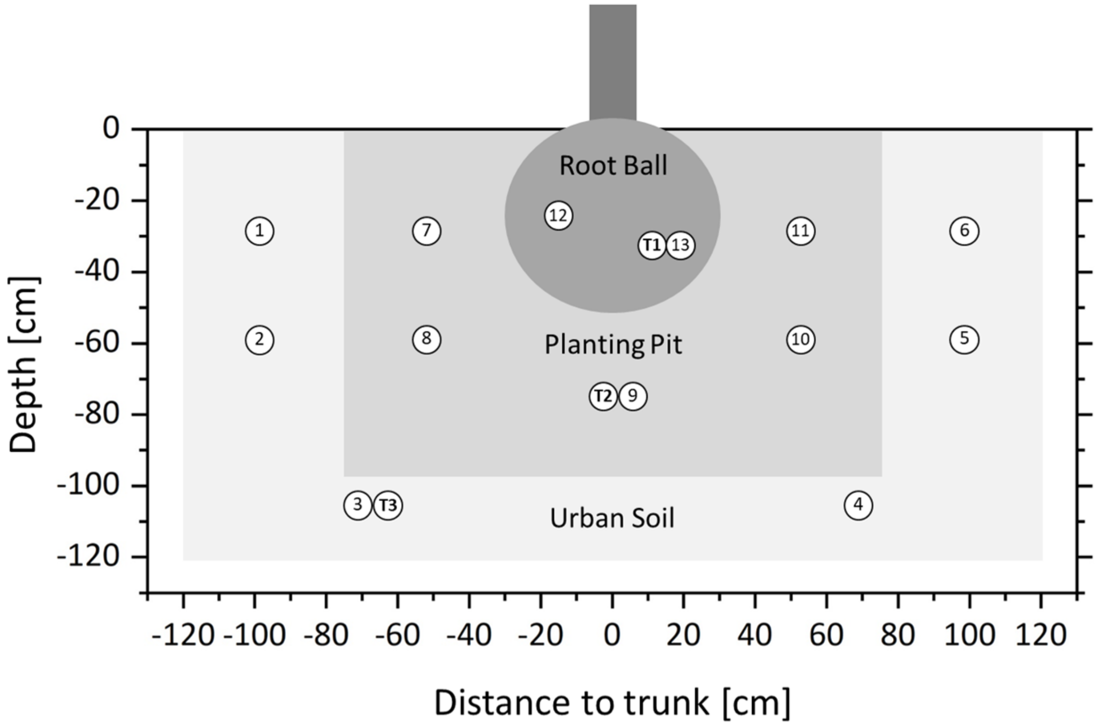


Figure 3.1: 2-D scheme of the measurement design per site. The greyish shades highlight the investigated soil compartments root ball (0.1 m³), planting pit (2.03 m³) and urban soil (4.77 m³) with a total soil volume of 6.81 m³. Numbers in the circles indicate internal sensor-numbers and show the arrangement of the SWP-sensors (n = 13), T1 – T3 in the circles indicate the soil temperature-sensor positions (n = 3).

3.2.3 Meteorological data

Hourly meteorological data were derived from three sites of the HUSCO meteo-network of the University Hamburg (www.mi.uni-hamburg.de/wetter.html) as well as from the Deutscher Wetterdienst (DWD) meteo-station in Hamburg-Fuhlsbüttel (DWD 2022). Daily means of air temperature, relative humidity and global radiation were related to the sites closest to each meteo-station. Atmospheric vapour pressure deficit (VPD) was calculated as the difference between saturated- and actual vapour-pressure using the daily means of air temperature and relative humidity. Potential evapotranspiration was calculated according to Haude (1955). Site specific total precipitation data were derived from open access radar based DWD RADKLIM precipitation data, where we extracted data from site coordinates as time series and quality checked them against DWD data from Hamburg Fuhlsbüttel. The data are available on a German-wide 1 km grid and a temporal resolution of 5 minutes until 2019 (Winterrath et al. 2018; DWD 2022).

3.2.4 Data processing

The monitored SWP-data were manually corrected for the actual soil temperatures using linear, depth weighted *in situ* soil temperature measurements from three soil depths (Shock et al. 1998; Allen 2000). The corrected data extended the lower measurement range of -2500 hPa, as 10 °C was initially set as default temperature for logger-internal temperature correction. For the calculation of the soil water stress intensity (eq. 3.2), values negatively exceeding the measurement-range (-2500 hPa) were considered as well. Data from individual sensors within the same soil compartment were combined to depth and volume weighted SWP values, one for each soil compartment. Soil volumes were therefore considered uniformly according to Appendix Table 3.2. Presented data in this study are based on calculated daily mean SWP. To quantify the annual occurrence of critical soil water availability within each soil compartment at each site, we used a critical SWP threshold value (water stress indicator) below which growth reduction and stomatal closure were reported for trees (von Wilpert 1991; Bréda et al. 1995; Granier et al. 2007). Therefore, the SWP data of the three soil compartments and the 17 sites were transferred separately to categorical variables of two levels: SWP negatively exceeding the critical value of -1200 hPa (von Wilpert 1991) were set as 1 (day below $\mathrm{SWP_C}$), SWP above -1200 hPa were set as 0 (day above $\mathrm{SWP_C}$). Following Puhlmann et al. (2019), we annually counted the days below $\mathrm{SWP_C}$ for each soil compartment at each site (eq. 3.1). To annually assess the water stress-intensity (eq. 3.2), we divided the integral of the SWP time series below $\mathrm{SWP_C}$ by the sum of days below $\mathrm{SWP_C}$ (eq. 3.1) for each soil compartment (Puhlmann et al. 2019).

$$Number\ of\ days\ below\ SWP_C = \sum_{i=Jan}^{Dec} \begin{cases} SWP_i < SWP_C : 1 \\ SWP_i \geq SWP_C : 0 \end{cases} \tag{3.1}$$

$$Soil\ Water\ Stress\ Intensity = \sum_{i=Jan}^{Dec} \begin{cases} SWP_i < SWP_C : \frac{SWP_i - SWP_C}{\sum SWP_i < SWP_C} \\ \quad SWP_i \geq SWP_C : 0 \end{cases} \tag{3.2}$$

3.2.5 Statistical analysis

The annual duration (number of days below SWPc) of critical soil water availability and the water stress intensity were compared between three soil compartments (root ball, planting pit & urban soil) and three years (2017-2019) using a two-way-repeated-measures ANOVA. This analysis includes all sites established latest before the growing season of 2017 (n=16) and excludes sites with large data gaps during one of the years (n=4), limiting the total number of compared sites to n=12. The relation of root-ball SWP to planting-pit SWP at 'freshly' planted trees (Y2-Y4) was compared between the years 2016 until 2019 using a linear mixed effect model for a one-way repeated design to account for replicated subsites (n=3) nested in 'sites', and Kenward-Roger correction of degrees of freedom. The relation of root ball SWP to planting pit SWP at the 'adapted' trees were compared between 2017, 2018 and 2019 using a one-way-repeated-measures ANOVA. All analyses were checked for sphericity ($p \leq 0.05$) and group means were compared using Tukey post-hoc comparison at p-level ≤ 0.05.

To test the applicability of using predictor variables such as meteorological variables, tree- and site-specific characteristics to predict the occurrence of days below SWP_C (response variable) within the soil compartments, we used a data-driven *randomForest* model (Breiman 2001). In addition we analyzed the importance of these predictor variables in relation to the decrease of model-accuracy (raw importance). Variables were then pooled and importance values were categorized (no, low, medium, high, highest) to account for possible estimation inaccuracies. The predictor variables consisted of short-term (daily means) and long-term (10-day means and sums) meteorological variables such as precipitation, air temperature, global radiation, relative humidity, potential evapotranspiration, climatic water balance (balance of precipitation and potential evapotranspiration (mm)) and vapour pressure deficit. Moreover, the predictor variables consisted of tree characteristics such as tree age and tree species (genus/species) (Table 3.1). Additionally we added measured and estimated site characteristics such as the soil temperatures (daily means and 10-day mean), the measured soil infiltration capacity (double-ring infiltrometer measurements), the sealed soil area (5 x 5 m grid and 10 x 10 m grid), soil properties such as soil texture, the organic C content and the pH value, the categorized appearance of herbaceous vegetation at the soil surface, the categorized estimated canopy openness, the categorized growing site (street, street bank or public square) and the categorized site localization (urban and sub-urban). The irrigation was integrated in form of two categories: 'irrigated' vs. 'non-irrigated' sites and whether irrigation occurred within the last 10 days or not. To avoid overrepresentation of specific characteristics, especially of tree age, we used calculated mean values for the three replicated sites (Table 3.1). Model accuracy was tuned and run with ntree= 200 and mtry=16 and the overall quality was checked using the out of bag error estimation. The mean decrease of accuracy for each response variable was calculated from five model runs with random seed numbers (equal for each soil compartment). Means and standard deviations were plotted, listed, and categorized by their importance for predicting SWP_C. The input variables are listed in Appendix Table 3.1.

Statistical analyses were conducted using OriginPro, v2019b (OriginLab Corporation, Northampton, MA, USA) and R v3.6.3 (R Core Team 2022) with *randomForest* and caret packages (Liaw & Wiener 2002; Kuhn 2021).

3.3 Results

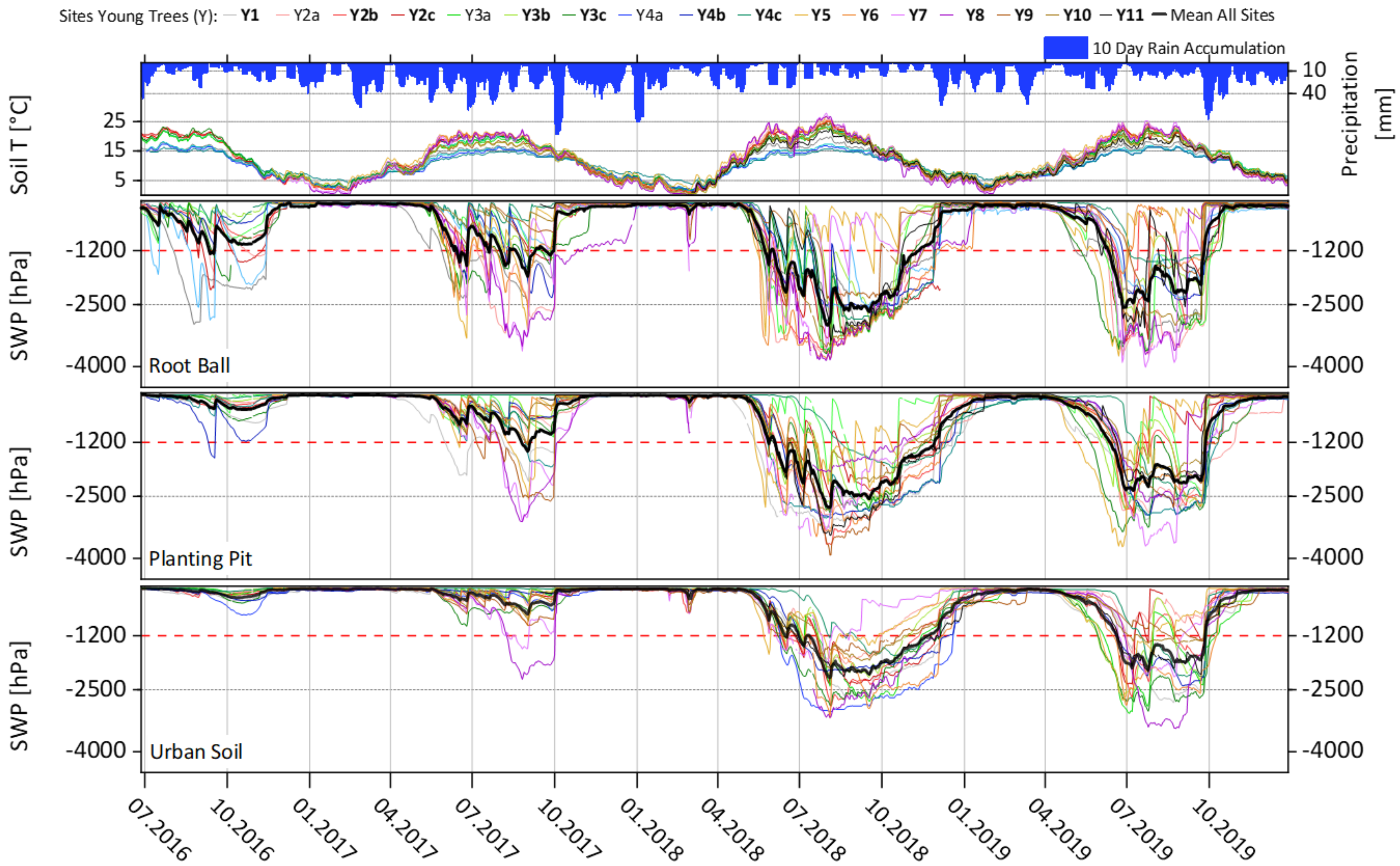
3.3.1 Variability of meteorological and soil temperature conditions

Annual atmospheric conditions covered a broad spectrum of variability over the course of the four years of monitoring (2016-2019). Compared to the 30-year precipitation average of 793 mm (1981-2010 for Hamburg-Fuhlsbüttel), the years of 2016 and 2019 can be classified as 'slightly dry average years' (738 mm and 754 mm, respectively). The year 2017 was an overall 'wet year' (989 mm), whereas the year 2018 was a 'hot and dry year' (518 mm) (Buras et al. 2020). The growing season (May - September) of 2018 was extraordinary dry (145 mm) compared to the long-time average of 359 mm precipitation. Winter precipitation (October – April) was above average in 2017/2018 (498 mm) and below average in the winter 2018/2019 (364 mm). During the growing season of 2018, atmospheric water demanding conditions ($VPD_{max}\ d^{-1} > 15$ hPa) were recorded on 85 days, 33 days more than in 2019 and 47 days more than in 2017 (Appendix Figure 3.1). Reaching 10.3 °C, the annual mean air temperature at the DWD meteo-station Hamburg-Fuhlsbüttel between 2016 and 2019 was consistently higher than the long-time average of 9.4 °C. The mean air temperature of 17.8 °C during the growing season of 2018 was the warmest during the monitoring period. Depth weighted soil temperatures varied across the 17 sites and ranged from 15.4 to 24.5 °C at the day of hottest daily air temperature (Figure 3.2). Soil temperatures were positively correlated with the percentage of sealed surface area and significantly differed between shaded and non-shaded sites (Appendix Figure 3.3 and Appendix Figure 3.5).

3.3.2 Seasonal dynamics of soil water potential

The soil water potential (SWP) at the investigated young urban street-tree sites showed a seasonal pattern with lowest SWP during the growing season (May – September) and highest values during the winter months in all soil compartments (Figure 3.2). Compared to the planting pit and the urban soil, SWP dynamic was most pronounced in the root ball throughout all seasons. Although the growing season of 2017 was extraordinary wet, the critical SWP threshold (SWP_C: SWP < -1200 hPa) was negatively exceeded in the root ball of most sites and also in the planting pit and urban soil at the 'adapted' sites. From 2018 onwards, SWP fell below SWP_C at all sites in each soil compartment. During the extraordinary hot and dry growing season of 2018, lowest average SWP for each soil compartment was recorded and SWP_C was first negatively exceeded between end of May (root ball) and beginning of July (urban soil). With the exception of two regularly irrigated sites (Y5 and Y7), the soil water availability was simultaneously critical at all sites during September 2018. During 2019, the SWP_C was negatively exceeded on an average of more than 20 days earlier than in 2018. Rewetting phases regularly increased the SWP above SWP_C during the growing season of 2017. In 2018 and 2019, phases

Figure 3.2: Dynamics of the SWP within the soil compartments root ball, planting pit and urban soil over the course of four years. Data are displayed for all 17 young street-tree sites Y1-Y11 (thin, coloured lines). The black line shows the course of average SWP with n number of sites available for calculation of average SWP per year: 2016 n = 10; 2017 n = 16; 2018 n = 17; 2019 n = 17. Red, dashed lines show the SWP$_C$ threshold at -1200 hPa. The site specific depth weighted soil temperatures and the 10-day precipitation sum (radar based DWD RADKLIM data (DWD 2020) of site Y5) are displayed at the top of the graph.



of intense soil drying were only shortly interrupted by soil rewetting and the average SWP remained almost constantly below SWP_C. In 2017 and 2019, SWP sharply increased above SWP_C with beginning of October and soils remained constantly moist, whereas in 2018 the SWP remained low and thus soils remained dry until the end of November (root ball) and the end of December (planting pit and urban soil).

The development of SWP during the growing seasons 2016-2019 was analyzed separately for freshly planted young trees (n=9; Y2a-Y4c)) and adapted young trees (n=6; Y5-Y10). The ratio of root-ball SWP to planting-pit SWP at the freshly planted sites followed a decreasing trend over time, most pronounced between the first two growing seasons after plantation in 2016 (Figure 3.3). At the established sites, no significant decrease was observed.

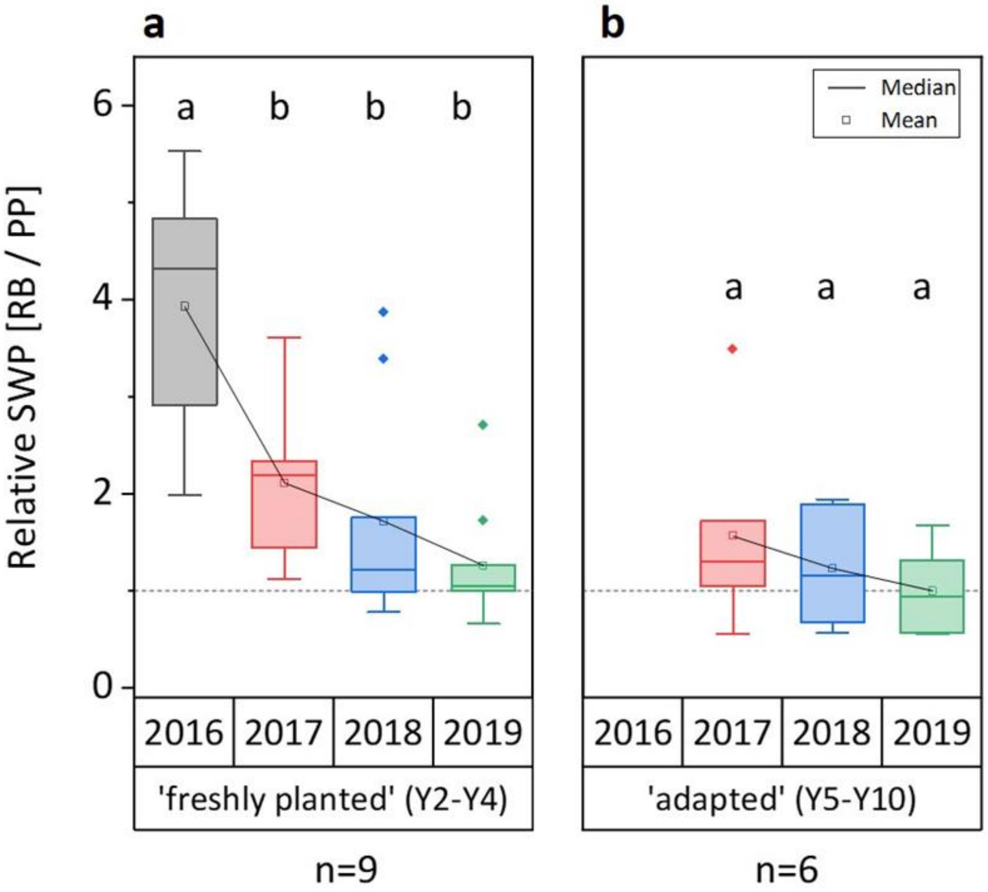


Figure 3.3: a: SWP of the root ball in relation to SWP of the planting pit during the growing seasons at the 'freshly planted' sites Y2-Y4 (n = 9). Statistical analysis was performed using a linear mixed model. Boxes with the same letters indicate no significant differences at the $p < 0.05$ level. Mean comparisons were performed by Tukey post-hoc comparisons. b: SWP of the root ball in relation to SWP of the planting pit during the growing seasons at the 'adapted' sites (n = 6). Statistical analysis was performed using a one way repeated measures ANOVA. Boxes with the same letters indicate no significant differences at the $p < 0.05$ level. Mean comparisons were performed by Tukey post-hoc comparisons.

3.3.3 Extent and intensity of critical soil water availability

During 2017, 51 ± 11 (Mean ± SE) days below SWP_C occurred in the root ball and 24 ± 9 days in the planting pit (Figure 3.4a). The difference between root ball and planting pit was only significant for the ‘freshly planted’ young trees ($p < 0.05$; data not displayed) not for the ‘adapted’ young trees. In 2018, the SWP in all soil compartments were significantly lower than in 2017 and fell below SWP_C on 135 ± 14, 152 ± 12, and 118 ± 12 days in the root ball, planting pit and the urban soil, respectively (Figure 3.4a). During the growing season of 2018, critical soil water availability in all soil compartments simultaneously occurred with atmospheric water demanding conditions (daily $VPD_{max} > 15$ hPa) for 30 days, predominantly during August and September (Appendix Figure 3.1). In 2019, there was no significant difference in the number of days below SWP_C between the planting pit and the surrounding soil, and atmospheric water demanding conditions simultaneously occurred with critical soil water availability on 23 days. The water stress intensity in the root ball and the planting pit was not significantly different between 2018 and 2019. Whereas the water stress intensity was most pronounced in the root ball and the planting pit, the intensity within the urban soil remained significantly lower during both years (Figure 3.4b).

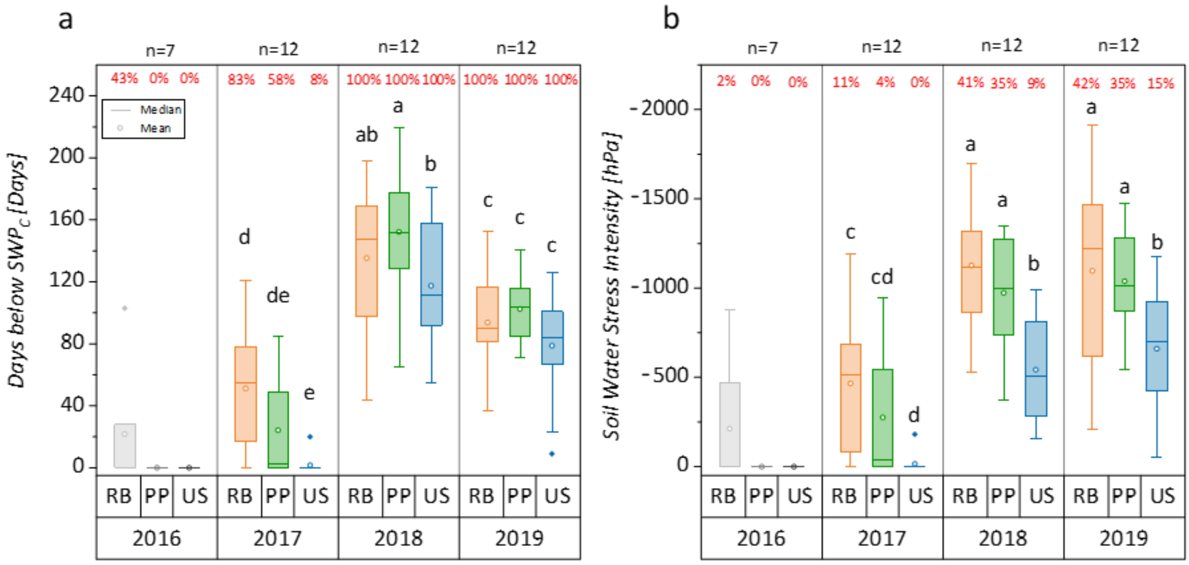


Figure 3.4: a: Annual sum of days below SWP_C as a mean of 12 of 17 sites. Red numbers in the top of the graph indicate the percentage of sites where days below SWP_C occurred on at least one day per year. Statistical analysis was performed using a two-way-repeated-measures ANOVA. Boxes with the same letters indicate no significant differences at the $p < 0.05$ level. Grey boxes (2016) were not considered for statistical analysis. b: Soil water stress intensity per day below SWP_C as a mean of 12 of 17 sites. Red numbers in the top of the graph indicate the average percentage of days below SWP_C when SWP also fell below -2500 hPa; Statistical analysis was performed using a two-way-repeated-measures ANOVA. Boxes with the same letters indicate no significant differences at the $p < 0.05$ level. Mean comparisons were performed by Tukey post-hoc comparisons.

3.3.4 Predicting SWP_C occurrence and variable importance

In all soil compartments, the annual number of days below SWP_C was strongly coupled to meteorological seasonality (Figure 3.2). However, between-site variance was well expressed, particularly in 2018 (Figure 3.4a), indicating additional influence of tree- and site-specific characteristics on the occurrence of soil water stress conditions. A *randomForest* model was computed using categorical and dynamic variables from all years and all sites (Appendix Table 3.1) as predictors for the occurrence of a day below SWP_C. The model quality was assessed by out of bag error estimation. The overall accuracy of the model for predicting daily SWP_C ranged between 97 - 98%, whereas it decreased to 93 – 96% when only considering the accuracy of predictions for days below SWP_C (Appendix Table 3.4). When considering only data from the growing seasons (Appendix Figure 3.2), the overall accuracy of predictions decreased to 95 – 97%.

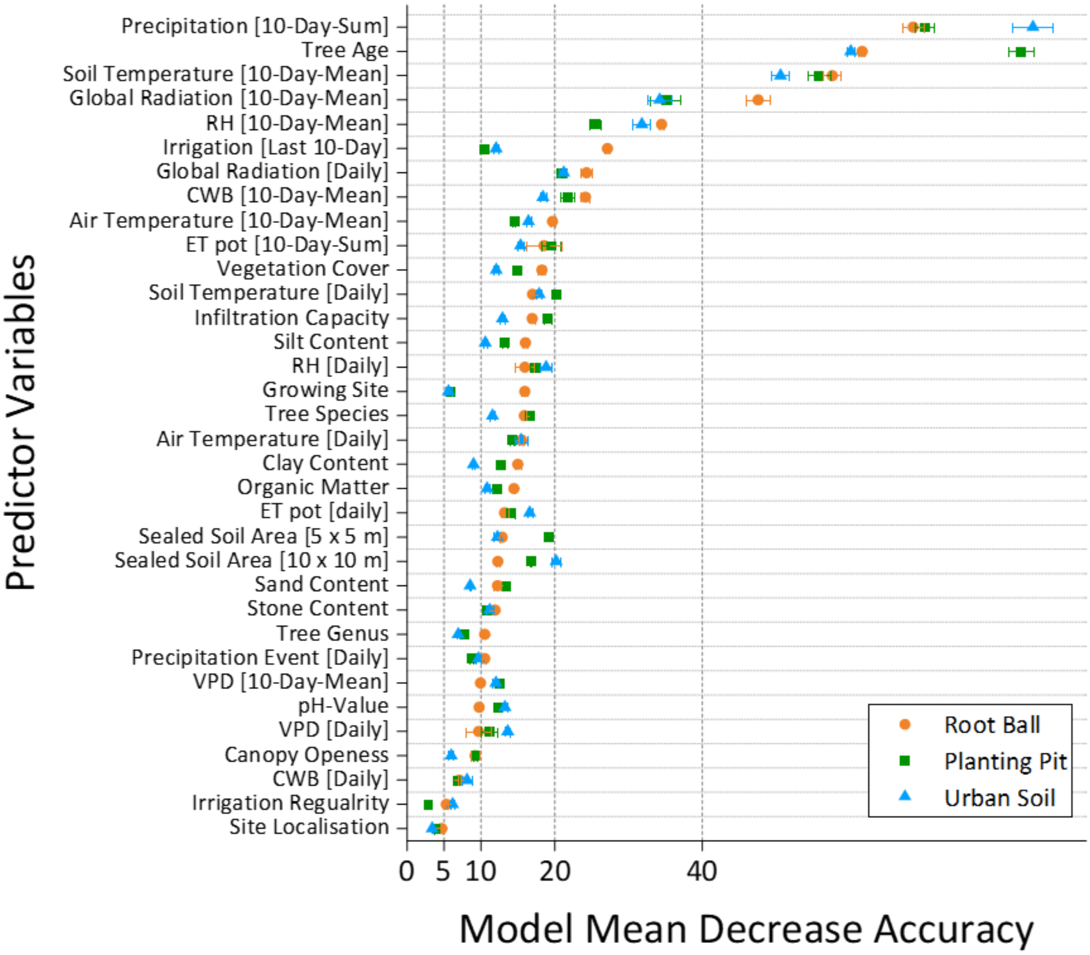
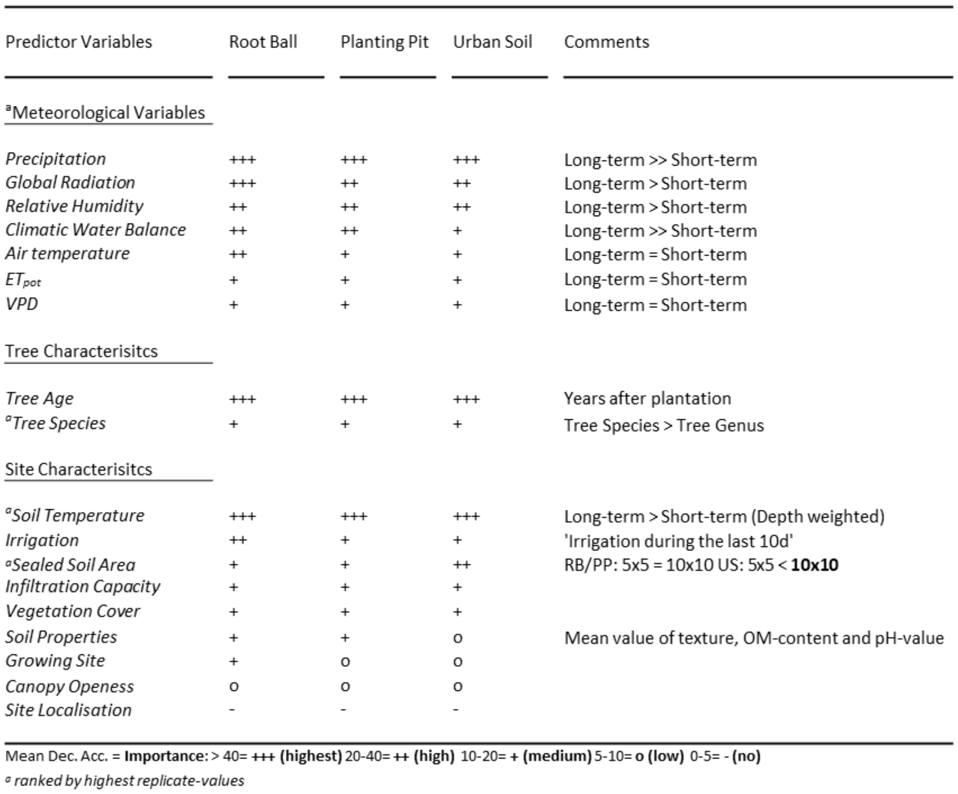


Figure 3.5: Raw output of the *randomForest* model displayed by the means of the mean decrease accuracy for each predictor variable. The ranking is based on the mean values of the root ball in ascending order. Error bars represent the standard deviations of five model runs with randomly selected seed numbers.

For each predictor variable, the *randomForest* model provides a value for the model accuracy (mean decrease accuracy), describing the importance of each predictor variable for the model prediction. Predictor variable, except 10-day precipitation sum, tree age, irrigation and sealed soil area, were ranked very similar for the three soil compartments (Figure 3.5). Precipitation (highest), global radiation (highest for root ball, high for planting pit and urban soil) and relative humidity (high) were the most important meteorological predictors for SWP_C within all soil compartments (Table 3.2). Long-term conditions (up to 10 day-means and -sums) were more important for predicting days below SWP_C than short-term conditions (daily means) and were most pronounced for the water input related variables (i.e. precipitation, climatic water balance and irrigation) (Figure 3.5). The tree age was of highest importance for SWP_C prediction in the planting pit and the overall second most important variable (Table 3.2). Soil temperature, as most important site characteristic variable, was more important for predicting the occurrence of SWP_C than air temperature. Irrigation was most important in the root ball. Infiltration capacity, sealed soil area, herbaceous vegetation cover, and tree species were of medium importance, while soil properties, canopy openness and general site information were less important or not important at all.

Table 3.2: Importance of predictor variables grouped by ‘meteorological variables’, tree characteristics’ and ‘site characteristics’, categorized and ranked by their importance for predicting the occurrence of critical soil water availability (response variable) and divided into the soil compartments root ball, planting pit and urban soil. Since some variables (marked with: [a]) were analyzed e.g. on their short-/long-term importance, these were ranked by the highest values of each replicate and listed as follows in the column *comments*: **>>**: 2 or more categories between the replicates; **>**: 1 category between the replicates, **=**: replicates were in the same category



Predictor Variables	Root Ball	Planting Pit	Urban Soil	Comments
[a]Meteorological Variables				
Precipitation	+++	+++	+++	Long-term >> Short-term
Global Radiation	+++	++	++	Long-term > Short-term
Relative Humidity	++	++	++	Long-term > Short-term
Climatic Water Balance	++	++	+	Long-term >> Short-term
Air temperature	++	+	+	Long-term = Short-term
ET_{pot}	+	+	+	Long-term = Short-term
VPD	+	+	+	Long-term = Short-term
Tree Characterisitcs				
Tree Age	+++	+++	+++	Years after plantation
[a]*Tree Species*	+	+	+	Tree Species > Tree Genus
Site Characterisitcs				
[a]*Soil Temperature*	+++	+++	+++	Long-term > Short-term (Depth weighted)
Irrigation	++	+	+	'Irrigation during the last 10d'
[a]*Sealed Soil Area*	+	+	++	RB/PP: 5x5 = 10x10 US: 5x5 < **10x10**
Infiltration Capacity	+	+	+	
Vegetation Cover	+	+	+	
Soil Properties	+	+	o	Mean value of texture, OM-content and pH-value
Growing Site	+	o	o	
Canopy Openess	o	o	o	
Site Localisation	-	-	-	

Mean Dec. Acc. = **Importance:** > 40= **+++ (highest)** 20-40= **++ (high)** 10-20= **+ (medium)** 5-10= **o (low)** 0-5= **- (no)**

[a] *ranked by highest replicate-values*

3.4 Discussion

3.4.1 Soil water stress under variable climatic conditions

Meteorological extremes, such as recorded for Europe (Schuldt et al. 2020) and Germany during 2018 (i.e. hottest and driest year since records began (DWD 2020)), are predicted to occur more frequently with climate change (Schlünzen et al. 2010; Trusilova & Riecke 2015). Soil water availability in the root zone of individual trees can be used as an indicator to assess growth limitations and loss of tree vitality (Gillner et al. 2017b; Thomsen et al. 2020), and is of major interest for urban tree management to cope with challenges of a changing climate. On individual tree level, sensor based measurements of soil water availability may be of high applicability and resolution and are thus to be used in preference to drought related variables derived from remote sensing data. However, sensor-based monitoring data of water availability in urban soils, particularly around developing young urban street trees, are yet scarce (Wiesner et al. 2016; Gillner et al. 2017b; Schaffitel et al. 2020) and lack of temporal and spatial resolution.

During 2018, the soil water potential (SWP) in the root ball and planting pit fell below a critical threshold of -1200 hPa (SWP_C) (von Wilpert 1991) at all monitored sites. This condition lasted for more than five months on average (Figure 3.4a). Other than expected, SWP in urban soil (down to 1 m depth) also fell below SWP_C at all sites on an average of 117 days indicating the presence of tree roots, however with less soil water stress intensity compared to the root ball and the planting pit (Figure 3.4a and 3.4b). Data from our study exceeded previously reported data for the equally extreme year of 2003 (Buras et al. 2020; Schuldt et al. 2020) from a German and French forest stand, with up to 111 days below SWP_C (Granier et al. 2007; Schmidt-Walter et al. 2019). However, compared to forests, where water can be also tapped from great depths and roots can grow without spatial restrictions in naturally grown soils, young street-trees have to supply themselves with a shallow and inadequate to the above ground demands developed root systems concentrated on the immediate surrounding soil (Figure 3.1) (Watson 2005). Furthermore, a direct exposition to incoming solar radiation (Roloff 2013), low atmospheric humidity with simultaneously higher temperatures and thus elevated atmospheric water demand (Gillner et al. 2017b), can explain causing longer-lasting durations of critical soil water availability in the urban environment (Figure 3.2 and Figure 3.4a) compared to results from Granier et al. 2007; Schmidt-Walter et al. 2019) in 2003. During the growing seasons of 2018 and 2019 the investigated trees had to cope with phases of critical soil water availability, partly with SWP below -2500 hPa (Figure 3.4b), with simultaneously high atmospheric water demanding conditions (Appendix Figure 3.1). Depending on their strategy to cope with such phases, trees are either likely to suffer from carbon starvation when stomata were closed already early and long-lasting during the growing season to prevent the loss of water vapor (isohydric behavior) or from cavitation when low plant water potentials result in turgor loss (anisohydric behavior) (McDowell et al. 2008; Sjöman et al. 2018). Recent findings suggest that during 2018, trees with on average early stem-growth cessation might not have experienced growth inhibition, since soils water capacities have been fully saturated from the previous year and the wet spring (Scharnweber et al. 2020), which is supported by our data for almost all sites. However, we expect that at least until September 2018, prolonging critical soil water availability and simultaneous high atmospheric water demand (Appendix Figure 3.1) led to both, elevated water stress and thus vitality reduction for anisohydric trees and less carbon assimilation for isohydric trees. Soil water availability persisted on a low level until December 2018, indicating soil water recharge to be incomplete with beginning of the growing season 2019 (Figure 3.2) and therefore exhaustion of available soil water below the critical threshold already in early July. Consequently, tree growth limitation, caused from incomplete soil water recharge and limited structural carbon assimilates, can be expected as recently found from Scharnweber et al. 2020. In addition to direct impacts of long lasting critical soil water availability (e.g. leaf senescence, stem diameter shrinkage, loss of stored C reserves), legacy effects (e.g. short shoots, partial crown dieback) might impact tree vitality and resilience even several years after the actual drought event (Bréda et al. 2006; Roloff 2013). Since the mortality rate of young trees in the establishment phase is already higher compared to established trees (Nowak et al. 2004), it is likely that vulnerability (e.g. due to biotic attack agents) additionally increases at young trees during prolonging and consecutive soil water stressing seasons (McDowell et al. 2011). Although each investigated tree survived throughout the measurement period, these are important aspects to be addressed in further investigations to understand the resilience and the adaptation potential of commonly used and potential future urban tree species to critical soil water availability (Gillner et al. 2017b).

Our results indicate that soil water availability within the root zone was highly critical during years of average (2019) to extraordinary dry and hot meteorological conditions (2018). The risk of long-lasting growth- and vitality losses is therefore likely given and can endanger the development of young street-tree populations to mature trees in particular when SWP remain constantly low in the following years. The information gathered from this data could additionally be used to evaluate the usability of drought related variables derived from high-resolution satellite images (Rhee & Im 2017) for defining limited soil water availability on single tree scale.

3.4.2 Site adaptation and root development

Whether a tree in the urban environment has to suffer from decreased soil water availability, depends on its ability to adapt to site conditions and develop and expand its root system. Mature oak trees on nowadays highly sealed urban sites can maintain high transpiration and growth rates despite low SWP in the uppermost 80 cm, by accessing deep lying soil layers with higher SWP (Thomsen et al. 2020).

Our study covered young trees – from freshly planted up to maximum 10 years after plantation –, where the root system of the freshly planted trees was not expected to exceed the monitored soil volume of approximately 7 m³ containing all soil compartments (Figure 3.1). The decreasing ratio between SWP in root ball and planting pit of freshly planted young trees revealed the root development into the entire planting pit within three years after planting (Figure 3.3). This is consistent with previous reports of root excavations at young street-tree sites two years after planting (Krieter & Malkus 1996). In contrast, the ratio between SWP in the root ball and the planting pit at the adapted trees was not significantly different between 2017 and 2019, indicating that roots had already fully tapped the planting pit before 2017. Root development into the urban soil occurred latest in the fourth year after plantation, indicated by an equal number of average days below SWP_C compared to the root ball and the planting pit (Figure 3.4a). We expect that tree roots developed slower into the strongly compacted urban soil compared to the backfilled structural soil substrates in the planting pits (Jim 1998; Rahman et al. 2011; Jim 2019a). This assumption is supported by the significantly lower infiltration capacity in urban soil compared to the planting pits (Table 3.1 and Appendix Figure 3.4). The significantly lower soil water stress intensity in the urban soil compartment compared to the root ball and the planting pit indicates that the trees were unable to effectively extract water from the surrounding soil. This difference is likely underestimated, as the lower measurement limit in planting pit and root ball was negatively exceeded for 35-42% of the total days below SWP_C (Figure 3.4b). The sandy textured urban soils (Table 3.1) provide very low hydraulic conductivity when the soil dries. This limits the water flow from soil surrounding the root to its surface and thus reduces the access to potentially available water (Blume et al. 2009; Schulze et al. 2019). Additionally, further root development is often limited by belowground infrastructure along modern streets (Jim 2019a), and the available soil water in the densely rooted planting pit may become rapidly depleted from increasing water demand of the aging trees (Jim & Ng 2018). In this case, more intense soil water stress - comparable to the root ball and the planting pit - would be observable in the following years when root density increases in the limited root zone.

3.4.3 Predicting SWP_C occurrence and variable importance

The extent of critical soil water availability can vary greatly between sites (Figure 3.2 and Figure 3.4a) (Clark & Kjelgren 1990). Consequently, implications for young urban trees related to reduced water availability can be assumed to be only partly characterized by using meteorological drought indices such as the standardized precipitation (-evaporation) index (SPI or SPEI index) (Moser et al. 2016; Paton et al. 2021).

Using a *randomForest* model approach demonstrated the capability of a data-driven method to predict the occurrence of SWP_C with high accuracy (Appendix Table 3.4). By adding relevant response variables, the *randomForest* model incorporates and evaluates the interacting processes responsible for a certain soil water status (above or below SWP_C) (Carranza et al. 2021). We therefore assume the model to be highly applicable for predicting soil water status in uncontrolled experimental setups and heterogeneous environments such as cities. In addition, the model provides the important predictors that influence model accuracy most. We identified precipitation, global radiation, and relative humidity as the most important meteorological variables to predict whether or not a day below SWP_C at a young urban street-tree site in Hamburg occurs (Table 3.2). Since the tree sites were selected to represent low connectivity to the ground water table and only few sites received irregular irrigation, precipitation was the major source for soil water replenishment. Soil water losses, on the other hand, are strongly related to global radiation which is correlated to sap flow rates and thus transpiration (Rahman et al. 2017a; Thomsen et al. 2020). During days of high incoming solar radiation, photosynthetic activity within the leaves is high (Li et al. 2018) and trees provide subsequent supply of CO_2 by keeping their stomata open as long as soil water is available. However, this is at the cost of water loss through transpiration. Contrary to findings of Rahman et al. 2017a and Thomsen et al. 2020 for sap flow rates, we found relative humidity to be a more important predictor for SWP_C than VPD. The occurrence of critical soil water availability at young street-tree sites can be mainly predicted by long-term- (up to 10 day), rather than by short-term (daily) meteorological conditions, which is most pronounced for precipitation and climatic water balance (Figure 3.5). Sufficient changes from critical SWP towards moist conditions were therefore most often represented by the accumulation of succeeding precipitation events (Figure 3.2). This suggest, that sufficient soil water recharge becomes less likely in future growing seasons, when periods without precipitation lengthen and the frequency of rainy days decreases as projected for climate change (Schlünzen et al. 2010; Meinke et al. 2018). When the intensity of precipitation exceeds the infiltration capacity of the soils during heavy precipitation events (Yang & Zhang 2011), which also tend to increase in frequency (Schlünzen et al. 2010; Meinke et al. 2018), soil water replenishment might be additionally reduced by increased surface runoff. Irrigation was unable to mitigate the occurrence of critical soil water availability in the whole root zone, reflected by lower importance for the planting pit and the urban soil compared to the root ball. This might be an effect of the low soil water retention characteristics of the present structural soil substrates (Table 3.1) and the concentration of provided irrigation to the soil surface close to the trunk. However, more information (e.g. timing, duration and amount of water) and an experimental setup focusing on the effect of different irrigation strategies would be required to provide a conclusive statement. Like observed for precipitation, long-term irrigation strategies covering a greater soil surface could have a more lasting effect on reducing the SWP in the whole root zone sufficiently.

Since soil water availability differed between the sites (Figure 3.2 and Figure 3.4a), we assume the occurrence of SWP_C at the investigated sites to be also linked to tree- and site specific characteristics

(Clark & Kjelgren 1990; Nielsen et al. 2007; Wiesner et al. 2016; Thomsen et al. 2020). The variable tree age, was the second most important variable for predicting the occurrence of critical soil water availability at young street-tree sites (Figure 3.5). Rötzer et al. 2017) hypothesized, that with increasing tree size the water demand of the trees increases depending on the higher foliage area per soil surface area. To cover the increasing water demand, the monitored freshly planted trees exploited a larger root zone indicated by decreasing SWP (Figure 3.2a and Figure 3.3). In case the rooting zone is spatial limited and the trees cannot acquire further water sources (Jim & Ng 2018), we assume, that a rapid depletion of stored soil water is possible under extreme as well as moderate climatic conditions. Therefore, young trees can experience periods of critical soil water availability, even in years of above average precipitation. Even after the wet spring and wet early summer of 2017 for example, four out of six adapted young street-trees were subjected to critical SWP in the planting pit on 26-56 days during the late summer of the same year (Figure 3.2). Other factors, such as phenology (Granier et al. 1999), strategies of controlling transpiration loss of water (McDowell et al. 2008; Rötzer et al. 2017; Stratópoulos et al. 2019b; Thomsen et al. 2020) and the ability of lowering the root water potentials (Larcher 2001) are expected to strongly regulate tree water consumption. These factors can be expressed differently between tree species of the same genus (Sjöman et al. 2015; Stratópoulos et al. 2019b) and even between phenotypes of the same tree species depending on its origin (Sjöman et al. 2018). This might explain our finding that tree species was more important for predicting critical soil water availability occurrence than tree genus (Figure 3.5).

Soil temperature was more important than air temperature for predicting the occurrence of SWP_C (Table 3.2). This may be explained by the limited spatial resolution of the used air temperature data (three meteo-stations representing 17 sites) compared to the soil temperature data that were directly measured at each site and in three depth levels. However, due to the pronounced variability of soil temperatures between sites, which reached up to 10 °C per day (Figure 3.2), we also suggest soil temperature to be more important, as it reflects site specific characteristics affecting water- and energy balance (e.g. the degree and type of soil sealing, the presence or absence of herbaceous soil covering vegetation and the degree of shading through tree canopies or buildings (Kotzen 2003; Armson et al. 2013; Morgenroth et al. 2013) (Appendix Figure 3.3 and 3.4 and Appendix Table 3.3 and Rahman et al. 2021). Therefore, soil temperature could possibly serve as an index variable, as it integrates site-specific characteristics at young street tree sites within the complex urban environment. For future applications in tree water management, the use of remote sensing data from high resolution satellite images may compensate the limitation of those point-based soil temperature measurements to predict critical soil water availability with the model developed. Thus, combining remote sensing data with necessary site specific data and a data-driven model, developed on basis of point measurements on single tree level, provides the opportunity to extrapolate the soil water availability data on larger scales (e.g. on street level), which has already been successfully done in agriculture (Rhee & Im 2017; Carranza et al. 2021). In addition and particularly for uncontrolled experimental designs under heterogeneous site conditions in cities, the development of functional proxies (multiple site-parameter combinations) could help to highlight the importance of site parameters as an integral of variables (e.g. Scharenbroch et al. 2017) by using both, simple statistical approaches and data-driven methods.

However, soil properties like soil texture were only of medium predictive importance. However, the advantage of measuring SWP instead of VWC was that SWP can be applied to estimate soil water availability independent of soil properties and was therefore expectable. Furthermore the soil compartments planting pit and urban soil at all sites were composed of sandy soil textures, which provide low water holding capacities and tend to drain rapidly (Craul 1985), this resulted in a relatively low data range and thus might have led to a low ranking of texture effects on the occurrence of SWP_C. However, this reflects the situation in Hamburg (Schickhoff & Eschenbach 2018) as well as globally (Greinert 2015; Jim & Ng 2018), where sandy soil textures are highly representative for street-tree sites. To address the effect of urban soils in more detail, future studies should investigate growth and adaptive potential of different tree species and cultivars in response to different coarsely textured urban soils and soil substrates in controlled settings. Future adaptation strategies should also include (1) improvements of soil water recharge and storage potential during heavy precipitation events (Nielsen et al. 2007; Roloff et al. 2009; Sjöman & Busse Nielsen 2010; Caplan et al. 2019; Stratópoulos et al. 2019b) when excess water percolation is guaranteed (2) provision of adequate root space to prevent early soil water depletion during dry periods when tree water demand has increased with aging and (3) if alternative adaptations and regularly irrigation are not possible, selection of tree species phenotypes naturally adapted to critical soil water availability (Sjöman et al. 2018).

There is an urgent need to improve soil water management at young urban street-tree sites to shorten phases of critical soil water availability and to ensure soil water supply and replenishment in extreme years such as 2018 and 2019. Further research is needed to clarify the effect of SWP_C measured in the root zone on growth, vitality, and long-term establishment of the trees investigated.

3.5 Conclusion

In this study, we provided insight into the dynamics of soil water availability and drying intensity at developing, young urban street tree sites. We also predicted the occurrence of critical water availability at these sites using meteorological variables, tree and site characteristics with a data-driven model that ranked the important variables influencing the prediction accuracy of the model.

Our results show that soil water availability within the root zone was highly critical during years of extreme and moderate meteorological conditions. In total, the average soil water potential (SWP) of all sites fell below SWP_C between three to five months per year. The risk of lasting growth- and vitality losses was and is in the future therefore likely and endangers the development of young street-tree population to mature trees. Roots of freshly planted trees expanded into the entire soil volume of the planting pits within the first three years. A further expansion into the urban soil was slower but visible by elevated SWP after four years. However, the ability of trees to extract water from these sandy textured soils was low compared to the planting pit. When further root development beyond the urban soil volume is limited, the available soil water in the densely rooted planting pit may become rapidly depleted from increasing water demand of the aging trees.

The *randomForest* analysis was applicable and was of high predictive accuracy. We identified that sufficient changes from critical SWP towards moist conditions were predicted best by the accumulation of succeeding summertime precipitation events, which are projected to decrease in frequency with climate change. Between-site variations of days below SWP_C were interlinked with a synergy of tree- and site specific characteristics. The tree age was the second most important variable describing the increasing water demand with aging. In order to adapt tree site conditions, the model revealed soil as important proxy for site sensitivity towards critical soil water availability. In our model approach, soil temperature is important, as it, contrary to air temperature, reflects site specific characteristics affecting water and energy balance. To address the effect of specific urban soil compartments on water capacity in more detail, future studies should focus on growth response and adaptive potential of urban tree species.

4 Growth Response of Nine Tree Species to Water Supply in Planting Soils Representative for Urban Street Tree Sites (Manuscript 2)

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4.1 Introduction

Establishing recently planted street trees is a critical step to achieve green infrastructure goals and to maintain the tree population in cities. This is particularly challenging, since growing conditions for urban street trees are highly unfavorable (Craul 1985; Clark & Kjelgren 1990; Jim 1998). Due to anthropogenic transformations and translocations, urban soils exhibit a high degree of spatial heterogeneity. Artificial sandy and stony substrates (Wessolek et al. 2011; Jim & Ng 2018), high degrees of soil compaction (Jim 1998), surface sealing (Armson et al. 2013; Morgenroth et al. 2013), and vertical and horizontal limitations of root distribution (Cermák et al. 2000) alter tree sites and, in particular, street tree sites in comparison with natural environments. However, there has been little research on the impact of artificial urban soils on tree growth and the long-term success of new plantings (Pregitzer et al. 2016). Climate change and the urban heat island are prolonging the tree growing season and increasing the inner-city atmospheric water deficit, thus raising the transpirational water demand of the trees (Roetzer et al. 2000). As observed in the summers of 2018 and 2019 (Schuldt et al. 2020; Schnabel et al. 2022), increased meteorological droughts (i.e., phases of deficiency and uneven distribution of precipitation) and storm events with high run-off shares are likely to occur more frequently in Mid-Europe, causing soil water scarcity in cities (Hartmann 2011). Since soil water replenishment by single and few precipitation events at freshly planted tree sites is less effective (Schütt et al. 2022b) and successive and frequent precipitation during summer is predicted to decrease in the future climate (Schlünzen et al. 2010), climate change is likely to exacerbate water limitation and thus the growing conditions of street trees. As a consequence, urban street trees are likely to grow slower than trees in rural environments and forests (Quigley 2004). However, direct growth comparisons are sparse, and findings are not consistent (Gillner et al. 2013; Pretzsch et al. 2017) and seem to be not appropriate to assess the effect level that soil constraints have on the growth of urban street trees. Therefore, on-site comparisons of various tree species and planting soils under identical climate conditions are necessary.

Freshly planted street trees, suffering from transplanting shock, have to adapt rapidly to urban site conditions and re-establish a root:shoot ratio adequate to meet the above-ground demands (Watson 2005). This results in low life expectancies of less than 30 years (Roman & Scatena 2011) and particularly large premature mortality rates for recently planted tree populations from nurseries into urban street sites (Nowak et al. 2004; Roman et al. 2014). To achieve fully developed ecosystem services in the long term, these initial growth conditions have to be further improved based on detailed investigations into the interaction of tree growth and urban planting soils with a focus on soil water characteristics. Because street tree sites usually act as multifunctional public spaces, however, the tree's demand itself often takes a secondary role in planning processes. For example, original local- or artificial soils are often replaced by technical soil–gravel mixtures (structural planting soils) prior to planting to ensure compaction stability for parking lots and pedestrian infrastructure (Grabosky & Bassuk 1996; Smiley et al. 2006; Rahman et al. 2011; Grabosky 2015). These structural planting soils contain high percentages of gravel (grain size > 2 mm), amended with soil–compost mixtures (grain size < 2 mm) that are dominated by a sandy texture (Grabosky 2015; Jim & Ng 2018). In addition to often small planting pits (Smiley et al. 2006; Grabosky & Bassuk 2016; Bretzel et al. 2020) in relation to standards (FLL 2015), it has to be questioned whether sandy-textured structural soil substrates can ensure sufficient water supply for young street trees (Jim 1998; Nielsen et al. 2007; Schütt et al. 2022b), particularly under climate change. However, the hydrology of structural soils and surrounding urban roadside soils and its effect on tree growth potential has not been systematically studied so far (Rahman et al. 2011; Riikonen et al. 2011; Grabosky & Bassuk 2016).

Tree growth habit is the result of intrinsically determinate reaction patterns to extrinsic factors (Quigley 2004). Therefore, sandy and coarsely textured planting soils (Craul 1985; Jim & Ng 2018; Schickhoff & Eschenbach 2018) with comparatively low organic matter contents (Somerville et al. 2019) are expected to significantly affect tree growth rates (Grabosky & Bassuk 1996; Jim 1998; Riikonen et al. 2011), but not in a uniform pattern (Pregitzer et al. 2016). Depending on the particular hydrological characteristics of their habitat, trees have evolved multiple physiological strategies to counteract substantial vitality loss in situations of limited water availability. Thus, stress reactions can differ quantitatively and/or qualitatively between species. It is still the subject of scientific debates, which strategies of stress reactions are most promising for surviving increasing stress incidences and which main intrinsic factors foster mortality risk (Mitchell et al. 2014; Adams et al. 2017; Trugman et al. 2018; Blackman et al. 2019). Since the drought strategies of particular tree species are yet not fully understood, the suitability of tree species for urban street site planting has been so far mainly determined by meta-studies, assessing the drought resistance of tree species based on the aridity of their natural habitat (Roloff et al. 2009). A classification according to additional site-specific criteria, such as individual soil requirements for these tree species, is missing (Roloff et al. 2009). To determine the suitability of tree species and cultivars as urban street trees, long-term observational studies under *in situ* conditions in different cities have been conducted (e.g., GALK-Straßenbaumtest: http://strassenbaumliste.galk.de/sblistepdf.php (accessed on 2 April 2021); (Böll et al. 2014; Stratópoulos et al. 2018; Schönfeld 2019)). However, a conclusive statement regarding the species-specific growth responses to urban planting soils is still missing.

The aim of the present study was to determine the constraints of artificial urban soils on the growth of different tree species with a focus on soil hydrological properties. In particular, we aim to answer the questions: (a) Which hydrological properties and dynamics are characteristic of the selected representatives of urban planting soils? (b) Did periods of critical soil water availability occur in urban planting soils vs. natural soils under the climatic conditions during 2019–2021? (c) Which growth patterns were measurable overall and in the responses of tree species to specific soil conditions? Our approach for a suchlike assessment is to simulate experimentally urban below-ground conditions at one single site to provide identical climatic conditions. Therefore, we established a large-scale experimental field study in a complete block design. A total of 135 standardized eight-year-old trees of nine tree species (DBH: 4.5 cm–5.1 cm) were each planted in pits of 7.5 m^3 filled alternately with urban-typical artificial planting soils and one reference (loamy silt). The tree species selection was conducted based on three criteria: (a) general suitability as an urban tree, (b) underrepresentation in Hamburg's (Germany) street tree population, and (c) availability in the tree nursery. The soil hydrological parameters were measured in the laboratory and in the field. Tree growth was monitored morphometrically and dendrometrically for three years.

4.2 Materials and Methods

4.2.1 Study Site

The experiment was carried out at an open field site (6,000 m²) in a tree nursery located 15 km south of Hamburg, Germany (Baumschule Lorenz von Ehren GmbH & Co. KG; 53°24′ N; 9°57′ E). The climate shows a marine influence (Koeppen & Geiger: Cfb), with the highest precipitation in summer, a slightly dryer autumn and winter, and low precipitation in the spring season. The long-term annual means (1981–2010) of precipitation and air temperature are 743 mm and 9.6 °C, respectively (DWD 2022). The topography is slightly sloping and the groundwater table is below 20 m from the soil's surface. The predominant soil types at the experimental research site are agricultural-affected Cambisols with fine-textured loamy silts above silty sands to pure sands. The water-holding capacity at field capacity (FC; 60 hPa) ranged between 33% and 38% v/v, and that at wilting point (WP; 15,000 hPa) ranged between 10% and 15% v/v in the upper soil horizons (analysis method in Section 4.2.4.).

4.2.2 Substrate and Tree Selection

The experimental site was set up in a randomized complete block design of nine tree species planted in three planting soils. Every species–substrate combination was replicated five times (five blocks), resulting in a total number of 135 trees. Two treatment soils represented urban artificial soil conditions along streets: (1) a pure sand ('Sand'), representing artificial urban soils around street tree plantings (Jim & Ng 2018; Schütt et al. 2022b), and (2) a one-layer gravel–soil medium (structural planting soil) mixed according to German standardized guidelines (FLL 2015), similar to 'Amsterdam Tree Soil' (Watson et al. 2014) and commonly used as backfill material at recently planted tree sites ('FLL'). The reference soil was supposed to represent optimal growing conditions. Therefore, we used a regional harvested natural topsoil similar to the Cambisols at the experimental site, which were considered very suitable for the production of trees in the nursery and for years have provided good yields and quality ('Loamy Silt'). Planting pits with dimensions of 2.5 m × 2.5 m × 1.2 m (7.5 m³) were excavated for each tree studied. The planting pits were arranged in a 4 × 35 grid with spacing from center to center of 3.5 m × 8 m (Figure 2.4 and Appendix Figure 4.1).

The tree species were selected on the basis (1) of long-term observational and literature-based studies focusing on the suitability of diverse native and non-native tree species as urban trees (GALK and KLAM (Roloff et al. 2009; Roloff 2021a) (Table 4.1)). Nine tree species were selected from a wide range of tree species and cultivars rated in GALK (n = 178) and KLAM (n = 235). To achieve greater variability in the growth response patterns, we selected not only the highest-scoring tree species, but also the overall tree species that differed in their scores for drought tolerance (Table 4.1). Additional criteria for tree selection were (2) an underrepresentation within Hamburg's street tree population as the trees were mostly not yet commonly planted and (3) the availability of the same-sized and aged trees cultivated at the same nursery to provide comparability for the former growing conditions. This resulted in the selection of the following nine tree species: *Tilia cordata* 'Greenspire' (*Tc*), *Quercus cerris* (*Qc*), *Quercus palustris* (*Qp*), *Carpinus betulus* 'Lucas' (*Cb*), *Ostrya carpinifolia* (*Oc*), *Gleditsia triacanthos* 'Skyline' (*Gt*), *Liquidambar styraciflua* (*Ls*), *Amelanchier lamarkii* (*Al*), and *Koelreuteria paniculata* (*Kp*) (Table 4.1).

Table 4.1: Tree species characteristics. Planting diameter at breast height (DBH in May 2019) and suitability classifications of the investigated tree species for use as street trees. STP HH is the actual percentage of the investigated tree species from Hamburg's total street tree population (state: 31 December 2020). Stock of tree species is listed according to age class: The tree species were determined via the Hamburg tree cadaster and show the street tree population according to age classes classified by planting year after 2010, between 1990 and 2010, and before 1990.

Tree Species 'Cultivar'	**Code**	**DBH**	**Suitability**		**STP HH [3]**	**Stock of Tree Species [3]**		
		(cm)	**KLAM [1]**	**GALK [2]**	**(%)**	**>2010**	**1990–2009**	**<1990**
Tilia cordata 'Greenspire'	*Tc*	5.1 ± 0.1	2.1	Well suited	1.3	737	1561	596
Quercus cerris	*Qc*	4.6 ± 0.2	1.2	Well suited	0.4	588	113	263
Quercus palustris	*Qp*	5.3 ± 0.1	2.2	Partly suited	0.9	400	720	924
Carpinus betulus 'Lucas'	*Cb*	4.6 ± 0.1	2.1	In test	<0.1	61	0	0
Ostrya carpinifolia	*Oc*	4.5 ± 0.2	1.1	Suited	0.1	187	90	0
Gleditsia triacanthos 'Skyline'	*Gt*	5.1 ± 0.1	1.2	Well suited	0.1	153	98	1
Liquidambar styraciflua	*Ls*	4.9 ± 0.4	2.2	Suited	0.3	352	155	54
Amelanchier lamarckii	*Al*	5.0 ± 0.1	3.1	n.d.	0.1	52	53	78
Koelreuteria paniculata	*Kp*	5.1 ± 0.2	1.2	Partly suited	<0.1	28	2	0

[1] KLAM = Climate Tree Species Matrix. Source: (Roloff et al. 2009; Roloff 2021a). [2] GALK = Deutsche Gartenamtsleiter-konferenz (GALK e.V.; German Garden Agency Directors Conference). Source: http://strassenbaumliste.galk.de/sblistepdf.php (accessed on 2 April 2021). [3] Source: Free and Hanseatic City of Hamburg, Department for the Environment, Climate, Energy and Agriculture.

In order to create representative conditions for urban tree sites to be planted, the dimensions of the selected trees at the planting date were in accordance with standards. The trees had therefore, similar initial stem diameters between 4.5 and 5.3 cm at breast height (Table 4.1). The selected study trees were harvested with a tree digger according to the B&B method (root ball excavated and burlap-wrapped (Allen et al. 2017)). Therefore, the volume of each root ball was almost similar, with maximum root ball dimensions of 0.5 m × 0.6m × 0.5 m (0.1 m^3). Single trees were planted in the excavated planting pits after the backfilling with the respective planting soils (Figure 2.4 and Appendix Figure 4.1). The planting soils were moderately compacted by consistently trampling throughout the backfilling process. After the first winter, small depressions in the soil surface, caused by natural settling at the corners of the planting pits, were refilled with the respective soil material. To ensure tree establishment in the early post-planting phase, we applied four irrigations using 'tree gator' watering bags (approx. 60 L) during the first year. Fertilization (N:P:K, Mg, and micronutrients (Mn and Zn)) was applied in spring 2020 and 2021 to minimize differences in the initial nutrient concentrations ('Sand' lowest and 'Loamy Silt' highest) and thus to minimize nutrient-related effects on tree growth.

4.2.3 Soil Water Monitoring and Meteorological Data

We installed a monitoring setup consisting of soil water potential sensors (SWP; WATERMARK 200SS, Irrometer Inc., Riverside, CA, USA)), volumetric water content probes (VWC; CS-650, Campbell Scientific Ltd., Bremen, Germany; Theta Probe ML2x; Delta-T Devices Ltd., Cambridge, UK), and soil temperature sensors (Irrometer Inc., Riverside, CA, USA). The data were logged at hourly intervals by WATERMARK M900 Monitors for SWP and soil temperature sensors (Irrometer Inc., Riverside, CA, USA), with CR-1000 data loggers for the CS-650 VWC sensors (Campbell Scientific Ltd., Bremen, Germany) at plots with *Qc* and with DL18 data loggers for the ML2x VWC sensors (Ecomatik, Dachau, Germany) at plots with *Al* and *Oc*. The monitoring setup on the experimental site was structured as follows: intensive monitoring at one plot of three tree species per planting soil (9 plots; tree species: *Qc*, *Al*, and *Oc*) and extensive monitoring at one plot of all tree species per planting soil (27 plots). The intensive monitoring covered eight SWP sensors with two replicates per depth (10 cm, 35 cm, root-ball, and 100 cm) and four VWC probes without replication at the same depths. The extensive monitoring covered four SWP sensors without replication, also at the same depths. Temperature sensors were installed next to the SWP and VWC sensors within four randomly chosen plots per planting soil. Soil temperature sensors were installed to allow correction for temperature's effect on SWP measurements. We installed the sensors simultaneously to the backfilling of the planting soils at the predefined depths. For installing the root ball sensors, the root balls were placed at approximately 40 cm depth and covered with the planting soils up to half, where the sensors were placed. Except for the root ball sensors, all sensors were placed with a distance of 75 cm from the horizontal center of the planting pit. The 36 monitoring plots were randomly distributed over the experimental site.

Meteorological data were recorded within one replication block in the middle of the experimental site by a meteorological station (Campbell Scientific, Logan, UT, USA). The air temperature and relative humidity were measured at 2 m height (HMP155A, Vaisala, Vantaa, Finland). For precipitation measurements, we used a tip-ping bucket rain gauge (52203, R.M. Young Co., Traverse City, MI, USA). All data were recorded within a 15 min interval using a CR-1000 data logger. The atmospheric vapor pressure deficit (VPD) was calculated as the difference between the saturated and actual vapor pressure using the daily means of air temperature and relative humidity.

4.2.4 Soil Physical Characteristics

We took disturbed and undisturbed soil samples from one plot of each planting soil in November 2019 after the first growing season. The undisturbed soil samples were analyzed in the lab for the fine soil texture composition, coarse soil texture composition and gravel content, total and organic C contents, and soil pH (in CaCl2) (Table 4.1). The water retention characteristics were assessed using undisturbed soil samples (soil cores of 100 cm^3 and 250 cm^3) for lab measurements. To derive the water retention curves, the water contents at characteristic pressure levels of pF 0.5, 1.3, 1.8, 2.1, 2.48, 3.48, and 4.2 were measured as a percentage of weight using pressure plate apparatus. Additionally, the water retention characteristics and unsaturated conductivity were determined with 250 cm^3 undisturbed soil samples using the fully automated measuring and evaluation system HYPROP (Pertassek et al. 2015; UMS GmbH 2015). The bulk density was determined by drying and weighing these undisturbed volumetric soil samples. Based on the calculated daily means of the measured SWP and VWC data, we also plotted the field retention curves for the three planting soils. The van Genuchten parameters for the functions of the three approaches were determined according to van Genuchten (1980) to describe the relationship between VWC and SWP. The data pairs of water content at levels of pF 0.5, 1.3, 3.48, and 4.2 of the pressure plate method were added to supplement the curves of the HYPROP measurements and the field retention curves, as the measuring devices for these methods had limited measurement ranges. In spring 2020, the infiltration capacities of the planting soils were measured using a double-ring infiltrometer. In order to quantitatively evaluate and compare the soil hydrological characteristics of the three planting soils, we considered the variables of the plant-available water capacity (PAWC), field capacity (FC), infiltration capacity (IC), and unsaturated hydraulic conductivity (K_s).

4.2.5 Vitality Assessment and Tree Growth Measurements

We assessed the tree vitality by visual inspections of each individual tree regularly at the beginning of September 2020 and 2021. Criteria leading to the vitality score (1, very vital - 5, strongly impaired) represent (1) the overall leaf conditions and (2) the crown density in comparison with a vital tree of the same species. The assessment followed a regular inspection scheme developed by the GALK (Deutsche Gartenamtsleiterkonferenz e.V.).

The stem growth and current-year shoot length were used as indicators for tree performance in the three planting soils. We measured the stem circumference of all trees at heights of 100, 130, and 150 cm in May 2019, January 2020, January 2021, and October 2021 to a decimal place using a measuring tape. Shoot growth was measured in September 2020 and September 2021. Five main external, sun-exposed branches per tree were randomly chosen and the shoot increment was measured in length. The annual average stem increment and shoot extension for each tree species per substrate were calculated as the average of all sampled replicates.

To study the tree species reaction to short-term changes in the environmental conditions by measuring continuously the intra-annual stem diameter variation, we installed 23 electronic point dendrometers (DD-L2, Ecomatik, Dachau, Germany; accuracy of ± 1.97 µm and temperature coefficient < 0.2 µm K^{-1}) in spring 2021. For dendrometer installation, three individual trees per species (with the exception of *Qc* (only n = 2) and *Kp* (no measurements)) growing in the planting soil ‘Sand’ were selected. At each tree, the dendrometers were installed with the dendrometer head on the outer bark at approximately 110 cm stem height. The sensors measured with a frequency of 15 min and were connected to both CR-1000 and DL-18 dataloggers.

4.2.6 Data Processing

The monitored SWP data were manually corrected for the actual soil temperatures using the *in situ* soil temperature measurements from the three planting soils (Shock et al. 1998; Allen 2000). The corrected data extended the lower measurement range of −2500 hPa, as 10 °C instead of a default temperature value of 24 °C was initially set as the constant temperature for logger internal temperature correction. To detect water stress conditions and to quantify the annual duration of critical soil water availability, we used the monitored SWP data below −63 hPa and transformed them into the volumetric water content data using the van Genuchten water retention functions (van Genuchten 1980) determined for each planting soil (VWC_{vG}). Thereafter, the relative extractable soil water content (REW%) was calculated from the VWC_{vG} depth weighted for a soil compartment from 0–35 cm and depth weighted for a soil compartment from 0–100 cm according to Granier et al. (2007):

$$REW\ (\%) = 100 \cdot ((VWC_{actual} - VWC_{PWP}) \cdot (VWC_{FC} - VWC_{PWP})^{-1}) \qquad (4.1)$$

where VWC_{PWP} is the VWC_{vG} at the wilting point and VWC_{FC} is the VWC_{vG} at field capacity, both measured in the lab using the pressure plate method. In the literature, water stress conditions are assumed to occur when the REW drops below the threshold of 40%, as transpiration is gradually reduced due to increasing stomatal diffusion resistance (Granier et al. 1999). Therefore, based on the calculated daily means, we calculated the number of days per growing season when REW < 40% to seasonally characterize water stress according to Granier et al. (2007).

The stem circumference measurements were height-related-transformed to the stem diameter increment at breast height (DBH), assuming a circular stem area. Data processing of the intra-annual stem diameter variations (SDV) was performed using R v. 4.2.1 (R Core Team 2022) with the package *treenetproc* (Knüsel et al. 2021). The workflow of *treenetproc* converts raw data (L0) into time-aligned time-series data (L1 data, in this study with hourly resolution), cleans the L1 data from outliers and data shifts, and linearly interpolates data gaps < 30 min (L2 data). From the L2 data, we extracted three relevant seasonal proxies (Knüsel et al. 2021). (1) The reversible, water-induced shrinkage and expansion of the stem diameter (maximum daily shrinkage (mds in µm d^{-1})). (2) The irreversible diametric expansion due to woody cell formation with the zero-growth concept, transformed into relative values for better comparison (stem diameter increment (SDI in % of seasonal maximum stem diameter)) (Zweifel et al. 2016). Thus, contrary to Köcher et al. (2012), no negative growth – due to a smaller diameter maximum on the following day – was considered in the analysis. (3) The tree water deficit (TWD), derived on a daily basis from the maximum precedent stem diameter and actual (daily) maximum stem diameter, representing the missing stem water in µm d^{-1} (Zweifel et al. 2016). Analyzing the response of intra-annual tree growth on soil hydrological and climate variables is only reliable within the main period of stem growth (Deslauriers et al. 2007). Since *treenetproc* returns values for onset and cessation starting from the second year only (Knüsel et al. 2021), we determined the length of the growing season of the instrumented trees (n = 23) as follows: onset of growth was reached when the actual daily growth rate at least equaled the seasonal average daily growth rate for at least seven consecutive days (period of 1st May 2021 to 30th September 2021). Growth cessation was, therefore, reached when the seasonal average daily growth rate was exceeded for the last time by the actual daily growth rate on at least seven consecutive days. As we expect mds in contrast to SDI to be a parameter reflecting the trees' water status in the short term, we used daily values for mds to analyze relationships with environmental parameters and weekly means for SDI (Köcher et al. 2012).

4.2.7 Statistical Analysis

The annual duration of temporal water stress conditions (number of days with REW < 40%) was compared between the three planting soils and the years 2020 and 2021 using a two-way ANOVA. The stem diameter increment and shoot growth as mean values for the years 2020 and 2021 were compared separately (a) within a species between the three planting soils and (b) between all species within each planting soil using a one-way ANOVA. All group means were compared using Tukey's post hoc comparison at p-level ≤ 0.05.

For analyzing the relationships of the weekly SDI and mds with the environmental variables REW% in 0–35 cm and 0–100 cm depth, precipitation, and VPD, single-factor correlations were calculated and the Spearman's correlation coefficient were reported. The environmental variables for the correlation analysis with SDI were also calculated as calendar week means.

Statistical analyses were conducted using OriginPro v2021b (OriginLab Corporation, Northampton, MA, USA) and R v4.1.2 (R Core Team 2022).

4.3 Results

4.3.1 Substrate Characteristics

The fine texture (< 2 mm) of the urban planting soils 'Sand' and 'FLL' composed predominantly of sandy grains (0.063–2 mm), whereas the dominant fine texture grain size of the 'Loamy Silt' was silt (2–63 µm) (Table 4.2). The structural planting soil ('FLL') was composed of 20% v/v gravel. The organic matter content of all investigated soils was below 1% w/w, whereas the 'Sand' had almost no organic matter (< 0.1% w/w) and the organic matter content in the 'FLL' was 0.6% w/w. All soils were backfilled into the planting pits loosely compacted to bulk densities between 1.40 and 1.44 g cm^{-1}. The plant available water capacity (PAWC) of the 'Loamy Silt' was highest, with 23% v/v, corresponding to 1,725 L per planting pit (Figure 4.1a). Compared to the 'Loamy Silt', the plant available water capacity of 'FLL' was < 50% and < 25% for 'Sand' (773 L per planting pit and 450 L per planting pit, respectively). The total pore volumes of the planting soils 'Sand' and 'Loamy Silt' were the same, at approximately 40% v/v, whereas the total pore volume of the planting soil 'FLL' was 32% v/v. The slope of the 'Loamy Silt' soil-water-retention curve was almost linear in the FC range, while in both artificial soils, the retention curve approached an exponential slope. The soil hydraulic conductivity of 'Sand' declined sharply at REW 25% (Figure 4.1b). The hydraulic conductivity in 'FLL' was constantly lower and fell below the hydraulic conductivity of 'Loamy Silt' at WP (100% REW) already before 70% REW. Although the hydraulic conductivity in 'Loamy Silt' compared with 'Sand' and 'FLL' had constantly lower values in the wet soil (>10% VWC) (Figure 4.1a), unsaturated conductivity of > 5−10 cm d^{-1} was provided within the whole range of PAWC until WP.

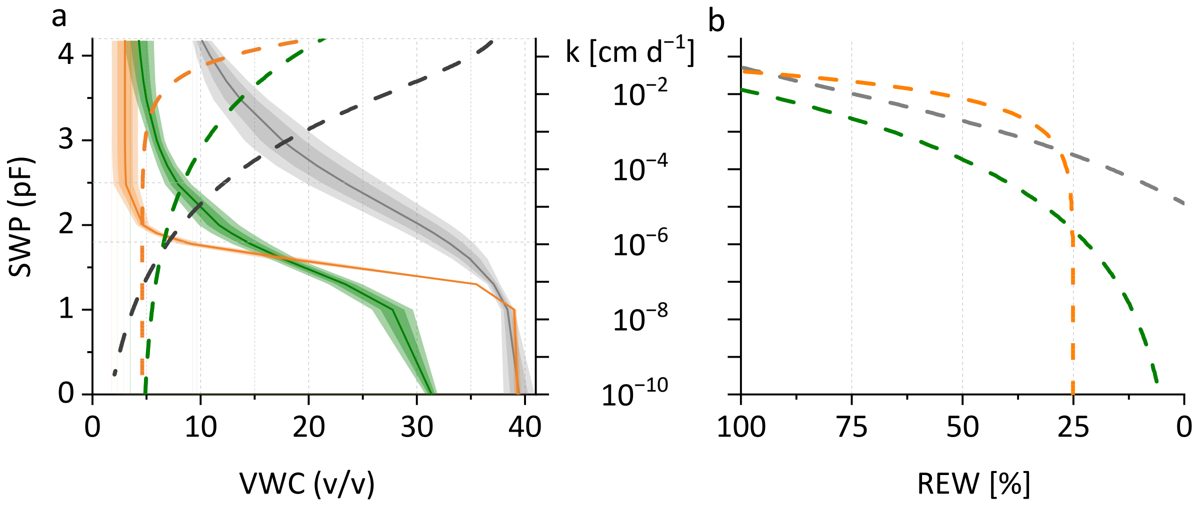

Figure 4.1: (a) Mean planting soil water retention curves (left y-axis) determined by pressure chamber, HYPROP, and field measurements in the three planting soils 'Sand' (orange), 'FLL' (green), and 'Loamy Silt' (grey). SWP is the soil water potential and VWC is the volumetric water content. Shaded areas highlight the standard deviation (light) and the standard error (dark). Dashed lines show the log-transformed fitted hydraulic conductivity (k) (right y-axis) as a function of VWC determined by the HYPROP apparatus; (b) log-transformed fitted hydraulic conductivity (k) as a function of the REW (relative extractable water) determined by the HYPROP apparatus.

Table 4.2: Soil properties of the three planting soils with OM as the organic matter content, BD as the bulk density, IC as the infiltration capacity, FC as the field capacity, and PAWC as the plant available water capacity.

Planting Soil	**Fine Tex. < 2 mm**			**Coarse Tex. > 2 mm**		**OM**	**pH**	**BD**	**Hydrological Properties**		
	Sand (v/v)	**Silt (v/v)**	**Clay (v/v)**	**(w/v)**	**(v/v)**	**(v/v)**	**$CaCl_2$**	**(g cm^{-1})**	**IC (cm min^{-1})**	**FC (v/v)**	**PAWC (v/v)**
‘Sand’	95	4	1	2	n.d.	0.1	6.8	1.4	1.5	9.1	6.0
‘FLL’	93	5	2	35	20	0.6	6.5	1.4	1.9	14.6	10.3
‘Loamy Silt’	29	61	10	1	n.d.	0.9	5.7	1.4	0.3	33.0	23.0

4.3.2 Environmental Conditions and Soil Water Availability

Compared to the mean 30-year growing season precipitation (May–September 1981–2010; DWD Station Hamburg-Neuwiedenthal (DWD 2022)) of 343 mm, the years of 2019 to 2021 were slightly dry years (231 mm, 231 mm, and 299 mm, respectively). With the beginning of the growing season in 2019, the root balls in all planting soils strongly dried below the REW 40% threshold value (Figure 4.2) (Granier et al. 1999). Irrigation replenished the root balls for short phases. Until the end of the growing season of 2019, the REW in the planting pits remained high in all three planting soils above the threshold value of 40%. During the growing season of 2020, three distinct dry out phases (each > 16 days) occurred, interrupted by replenishing precipitation events.

The first phase was characterized by strong soil water depletion below the threshold value only in the root balls. Subsequently, two dry periods led the average REW to drop below the threshold even within the planting soils, prioritized at 10 and 35 cm depths, indicating that tree roots then tapped water from the planting soils in the top soil layer. In 2021, two dry phases occurred, with the REW within the root balls being almost completely depleted and the soil water storage within all planting pits being minimized. However, in ‘FLL’ and ‘Sand’, the soil water storage was replenished by drought-breaking precipitation events, while soil drying in ‘Loamy Silt’ continued. Despite the higher precipitation in 2021, the soil water storage at 0–100 cm depth was depleted below the threshold of 40% REW on evidently more days ($p \leq 0.001$) compared with 2020, indicating progressing root density. Differences in drought incidence between the planting soils were not significant, but we observed a clear tendency of a reduced amount of water stress days in ‘Sand’ during 2021 (Figure 4.3).

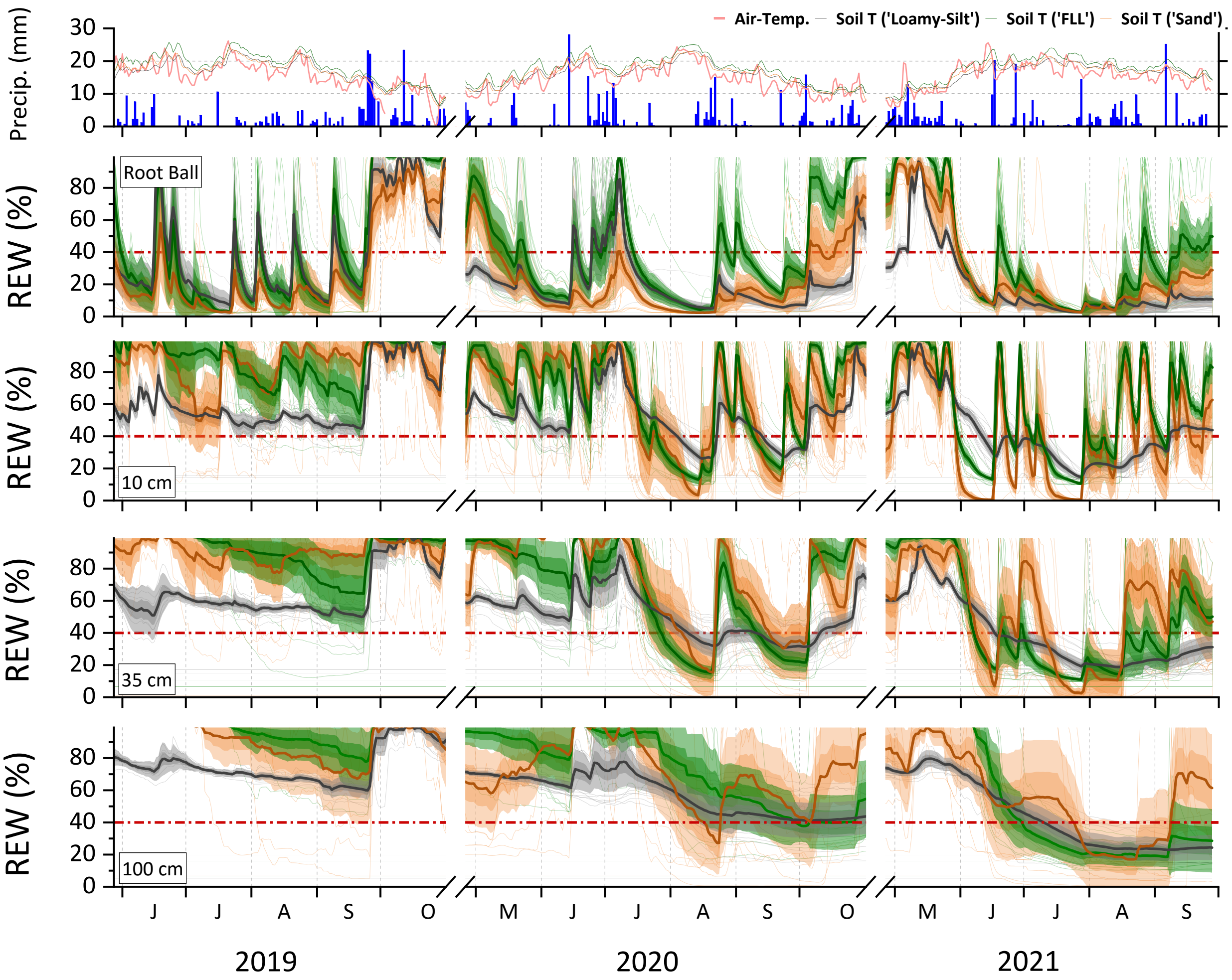

Figure 4.2: Dynamics of relative extractable water (REW %) at three depths and within the root ball in the three different planting soils (‘Sand‘(orange), ‘FLL‘(green), and ‘Loamy Silt‘(grey)) during the growing seasons of 2019, 2020, and 2021. Bold lines represent the means of all investigated planting pits per planting soil. Shadowed areas indicate the standard error (dark) and the standard deviation (light). Reddish dashed lines show a threshold value of 40% REW. Corresponding precipitation, air, and soil temperatures are given at the top of the graph.

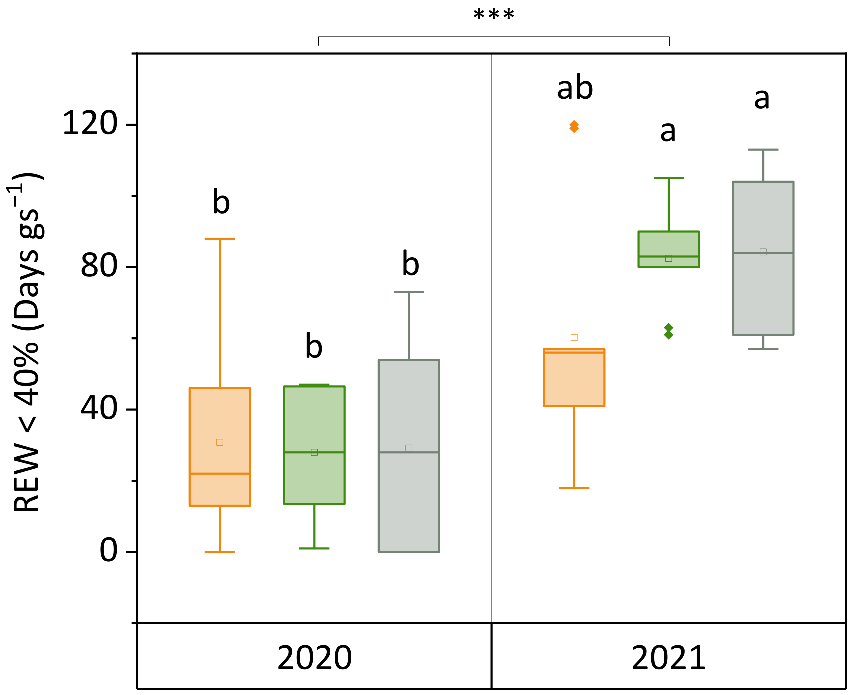

Figure 4.3: Sum of the number of days with REW < 40% (0–100 cm depth) during the growing sea-son (gs) as a mean of the years 2020 and 2021 in the three planting soils 'Sand' (orange), 'FLL' (green), and 'Loamy Silt' (grey). Statistical analyses were performed by using a two-way ANOVA. Boxes with the same letters indicate no significant differences between the substrates at the $p \leq 0.05$ level. *** indicates significant differences between the years at the $p \leq 0.001$ level. Mean comparisons were performed by Tukey post hoc comparisons.

4.3.3 Tree Growth Analysis

Across all investigated species, annual growth was highest in 'Loamy Silt' and lowest in 'Sand' (Appendix Figure 4.2). Overall, the annual stem diameter increment was highest during 2021, whereas the annual shoot growth was greatest during 2020 (Appendix Figure 4.2). The smallest growth with no significant differences between species and planting soils, was measured in 2019. The growth responses of the investigated tree species in the three planting soils varied strongly (Figure 4.4a). In 'Loamy Silt', *Qc* and *Tc* showed the highest growth, whereas *Ls* and *Kp* showed the lowest growth. For the DBH growth response toward the planting soils, we identified four general patterns:

1. Significant difference in DBH growth between all three planting soils (*Tc* and Qp*)*.

2. Significantly less DBH growth only in 'Sand' (No significant difference between 'FLL' and 'Loamy Silt' (*Oc*, *Ls*, and *Al*).

3. Significantly less DBH growth in 'Sand' and 'FLL' than in 'Loamy Silt' (*Qc*, *Cb*, and *Gt*).

4. No difference in DBH growth between all planting soils (*Kp*).

Across all species, the tree DBH growth on ‘Sand’ and ‘FLL’ was, on average, −64% and −29%, respectively, restricted compared to the optimum planting soil. *Kp* was excluded from the comparison. On ‘Sand’, *Qp* and *Al* were most restricted (−85% and −81%, respectively), whereas *Tc* and *Gt* were the least negative affected species (−44% and −54%, respectively) compared with the optimum soil. On ‘FLL’, again, *Qp* and *Cb* were most restricted (−50% and −46%, respectively), whereas *Ls* and *Al* were the least negative affected species (−10% and −12% respectively) compared with the optimum soil. The species *Al*, *Kp*, *Ls*, and *Oc* showed the same growth patterns found for their DBH growth, and also for their shoot growth (Figure 4.4b). The remaining species responded differently in terms of shoot growth compared with DBH growth. Across all species, tree shoot growth on ‘Sand’ and ‘FLL’ was, on average, −50% and −18%, respectively, restricted compared to the optimum planting soil. On ‘Sand’, *Qp* was, by far, the most restricted species (−72%), whereas *Gt* was the least negative affected species (−27%) compared with the optimum soil. On ‘FLL’, again, *Qp* was most restricted in terms of growth (−42%) compared with the optimum soil, whereas *Oc*, *Al*, *Kp*, *Ls*, *Qc*, and *Tc* were not significantly affected.

The assessed vitality scores of the years 2020 and 2021 were, across all species, the highest (i.e., lowered vitality) for the trees growing on ‘Sand’ (Table 4.3). In both years, *Al* and *Qp* had, on average, the highest values on ‘Sand’, whereas *Tc* had the lowest, which was also true for ‘FLL’ and ‘Loamy Silt’. The vitality scores of trees growing on ‘FLL’ and ‘Loamy Silt’ were mostly < 2. Only *Kp* showed values > 2, which was, in particular, striking for these trees growing in the optimum soil. We also noticed high vitality values for two individuals of *Qc* growing on the optimum soil, which was expressed by the elevated SD (Table 4.3).

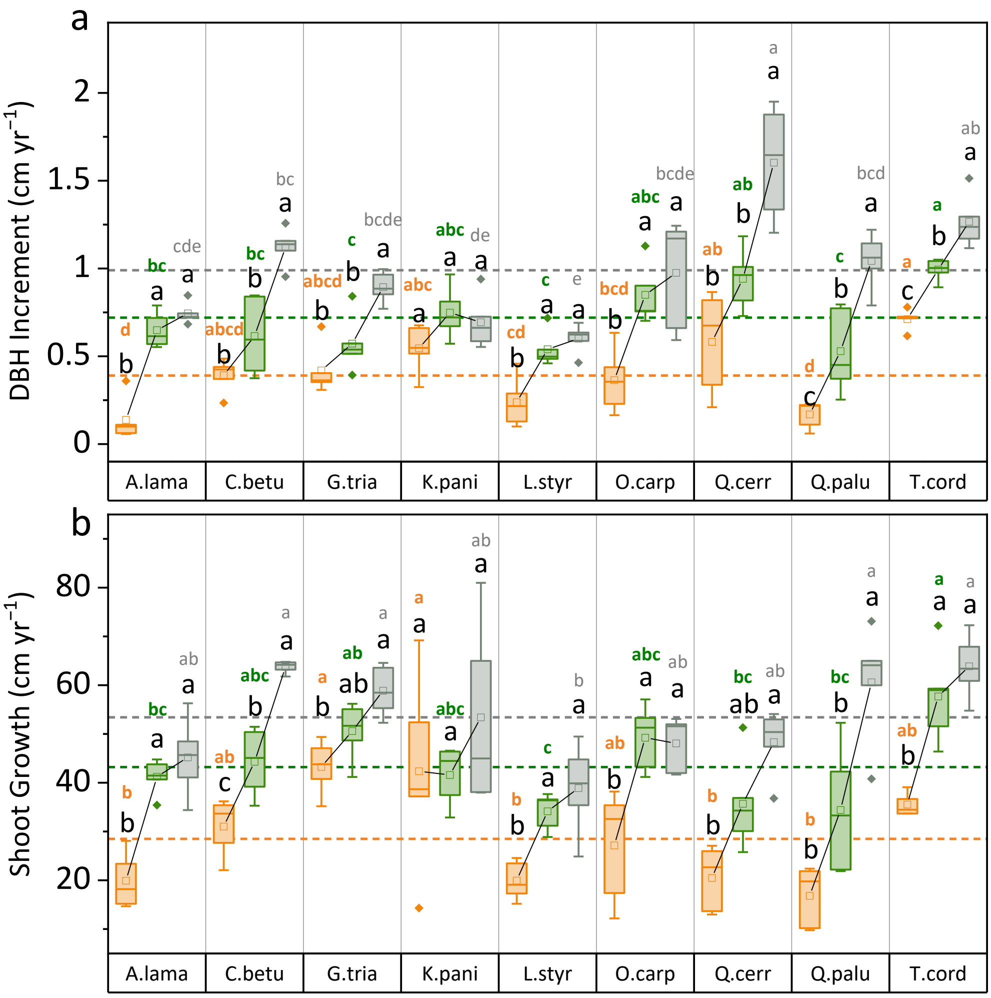

Figure 4.4: (a) Boxplots of annual DBH growth and (b) annual shoot growth of all nine tree species and as a mean of the years 2020–2021. Colored dashed lines show the mean growth across all species for the three planting soils ‘Sand‘ (orange), ‘FLL‘ (green), and ‘Loamy Silt‘ (grey). Statistical analyses were performed by using a one-way ANOVA. Boxes with the same letters (black) indicate no significant differences at the p ≤ 0.05 level within a species between the planting soils. Boxes with the same letters (see color assignment above) indicate no significant differences at the p ≤ 0.05 level within a planting soil between the species. Mean comparisons were performed by Tukey post hoc comparisons.

Table 4.3: Tree vitality score assessed by visual inspections of the tree crowns in September 2020 and 2021. Values, ranked from 1 (vital) to 5 (strongly impaired), are presented as the means ± SD for each species x planting soil combination (n = 5).

Tree Species 'Cultivar'	**Vitality Score** [1]					
	'Sand'		**'FLL'**		**'Loamy Silt'**	
	2020	**2021**	**2020**	**2021**	**2020**	**2021**
Tilia cordata 'Greenspire'	1.6 ± 0.9	1.4 ± 0.5	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0
Quercus cerris	2.2 ± 0.4	2.4 ± 0.5	1.4 ± 0.5	1.2 ± 0.4	1.6 ± 0.9	1.8 ± 0.8
Quercus palustris	2.8 ± 0.4	2.8 ± 0.4	1.6 ± 0.5	1.4 ± 0.5	1.0 ± 0.0	1.6 ± 0.5
Carpinus betulus 'Lucas'	2.2 ± 0.4	1.8 ± 0.4	1.8 ± 0.4	1.2 ± 0.4	1.2 ± 0.4	1.0 ± 0.0
Ostrya carpinifolia	2.6 ± 0.5	2.2 ± 0.8	1.8 ± 0.4	1.8 ± 0.4	1.2 ± 0.4	1.2 ± 0.4
Gleditsia triacanthos 'Skyline'	2.4 ± 0.5	1.6 ± 0.5	2.2 ± 0.4	1.6 ± 0.5	1.2 ± 0.4	1.0 ± 0.0
Liquidambar styraciflua	2.2 ± 0.4	2.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.2 ± 0.4	1.2 ± 0.4
Amelanchier lamarckii	3.0 ± 1.0	3.6 ± 0.9	1.6 ± 0.5	1.6 ± 0.5	1.4 ± 0.5	1.0 ± 0.0
Koelreuteria paniculata	2.4 ± 0.9	2.8 ± 0.8	2.4 ± 0.9	2.0 ± 0.7	2.4 ± 1.1	3.2 ± 1.5

[1] According to vitality assessment procedure from GALK = Deutsche Gartenamtsleiterkonferenz (GALK e.V.; German Garden Agency Directors Conference).

Intra-annual stem diameter measurements for eight tree species (except for *Kp*) in 'Sand' showed a high variation of net growth (Figure 4.5). Growth onset was, on average, at the beginning of June and ceased, on average, at the beginning of August. During phases with REW < 40%, the daily stem diameter variations were pronounced with amplitudes varying evidently between species—they were weak in *Gs*, *Oc*, and *Qc*, and strong in *Tc* and *Ls*. The tree water deficit (TWD) is defined to occur when the maximum precedent stem diameter is greater than the maximum stem diameter of the actual day. Overall, the TWD was only weakly expressed (< 120 µm d^{-1}) and occurred for individuals of almost all species when REW < 40% (data not displayed). However, the TWD during the drought phases was most pronounced for *Al* and *Ls*, with single trees reaching maximum values of 1,130 and 627 µm d^{-1}, respectively. Single variable correlations were used to test the impact of the environmental variables REW at 0–35 cm and 0–100 cm, precipitation, and VPD on the tree species growth reactions using the weekly means of relative stem diameter increment (SDI) and the maximum daily shrinkage of the stem diameter (mds). The SDI of all trees investigated, except for *Qc*, was positively correlated with REW at least on the depth level ($p \leq 0.05$), rather than with precipitation or VPD (Table 4.4). SDI showed the strongest correlations (Spearman's R > 0.6) with REW for the species *Oc*, *Gt*, and *Ls*. The correlations of SDI and REW in 0–35 cm were, for *Gt* and *Al*, more significant than the correlations at 0–100 cm, whereas the growth of *Qp* and *Cb* was correlated more significant with REW 0–100 cm. Mds was correlated with both the soil water status and VPD. Mds and REW at both depth levels were positively correlated in all investigated species ($p \leq 0.001$), with the strongest correlations (Spearman's R > 0.6) for *Tc*, *Qc*, *Cb*, and *Al*. VPD was significantly negatively correlated with mds in all species ($p \leq 0.001$), except for Gt ($p > 0.1$) (Table 4.4).

Table 4.4: Spearman correlation coefficients ® for the correlation of the relative stem diameter increment as weekly means (SDI; n = 20 data points per individual tree) and maximum daily shrinkage (mds; n = 173 data points per individual tree) of the stem diameter with the hydrological and climatological variables REW (relative extractable water), p (precipitation), and VPD (vapor pressure deficit) in eight species. Investigated period is defined according to the species-specific growing season length (Table 4.3)).

Weekly SDI	*n*	**REW**$_{0–35\ cm}$	**REW**$_{0–100\ cm}$	*p*	**VPD**
Tilia cordata 'Greenspire'	3	0.43 **	0.53 **	ns	ns
Quercus cerris	2	ns	ns	ns	ns
Quercus palustris	3	0.42	0.45 ***	0.43	−0.41
Carpinus betulus 'Lucas'	3	0.32	0.51 **	ns	ns
Ostrya carpinifolia	3	0.69 ***	0.85 ***	0.53 **	ns
Gleditsia triacanthos 'Skyline'	3	0.64 ***	0.37	ns	ns
Liquidambar styraciflua	3	0.61 ***	0.73 ***	ns	ns
Amelanchier lamarckii	3	0.44 **	ns	0.38 **	ns
mds					
Tilia cordata 'Greenspire'	3	0.67 ***	0.72 ***	0.23 **	−0.42 ***
Quercus cerris	2	0.6 ***	0.64 ***	ns	−0.57 ***
Quercus palustris	3	0.47 ***	0.48 ***	ns	−0.43 ***
Carpinus betulus 'Lucas'	3	0.67 ***	0.53 ***	0.16 **	−0.38 ***
Ostrya carpinifolia	3	0.35 ***	0.4 ***	ns	−0.49 ***
Gleditsia triacanthos 'Skyline'	3	0.34 ***	0.39 ***	ns	ns
Liquidambar styraciflua	3	0.6 ***	0.42 ***	0.19 **	−0.4 ***
Amelanchier lamarckii	3	0.63 ***	0.43 ***	0.26 **	−0.51 ***

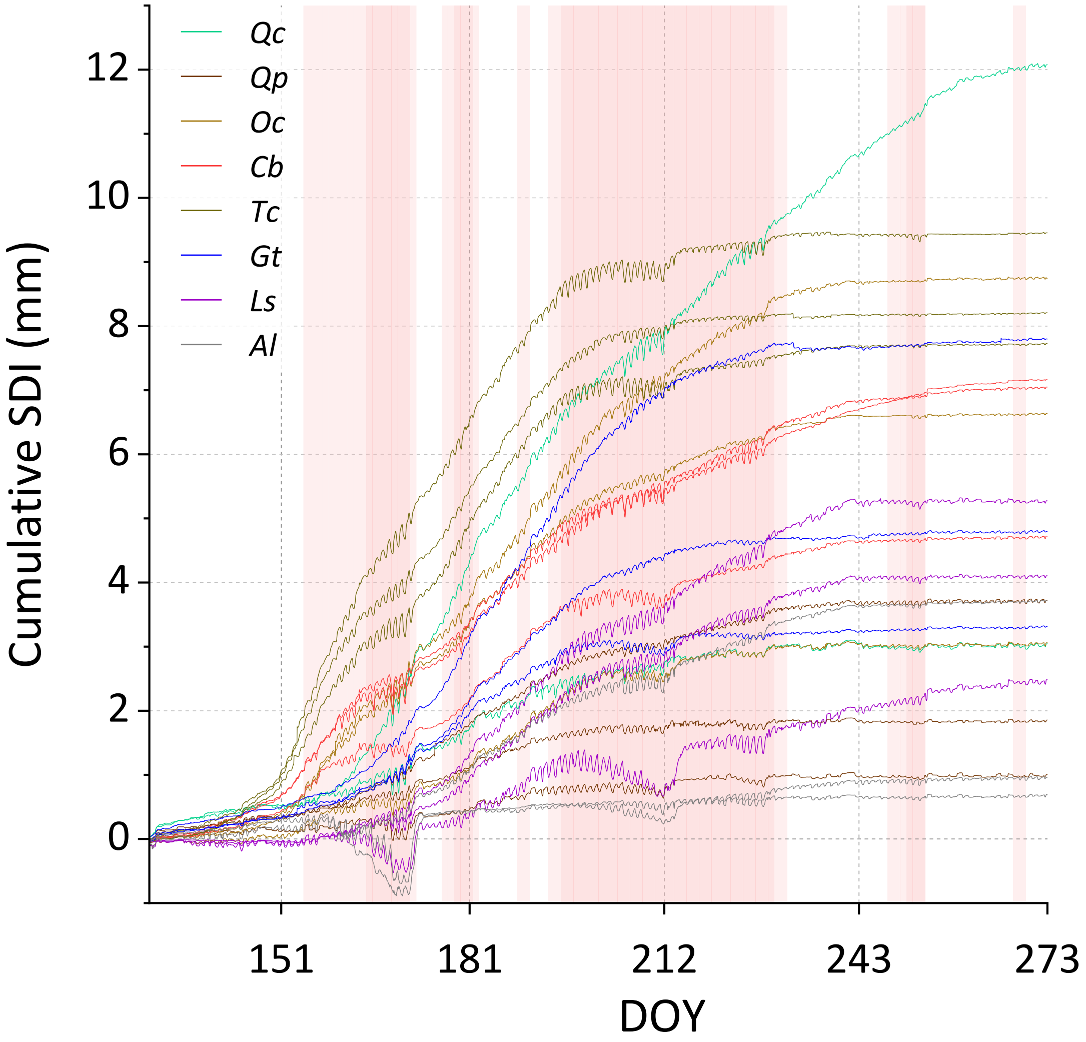

Figure 4.5: Cumulative stem diameter increment (SDI) of eight tree species grown in ‘Sand’ during the growing season of 2021. Reddish areas indicate phases when REW was <40% (light red: 0–35 cm; dark red: 0–100 cm).

4.4 Discussion

4.4.1 Substrate Characteristics

New street trees are often planted in artificially, sandy-textured soil (Jim & Ng 2018; Schickhoff & Eschenbach 2018) or specific load-bearing substrates to resist compaction (Grabosky & Bassuk 1996). Up to now, these substrates were not well characterized in terms of soil hydrological properties (Yilmaz et al. 2018), and it is unclear how the growth and vitality of specific tree species respond to the individual substrate conditions (Pregitzer et al. 2016). We used an experimental field study with nine selected tree species and two urban tree sites representing planting soils to investigate this response under controlled field conditions.

Soil water availability is the most important parameter controlling tree growth (Bréda et al. 1995; Allen et al. 2010; Puhlmann et al. 2019). With 10%, the plant available water capacity (PAWC) of 'FLL' was within the range reported for similar technical substrates (7–11%) (Grabosky et al. 2009) and exceeded the PAWC of 'Sand' (6%). 'Loamy Silt' had more than twice the amount of plant available water, mainly stored in the medium-sized pores of the dominating silt grains (Figure 4.1). As expectable, under field conditions, the REW in 'Sand' and 'FLL' was reduced sufficiently and faster than that in the optimum soil with the beginning of the growing season. However, regarding the seasonal average, no difference between the REW negatively exceeding the threshold value of 40% in the artificial soils and 'Loamy Silt' was visible (Figure 4.3). We assume that the different abilities to transport water caused this finding for the three planting soils. Precipitation water infiltrated the artificial soils faster and more effectively due to the higher infiltration capacity (IC), replenishing the PAWC, particularly at the 10 cm and 35 cm depths regularly. On the other hand, we assumed trees growing in the optimal soil to exploit the soil water stored more effectively, particularly at low soil water potentials, regardless of the absolutely higher quantity. This is reflected by the different hydraulic conductivities of the substrates during the process of drying (Figure 4.1b).

The large proportion of medium and fine pores in the total pore system of 'Loamy Silt' caused, under moist conditions (< pF 1.8), slower water transport, but that under unsaturated conditions (> pF 1.8–4.2) was almost constant. Compared to the 'Sand' and 'FLL', where large pores became quickly non-conductive with increasing soil water potential (Li et al. 2006), a higher amount of water was thus quantitatively available to the trees in 'Loamy Silt'. While the tree roots in the 'Loamy Silt' could be resupplied with soil water with almost no restriction, the development of dry zones around the tree roots (Schulze et al. 2019), causing hydraulically disconnection from surrounding wet soil, was most likely the limiting factor for water supply in sandy and coarse porous soils, causing stomatal closure (Abdalla et al. 2021) and thus reduced water consumption. Hence, the drought stress avoidance strategies of trees relying on reducing the plant water potential (anisohydric reaction type) were likely to be not successful in sandy or coarsely porous artificial soils (Sjöman et al. 2018). In order to tap further soil water, a tree able to adapt to sandy and coarse porous soils must invest in the production of fine roots that grow towards available water to bypass dry soil patches. Most likely, the exchange of soil water between the SWP sensor and soil is also affected in a comparative way. This resulted in wide standard deviations of the mean REW in 'Sand' and 'FLL' (Figure 4.2), suggesting that sufficient soil drying was only detected by sensors close to roots. Thus, a high sensor density would be needed to capture the spatial heterogeneity of the soil water distribution within sandy and coarse porous soils.

Overall, the seasonal water stress conditions determined by using the REW threshold value reported for forests (Granier et al. 2007) have been comparatively low (Granier et al. 2007; Schmidt-Walter et al. 2019; Schütt et al. 2022b) (Figure 4.3). In addition to the explanations mentioned, this may have resulted from an underdeveloped root:shoot ratio within three years after planting and regular and intense soil water replenishment from precipitation. The latter, however, would have been lower under actual urban site conditions due to sealing with impermeable pavements and soil compaction. Therefore, the use of rain-out shelters would have been necessary to simulate prolonged drought situations, as used by Stratópoulos et al. (2019a).

4.4.2 Tree Growth Analysis

So far, data regarding species-specific belowground requirements generated from growth response to ensure the establishment, initial growth, and long-term survival of young street trees in urban environments are scarce. The second- and third-season growth data of the trees planted in artificial soils were in the range of those of other studies for DBH- (Bühler et al. 2006; Smiley et al. 2006; Rahman et al. 2011; Lawrence et al. 2012; Boukili et al. 2017) and shoot growth (Riikonen et al. 2011). In the first growing season, DBH- and shoot growth were similar among species, being low in all soils compared with those in the following years (Appendix Figure 4.2). This growth depression in the first year is in accordance with the finding of Bretzel et al. (2020) suggesting that trees need time to recover from a transplanting shock (i.e. reestablishing the root:shoot ratio) and initially mainly profit from the uniform root ball soil conditions and irrigation (Watson 2005). This nexus is supported by our observation of high water consumption in the root ball and low consumption in the planting soils at all depths (Figure 4.2). In the second and third growing seasons, the growth of all species was constrained on the artificial soils compared with the optimal soil (Loh et al. 2003; Smiley et al. 2006; Pregitzer et al. 2016). This is contrary to the findings of Rahman et al. (2011) and Grabosky & Bassuk (2016), who reported higher tree growth in the structural planting soils of 1,3–3,2 cm yr^{-1} DBH (*Quercus bicolor*, *Quercus phellos*, and *Pyrus calleryana* 'Chanticleer'), compared with 0.3–0.6 cm yr^{-1} in the artificial soils in our study. In particular, these authors found higher or equal growth of trees in structural soils compared with trees in tree lawns. However, data regarding the soil properties and soil characteristics (i.e., texture, organic matter content, bulk density) are not available and due to the smaller planting pit dimensions and multiple urban environmental constraints in these *in situ* studies, a comparison of the results with our study should be conducted with caution. Furthermore, it is likely that tree roots developed in the whole planting pit and extended into the surrounding soil a few years after planting (Krieter & Malkus 1996; Schütt et al. 2022b). This was supported by random excavations at the edges of the planting pits at the end of the third growing season, by the gradual reduction of REW down to 100 cm depth in all substrates until 2021 (Figure 4.2), and by the elevated growth of trees in 'Sand' and 'FLL' in 2021 compared with that in 2020 (Appendix Figure 4.2). As opposed to our experimental site, where natural 'Loamy Silt' surrounded the planting pits, in urban settings, a growth decrease would be most likely when tree roots extend into the surrounding soils comparable to 'Sand' (Jim 1998; Jim & Ng 2018). We therefore assume that a smaller planting pit and thus an earlier extension of roots into the surrounding soil, when possible, would also decrease tree growth and would make long-term comparison between soil conditions inappropriate (Grabosky & Bassuk 2016).

Little attention has been paid to the morphological and physiological responses of tree species to artificial urban soils (Lawrence et al. 2012; Pregitzer et al. 2016). Across all substrates, we found the strongest annual DBH growth rates for *Qc* and the lowest for *Ls*, and the strongest annual shoot growth for *Tc* and the lowest also for *Ls* (Figure 4.4a and 4.4b). The response of the investigated tree species was different (Smiley et al. 2006; Pregitzer et al. 2016).

Although *Tc* invested strongly in stem growth, even under the unfavorable soil conditions of 'Sand' and 'FLL', the vitality scores, particularly in 'Sand', indicated apparently good performance also in the third growing season. This outcome is in contrast to the findings from Stratópoulos et al. (2019a), where the isohydric *Tc* (Moser et al. 2017) was highly affected by water scarcity, showing early leaf senescence. Since in that study, extreme drought situations were caused on sandy loam by using rain-out shelters, it seems plausible that *Tc* is unable to extract water from drying, fine-grained soils (Gillner et al. 2017b). In the sandy and coarse porous artificial soils used in our study, *Tc* showed, contrary to Moser et al. (2016), no growth reduction during the phases of low REW in the 'Sand' and, despite the high mds, almost no TWD (Figure 4.5). These observations indicate that *Tc*, at least the cultivar 'Greenspire', is seemingly well-adapted to artificial urban soils characterized by low hydraulic conductivity. We hypothesize that this adaptation comes with a drought strategy that does not rely on increasing the suction power of roots, but on growing roots towards the water. This hypothetic reaction pattern of *Tc* in urban soils and the long-term effect on the C-balance should be investigated further in order to reliably assess the mortality risk in urban environments under climate change.

Contrary to *Tc*, the overall growth rates of *Ls* were very low (Lawrence et al. 2012) (Figure 4.4). However, compared with the optimal soil, the DBH and shoot growth were equal or above average for all species in 'Sand' and 'FLL', respectively, and trees in 'FLL' maintained the best possible vitality score (Figure 4.5). During the growing season, the growth of *Ls* was strongly correlated with REW (Table 4.4), indicating that investment in above-ground biomass was reduced during phases of low REW. This suggests that, under drought conditions, assimilated and stored C had not been allocated to growth, but rather to mechanisms successfully coping with drought stress. This is in accordance with Lawrence et al. (2012), who found the lowest annual mortality rates for *Ls* among 10 species investigated in a subtropical city in Florida, USA. This indicates, in accordance with our results, that *Ls* is capable of withstanding dry soils (Baraldi et al. 2019) and that, in general, high growth rates in urban soils alone are not a categorical identifier for the adaptability of a tree species to the harsh urban environment under future climates.

In contrast to 'FLL', the growth of *Al* in 'Sand' was different to that of *Ls* and almost the lowest of all species, while simultaneously being obviously non-vigorous (Table 4.3). *Al* was the only species that grew less in 2021 compared with 2020 (data not shown) and where SDI and mds were correlated mainly with REW in the upper soil compartment (Table 4.4). Thus, we assume that *Al* was neither unable to develop a sufficient, deep-rooting system within the planting pit, nor expand its roots into the favorable surrounding soil.

The *Quercus* species *Qc* and *Qp* showed overall high growth rates in the optimal soil. The DBH growth of *Qc* in the artificial soils was higher than the average of all species. The tree growth in 'Sand' was particularly variable, which suggests different abilities of individuals to react to coarse-textured soil with a low OM content within the species. *Qp*, on the other hand, experienced the largest growth inhibition of all tree species in sandy soils compared with the optimal soil. Currently, *Qp* is, among the studied species, one of the most abundant species in Hamburg's street tree population. However, it appears to be highly reactive to poor soil conditions. Furthermore, care should be taken that soils in *Qp* planting sites have pH values < 6.5 to prevent leaf chlorosis (Watson & Himelick 2004), which was visible for the trees in the 'Sand', but not in 'FLL' (Tables 4.1 and 4.3), whereas soil compaction and water logging might play minor roles in *Qp* growth (Watson & Kelsey 2006). Regardless of the constraints in the artificial soils, heavy precipitation caused prolonged waterlogging conditions during June 2020 and affected the 'Loamy Silt' trees of *Qc* in terms of vitality and *Kp* in terms of growth and vitality (Table 4.3). This suggests that both tree species need well-aerated, non-compacted soils at sites that do not tend toward waterlogging (Roloff et al. 2018). Despite the high variability in shoot growth in 'Sand', the DBH growth of *Kp* was comparatively high in the artificial soils. We assumed that *Kp* combined the ability of both, lowering its water potential in fine-grained soils (Sjöman et al. 2018), and growing with roots towards the water in coarsely textured and porous soils. However, the comparatively poor vitality of *Kp* in the artificial soils may have also resulted from the low REW conditions during mid-June 2021, since *Kp* is reported to be very sensitive to early growing season drought (Sjöman et al. 2018).

The DBH growth rates of *Cb* and *Oc* in the optimal soil were higher than those reported by Stratopoulos (2020) with similar soil properties. Compared with the optimal soil, *Cb* and *Oc* showed, in our study, similar growth reduction between 60% and 65% in 'Sand'; Stratopoulos (2020) also reported similar growth reduction for treatment plots where precipitation water infiltration was prevented by rain-out shelters; however, growth was reduced by up to 79% compared with the control plot. Contrary to growth in 'Sand', *Oc* showed in 'FLL' substantially higher growth than the more vital *Cb* compared with the optimum soil; Stratópoulos et al. (2019b) concluded that both species had the lowest resistance of growth under drought conditions in fine-grained soils. However, we found both species to be not affected above average in artificial planting soils, despite the low PAWC.

Considering that *Gt* had above-average growth and the lowest mds rates in 'Sand', it seems most likely that *Gt* is suitable for harsh urban street tree sites and persists under water-stress conditions (Smitley & Peterson 1996). However, the strong and significant correlation of growth with REW at 0–35 cm suggests that the roots are more likely to grow near the surface. This can be problematic and requires further investigation.

Under the slightly dry, but less extreme, meteorological conditions in terms of air/soil temperatures and relative humidity compared with inner cities, the studied trees established within the study period of three years. For the trees, the selected artificial planting soils were thus sufficient for survival in the short term. In the long term, it is most likely that the formation of above ground biomass, the assimilation of carbohydrate reserves, and the provision of ecosystem services may be limited. However, at actual urban street tree sites, trees will face additional constraints affecting tree growth. Further investigations are necessary to understand the mechanistic adaptations of tree species in response to planting soils (permanent stress) and periods of low REW (temporal stress), particularly regarding patterns of carbon allocation under permanent and temporal soil water stress (Trugman et al. 2018). Our investigations provide a first in-sight into growth-limiting conditions and tree species-specific differences triggered by 'artificial soils' with different hydrological properties, and the experimental design was proven successful and should be continued in the future. In addition, other relevant tree species not considered in this study should be investigated for their growth behavior under soil conditions representative of urban street sites. Such tree species could include *Robinia pseudoacacia* (Moser-Reischl et al. 2019; Klisz et al. 2021), *Quercus robur* (Netsvetov et al. 2019; Thomsen et al. 2020), or *Platanus spp*. (Dervishi et al. 2022), which have shown properties suitable for urban road-side conditions.

4.5 Conclusions

We showed that sandy-textured urban planting soils—one representing structural pit filling and one representing local surrounding soil conditions—have low plant available water capacities and were restricted in terms of hydraulic conductivity when the soil dries. Thus, when the soil water potential decreased and the pore space became non-conductive due to the high percentage of air-filled pores, the amount of water quantitatively available for the tree decreased. Therefore, trees that invest more in the fine root system to bypass soil non-conductivity (e.g., *Tilia cordata* ‘Greenspire’ and *Liquidambar styraciflua*) might be more successful in sandy and coarse porous soils than trees that lower their water potential, which might be successful in fine-textured drying soils (e.g., *Koelreuteria paniculata*, *Quercus cerris*; (Sjöman et al. 2018)). However, the tree growth of all species on the artificial urban soils was significantly constrained. The selected artificial planting soils were sufficient to survive, but most likely did not encourage the trees to build up above ground biomass, to assimilate carbohydrate reserves, or to pro-vide effective ecosystem services in the long term. Thus, improving the hydrological properties of planting soils at street tree sites is crucial to allow recently planted trees to grow and thrive.

5 Stomatal reaction patterns on soil water potential and temperature dependence of assimilation are decisive to carbon assimilation, stress incidences and growth – evidences from monitoring young urban street trees (Manuscript 3)

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5.1 Introduction

Climate change is projected to increase the frequency and intensity of present and upcoming drought-events worldwide (IPCC 2021). In Mid-Europe, drought-events such as summer 2003 or currently the consecutive ‘hotter droughts’ (Allen et al. 2015) during 2018 and 2019 affected tree growth, carbon cycling and mortality rates in forests remarkably (Buras et al. 2020; Schuldt et al. 2020). Even trees of comparatively resistant and intact forest ecosystems being hydrologically inconspicuous in the past showed strong stress responses after 2019 (Schnabel et al. 2022). Trees of urban environments are likely to respond even stronger to harsh meteorological- and site conditions since long lasting periods of critical soil water availability have been recorded (Schütt et al. 2022b) and likely negatively threaten the tree’s water status (Clark & Kjelgren 1990; David et al. 2015).

Street trees are thus a vital element of urban ecosystem functioning and ensure the provision of important ecosystem services such as cooling and shading. To maintain urban ecosystem functioning in the face of climate change and urban densification, planting of new, ‘climate-resilient’ tree species is often recommended (e.g. Roloff et. al 2009). However, the risk of premature mortality of those nursery grown young trees is substantial in urban environments (Roman & Scatena 2011; Roman et al. 2014). So far insufficient information is available on tree species capable of assimilating sufficient amounts of carbon and utilizing it to build up biomass to enable recently planted young trees maintaining physiological integrity over the long term under future urban conditions.

Old grown, well established trees have been shown to be drought-resilient due to extended root systems reaching deep and distant soil water sources that are refilled in wintertime as precipitation is sufficient and depletion due to transpiration is minimal (Osone et al. 2014; Savi et al. 2015; Gillner et al. 2017a; Thomsen et al. 2020). In contrast, recently planted urban street trees are supposed to be strongly vulnerable to even moderate dry spells since they depend on available water in the confined soil volume around their compact root balls (Schütt et al. 2022b). Based on literature- and dendro-ecological studies, non-native tree species from dry habitats are suggested to be better adapted to soil drought resulting from climate change than native, commonly used tree species (Roloff et al. 2009; Sjöman et al. 2012). Hence, those tree species are already increasingly considered for roadside plantings when available in tree nurseries (Freie und Hansestadt Hamburg 2022). However, to successfully adapt future street tree population to a changing climate, a characterization of tree species in terms of suitability for the urban environment under water deficit conditions is necessary. Thus, we wanted to know to which extent recently planted street trees are physiologically affected by the hydrological dynamics in their artificial soil environment in densely built-up urban environments.

Sufficiently available soil water allows maximum stomatal conductance and hence high rates of CO_2 uptake. Thus, soil water availability is crucial for the trees' carbon balance, allocation pattern and hence, growth and vitality. When soil water availability lowers, trees initiate stomatal regulation to reduce the loss of water. As a consequence, the diffusion of CO_2 from the atmosphere into the leaf and therefore the supply of CO_2 for the carboxylation of ribulose-1,5-bisposphate in the Calvin Cycle becomes restricted. The consequence for the C-balance is not only a decline of assimilate gain proportional to the lowered CO_2 flux, since C must be invested in live saving stress reactions: due to lowered C flux less energy acceptors (3-phosphoglycerate) are formed, whilst energy capture remains unchanged resulting in an over-energization of the photosynthetic apparatus, causing the formation of reactive oxygen species (ROS) which react with lipids and proteins causing damages to cellular structures and metabolic pathways (Lawlor & Tezara 2009). Vitality of the leaf cells can only be maintained by the activation of defense systems that dissipate excess energy, detoxify ROS, and protect, repair or replace damaged proteins and cell components (Wujeska et al. 2013). These and other drought stress reactions like e.g. osmoregulation come with gene activation, synthesis and activation of respective enzymes and the use of metabolites that would otherwise have been used for growth and development. Although the costs of these stress reactions have not yet been specified in detail e.g. in terms of shares of allocated C, it seems probable that the respective investments are relevant for the C-balance. Thus, if drought causes relevant stomatal limitation of carboxylation, C investments into stress reactions can be expected to increase reciprocally with reductions of assimilation causing a progressively increasing C-deficit as stomatal conductance decreases. However, the particular drought adaptation of an individual tree species can differ and particularly tree species from drier habitats might not *per se* be appropriate to cope with urban type hydrological deficiency. Hence, incidence and intensity of stomatal limitation can be used as robust parameter to assess the impact of hydrology on the physiology of a tree with respect to stress costs and C-balance.

We estimated stomatal limitations of 14 young urban street trees during the course of four vegetation periods (2018 – 2021): *In situ* measurements of leaf conductivities at varying hydrological conditions were used to generate empirical regression models of species specific stomatal reaction on soil moisture and air humidity. These stomatal models were fed with soil water data, monitored continuously for each individual tree over a time span of four years, and VPD data from a DWD meteo-station, resulting in individual time courses of modeled leaf conductivity. Subsequently, the stomatal limitation of the modeled assimilation has been estimated. Therefore, the species specific dependence of assimilation on intercellular CO_2 concentration was modelled according to a parametrized model of Farquhar & Sharkey (1982), using the modeled leaf conductivities and the literature based temperature dependent values of enzyme kinetics for each tree species (temperature correction according to (Sharkey et al. 2007; Sharkey 2016)). The integration of these estimates with tree performance parameter like relative basal area increment and $\delta^{13}C$ values allows to characterize the studied tree species with respect to their C-balance at urban hydrological conditions.

Thus, the objectives of our three years field studies were to determine (a) to which extent different species of young trees respond to the soil hydrological dynamics at urban sites, (b) to which extent different stomatal reaction patterns can cause limitation of assimilation, and (c) whether resulting differences in stress incidences and intensities can be explained by attributes of the tree species.

5.2 Material and Methods

5.2.1 Study area and site selection

The study was carried out in the city of Hamburg, Germany (53° 33′N, 10 ° 0′ E). The climate shows a marine influence (Koeppen & Geiger: Cfb), with highest precipitation in summer, slightly dryer autumn and winter and low precipitation in spring season. The long-term annual means (1981–2010) of precipitation and air temperature are 793 mm and 94 °C, respectively (DWD 2022). Natural soils, developed from glacial and fluvial deposits, are dominated by loamy Cambisols and sandy Podzols (Schickhoff & Eschenbach 2018) and are in the urbanized areas strongly influenced by anthropogenic processes and artefacts (Greinert 2015). Furthermore, at sites along roads, soils were regularly replaced or buried by coarse textured sandy and technogenic substrates (Jim 1998; Schickhoff & Eschenbach 2018). At 14 study sites along urban roads, sensor installations were conducted between 2016 and 2017. Through permit restrictions, replication of soil water monitoring within the streets was only possible at two streets, where sensors have been installed at three individual tree sites with the same species and planting age (young street tree sites No. 2 and 3 (Y2 a-c and Y3 a-c); Table 5.1 and Schütt et al. 2022b). The trees, previous to transplanting grown in nurseries and harvested by root ball excavation (Allen et al. 2017), were planted between 2007 – 2017 with planting-ages of about 12–15 years with diameter (in breast height (DBH)) between 6–16 cm.

5.2.2 Species x site combinations, site characteristics and soil water monitoring

The tree species investigated were *Quercus cerris* (*Qc*, n = 3, Y2 (a-c)), *Prunus serrulata* (*Ps*, n = 1, Y11), *Quercus robur* (*Qr*, n = 2, Y5 and Y6), *Quercus palustris* (*Qp*, n = 2, Y7 and Y8), *Acer platanoidis* ‘Fairview’ (*Apl*, n = 3, Y3 (a-c)), *Acer* pseudoplatanus (*Aps*, n = 2, Y9 and Y10) and *Carpinus betulus* ‘Lucas’ (*Cb*, n = 1; Y1). The different combinations of tree species and urban site conditions that varied in terms of structural soil type, soil composition (however mainly sand dominated), infiltration capacity of the planting pit and the urban soil and the degree of soil sealing as shown in Table 5.1 are abbreviated in the following by ´*species x site combination*´. Belowground soil water tension dynamics were measured in three soil compartments: root ball, planting pit and (surrounding) urban soil. At each site a monitoring system consisting of 13 SWP sensors (WATERMARK 200SS, Irrometer Inc., Riverside, CA, USA) and three soil temperature sensors (Irrometer Inc., Riverside, CA, USA) was installed as described in Schütt et al. 2022b. Two SWP-sensors were placed in the root ball (20 – 40 cm depth), five SWP-sensors were placed in the planting pit (30 – 75 cm), whereby each of the two sensors in 30 cm and 55 cm were replicated in opposition to each other with the tree in the center and the sensor in 75 cm was placed in the center of the planting pit. Remaining six SWP-sensors were placed in the urban soil (30 – 105 cm) and also replicated with two opposing sensors in each depth. The drilled soil material was analyzed regarding soil texture, stone content, pH and organic matter (Schütt et al. 2022b). SWP data were automatically logged in 1-h intervals using a WATERMARK M900 Monitor (Irrometer Inc., Riverside, CA, USA) in the period between 2018 and 2021. Daily meteorological data were derived from the Deutscher Wetterdienst (DWD) meteo-station in Hamburg-Fuhlsbüttel (DWD 2022).

Table 5.1: Species site x combinations and their respective site characteristics i.e. infiltration capacity (IC) and degree of soil sealing, and soil physical parameters of soil samples collected at the monitored young tree sites. Soil samples were taken as non-volumetric, mixed samples from planting pit and urban soil. Means of soil texture and stone content in the soil compartments planting pit and urban soil were calculated depth weighted per site. DBH = diameter in breast height (measured in 2019). FAO class. = texture class according to FAO with S = sand and L S = loamy sand. For further information see Schütt et al. 2022b.

						Planting Pit						Urban Soil						
Site Nr.	Tree species	Abr.	Planting year	DBH (2019) [cm]	Est. Type of Structural Soil acc. to FLL (2010)	Soil texture (depth weighted) [%]					IC [cm min^{-1}]	Soil texture (depth weighted) [%]					IC [cm min^{-1}]	Sealing [%]
						Sand	Silt	Clay	FAO Cl.	Stone		Sand	Silt	Clay	FAO Cl.	Stone		Grid 5x5 m
Y01	*Carpinus betulus* 'Lucas'	*Cb*	2016	9.3	FLL- one layer	87.9	5.4	6.7	S	52.8	1.8	73.8	13.9	12.2	L S	29.5	0.4	16
Y02a	*Quercus cerris*	*Qc*	2016	8.9	FLL- two layer	83.4	9.9	6.7	L S	40.2	1.1	77.7	12.3	10.0	L S	12.0	0.5	80
Y02b	*Quercus cerris*	*Qc*	2016	9.3	FLL- two layer	84	10.4	5.6	L S	29.0	3.1	76.7	13.3	10.0	L S	11.4	0.4	53
Y02c	*Quercus cerris*	*Qc*	2016	10.1	FLL- two layer	82.1	11.3	6.6	L S	36.0	3.4	88.9	8.3	2.8	S	13.4	1.2	52
Y03a	*Acer platanoides* 'Fairview'	*Apl*	2016	10.2	FLL- two layer	86.9	7.9	5.3	S	29.9	2.4	80.8	12.4	6.8	L S	14.1	0.9	62
Y03b	*Acer platanoides* 'Fairview'	*Apl*	2016	9.8	FLL- two layer	87.8	6.8	5.4	S	32.4	3.6	87.8	8.5	3.7	S	13.3	1.0	60
Y03c	*Acer platanoides* 'Fairview'	*Apl*	2016	7.9	FLL- two layer	85.9	8.4	5.7	S	34.3	1.6	93.0	4.5	2.5	S	13.7	0.5	62
Y05	*Quercus robur*	*Qr*	2015	8.2	FLL- one layer	92	4.9	3.1	S	12.3	2.4	93.2	4.9	1.9	S	17.7	1.7	59
Y06	*Quercus robur*	*Qr*	2014	8.5	FLL- one layer	87.7	7.3	5	S	29.4	4.2	97.0	1.5	1.5	S	3.8	1.5	40
Y07	*Quercus palustris*	*Qp*	2012	18.8	FLL - Vulkatec	82.2	13.5	4.2	L S	56.4	0.3	82.2	13.5	4.2	L S	56.4	0.3	100
Y08	*Quercus palustris*	*Qp*	2007	20.5	FLL - Vulkatec	82.2	14.1	3.6	L S	43.2	0.9	82.2	14.1	3.6	L S	43.2	0.9	100
Y09	*Acer pseudoplatanus*	*Aps*	2013	12.7	FLL- one layer	77.2	11.7	11.1	L S	36.0	0.6	87.6	9.4	3.0	S	4.6	1.6	71
Y10	*Acer pseudoplatanus*	*Aps*	2011	14.0	FLL- one layer	84.3	9.0	6.7	L S	29.4	3.8	90.5	5.8	3.7	S	15.1	0.4	38
Y11	*Prunus serrulata*	*Ps*	2017	7.1	FLL- one layer	NaN	NaN	NaN	NaN	48.0	0.8	84.2	9.3	6.4	NaN	6.3	0.1	20

5.2.3 Stomatal conductance

Stomatal conductance (g_S) was measured at in total 42 days during the growing seasons (May – September) of 2019 and 2020 by using a portable leaf porometer (SC-1, Decagon Devices Inc., Pullman, WA, USA). Campaigns were scheduled to cover variable soil water conditions for each site. Measurements were carried out on cloudless days between 10 AM and 5 PM (median time: 2 PM). For logistic and other reasons the campaigns lead not to parallel and even number of dataset for all sites. Replicate measurements on five randomly selected light exposed leaves were taken to reflect g_S of an individual tree at a given time. The leaves were cut for reasons of operability and measurements were started immediately after cutting since previous tests show that stomatal reactions due to cutting were not measurable within this time span.

5.2.4 BAI measurements

To gain most accurate results of stem growth, we measured the stem circumference of all trees to a decimal place at heights of 100, 130, and 150 cm (c_{100}, c_{130} and c_{150}, respectively). Each year with beginning in 2018, measurements were performed during December. The stem circumference measurements were height-related-transformed to the stem diameter increment at breast height (DBH), assuming a circular stem area.

$$\mathrm{DBH} = \frac{\frac{c_{100}}{\pi} \cdot 0.15 + \frac{c_{130}}{\pi} \cdot 0.25 \cdot \frac{c_{150}}{\pi} \cdot 0.10}{0.5} \tag{5.1}$$

Based on the first measured data point in December 2018, we calculated the basal area and basal area increments (BAI) in cm² assuming a circular tree trunk. In relation to the basal area of each previous year (starting with 2018's BAI as reference) we calculated the relative basal area increment in percent (rBAI (%)) for the years 2019 – 2021.

5.2.5 Carbon isotope composition

Three plant biomass samples of each investigated tree were collected in each year (2018-2021). In the first three years, samples were taken at the end of the growing season from shoot increments of the respective year (2018-2020). Due to reasons of operability, in 2021 leaves instead of shoots, were collected from shoot tips already in September. The shoots and leaves were oven-dried at 65 °C. Aliquots of oven dried samples (50 µg) were weighted into 4x6 mm tin cups (HEKAtech, Germany) for C isotope determination using a Europa Scientific ANCA-SL Stable Isotope Analysis System (Europa Scientific, Crewe, UK). The samples were analyzed for δ^{13}C using a using a Viena Pee Dee Belemnite as standard. Carbon isotope composition was expressed as

$$\delta^{13}\mathrm{C} = [(\frac{R_S}{R_b})/R_b] \times 1000 \tag{5.2}$$

, where R_s is the ^{13}C/ ^{12}C ratio of the sample and R_b is the ^{13}C/^{12}C ratio of VPDB (Vienna Pee Dee Belemnite) standard.

5.2.6 Data processing

We manually corrected the SWP-data for measured soil temperature. Data from individual sensors at each site (n = 13) within the same soil compartment were combined to depth and volume weighted SWP values, one for each soil compartment and one for the total soil volume (approximately 6.7 m³) (Figure 3.1). We transformed hourly measured SWP-data into daily means. To gain a gap free SWP dataset, we filled short temporal data gaps, caused by sensor- and datalogger defects, by using a data-driven *randomForest* model (Breiman 2001). The applicability to use predictor variables such as meteorological variables, tree- and site-specific characteristics for predicting the soil compartment specific SWP-data has already been proven in this experimental setup for the time-period of 2016 – 2019 (Schütt et al. 2022b). To fill data gaps for the dataset used in this study (2018 – 2021), we used the "*predict*" function of the *randomForest* model to calculate the missing SWP-data. Therefore, we trained the model with the available SWP-data from all available sites and the set of predictor variables. Subsequently, the model was run to estimate the missing SWP-data by using the predictor variables.

Measured daily mean $g_{S\,H2O}$ data in mmol m^{-2} s^{-1} were converted to $g_{S\,CO2}$ (further on "g_S ") according to

$$g_{S\,H2O} / g_{S\,CO2} = 1.605 \text{ (Jarvis 1971)} \tag{5.3}$$

The dependence of g_S on SWP and VPD was modelled empirically by testing logarithmic (eq. 5.4) and multiple linear regressions (eq. 5.5), where a & b as well as $ß_{0\text{-}2}$ were regression coefficients of the respective variables. The dependence of g_S on SWP was analyzed separately for the SWP data of the different soil compartments root ball, planting pit, urban soil and total soil volume.

$$\mathrm{g_S = a - b \cdot ln(SWP)} \tag{5.4}$$

$$\mathrm{g_S \ = \ ß_0 \ + \ ß_1 \ \cdot \ SWP \ + \ ß_2 \ \cdot \ VPD} \tag{5.5}$$

We selected the functions with highest correlation coefficients for each *species x site combination* and modelled species specific $g_{S\,\mathrm{mod}}$ for the growing seasons 2018 -2021. The 90th percentile of each species measured g_S data was used in the following as maximum g_S ($g_{S\,\mathrm{max}}$).

To determine the effect size of g_s reductions on the species specific potential carbon uptake, we adapted the model of Farquhar et al. 1980 to our data. Thereby we approximated CO_2 demand functions through calculations of the CO_2 limited (A_c) (eq 5.6) and the sugar ribulose-1,5-bisphosphat (RubP) limited (A_j) rate of photosynthesis (eq. 5.7):

$$\mathrm{A_c = \frac{V_{c\,max} \cdot (c_i - \Gamma^*)}{c_i + K_m} - \ R_d} \tag{5.6}$$

$$\mathrm{A_j = \frac{J_{max} \cdot (c_i - \Gamma^*)}{4 \cdot (c_i + 2 \cdot \Gamma^*)} - \ R_d} \tag{5.7}$$

where A is the rate of photosynthesis (assimilation) [µmol m^{-2} s^{-1}], $V_{c\,max}$ is the rate of carboxylation at CO_2 saturation, c_i is the intercellular CO_2 partial pressure, Γ^* is the CO_2 compensation point, K_m is the Michaelis-Menten constant of effective carboxylation of ribulose-1,5-bisphosphat-carboxylase-oxygenase (RuBisCO), J_{max} is the maximum electron transport capacity at saturating light and R_d is the mitochondrial respiration.

Since no data of CO_2-dependence of assimilation (A/C_i curves) for the investigated species were directly measured with an infrared gas analyzer in the field, we conducted the model parametrization assuming default values according to (Sharkey et al. 2007) and Farquhar & Wong (1984): K_m= 0.97 mbar bar^{-1}, Γ^*= 37 µbar bar^{-1} and R_d= 0.011 * V_{cmax}. Species specific mean values for RuBisCO maximum carboxylation capacity (V_{cmax}) and maximum electron transport capacity at saturating light (J_{max}) were derived from two sources: the Plant Trait Database (Future Earth et al. 2023) by searching for the trait ID's 186 and 289 (Photosynthesis carboxylation capacity (V_{cmax}) per leaf area (Farquhar model) and

Photosynthesis electron transport capacity (J_{max}) per leaf area (Farquhar model), respectively) and from unpublished measurements derived in a field survey in a nursery experiment described in (Schütt et al. 2022a). From all plausible and comparable data points we obtained, particularly in terms of environmental conditions (location: Germany, temperature range), we calculated for each species and each of both parameters a mean value (Table 5.2). As no data has been derived for *Ps* so far, we continued by using the mean of the available tree species data to represent the data range best.

Table 5.2: Means and standard deviations (SD) of the obtained $V_{c\,max}$ and J_{max} values from literature and own study review. The shown data contain values for all tree species except *Prunus serrulata*. To be able to represent also data for the so far missing tree species, we calculated a mean from the available data. Source of the data: (Future Earth et al. 2023) and from unpublished measurements derived in a field survey in a nursery experiment described in (Schütt et al. 2022a).

Tree Species	$V_{c\,max}$		J_{max}	
	Mean	SD	Mean	SD
	µmol m^{-2} s^{-1}	µmol m^{-2} s^{-1}	µmol m^{-2} s^{-1}	µmol m^{-2} s^{-1}
Acer platanoides	57.1	24.3	110.4	48.8
Acer pseudoplatanus	59.6	18.5	98.2	22.7
Quercus cerris	67.9	14.1	118.5	17.9
Quercus robur	49.9	22.9	58.9	20.7
Quercus palustris	60.2	7.9	98.8	10.2
Prunus serrulata	58.9	6.5	96.9	22.9

According to the method used, the values derived had been adjusted to a single temperature (25 °C) by default. However, as V_{cmax}, J_{max}, K_m, R_d and Γ^* are temperature dependent, we conducted a temperature correction for each temperature step (rounded without decimal) of the daily average temperature range between 10 AM – 5 PM) during the four years record that ranged between 5 °C and 33 °C by using the PC&E A/C_i curve fitting tool (V 2.0) according to (Sharkey et al. 2007; Sharkey 2016). By applying these species specific and temperature corrected values according to equations (5.6) and (5.7) we generated for each temperature step a species specific A/C_i curve. By applying 420 µbar as default atmospheric CO_2 partial pressure (C_a), we calculated in the following the associated g_S values following equation (5.8) for each assimilation equation (5.6) and (5.7) and each 5 µbar step of CO_2 intercellular partial pressure inside the leaf (C_i):

$$\mathrm{A_{OP}} = \mathrm{g_S} \cdot (\mathrm{c_a} - \mathrm{c_i}) \rightarrow \mathrm{g_S} = -\mathrm{A_{OP}} \cdot \left(\mathrm{c_i^{-1}} - \mathrm{c_a^{-1}}\right) \tag{5.8}$$

From a linear interpolation the derived A/g_S relation (one for each straight temperature step), we extracted the A values for each straight g_S value. Thus we derived for each *species x site combination* and thereby each modeled g_S value and its corresponding temperature a value for the potential operation range of assimilation (A_{OP}). Stomatal limitation of assimilation in percent of maximum assimilation was calculated by the quotient of the actual assimilation ($A_{OP\ (gS\ actual)}$) and the assimilation by assuming maximum stomatal conductivity ($A_{OP\ (gs\ max)}$) as follows:

$$\mathrm{A_{lim}}\ (\mathrm{g_{S\ mod}}) = \frac{\mathrm{A_{OP\ (gS\ actual)}}}{\mathrm{A_{OP\ (gS\ max)}}} \tag{5.9}$$

The quantitative value A_{lim} was further used to estimate the impact of a limited assimilation (initiated by decreasing SWP) that approximates a stress incidence.

5.2.7 Statistical analysis

Statistical analyses were conducted using OriginPro, v2019b (OriginLab Corporation, Northampton, MA, USA) and R v3.6.3 (R Core Team, 2022) with *randomForest* and caret packages (Liaw and Wiener, 2002; Kuhn, 2021). The *randomForest* input variables are listed in (Schütt et al. 2022b).

5.3 Results

5.3.1 Meteorological conditions and soil water availability

Meteorological conditions during the studied period can be classified as 'hot and dry' compared to the long-time average. In terms of precipitation the growing seasons of the years 2018 and 2020 recorded a total of -237 and -128 mm compared to the long-term average sum of 359 mm, whereas 2019 and 2021 had average precipitation. Reaching 16.6 °C, the growing season's mean air temperature across all investigated years was on average 1 C higher than the long-time average. Mean air temperature of 17.8 °C during the growing season of 2018 was the warmest during the monitoring period. During the growing season of 2018, 2019 and 2020, atmospheric mean water demand (VPD) reached 15.3, 12.5 and 13.0 hPa. For the years 2018, 2019 and 2020, the measured SWP were lowest in the three soil compartments ranging in the root ball between -170 and -195 kPa, in the planting pit between -147 and -180 kPa and in the urban soil between -124 and -140 kPa (Appendix Figure 5.1). The dynamics of SWP showed a broad variability between the single sites (Appendix Figure 5.2) and between the investigated years (see Schütt et al. 2022b).

5.3.2 Effect of environmental conditions on stomatal conductivity

The g_s of all investigated tree species, except *Carpinus betulus* 'Lucas' (*Cb*)*,* were significantly negative correlated with SWP (Figure 5.1, Table 5.2). g_s of *Qc* and *Ps* reacted strongly linear negative on both, SWP and VPD, whereas g_s for the remaining species only responded negatively to SWP described most accurately by a logarithmic function (eq. 5.4; Table 5.2). The instrumentation of different root zones with SWP sensors allowed the correlation of g_s with SWP data from different soil compartments and the total soil (Appendix Table 5.1). The *species x site combinations* showed contrasting g_s responses to the SWP of the different soil compartments. For the sites with *Acer plantanoides* 'Fairview' (*Apl*), *Quercus palustris* (*Qp*) and *Ps*, g_s was explained best by SWP as a mean of the whole rooting zone (SWP_{tot}) (Table 5.2 and Appendix Table 5.1). For *Apl* and *Qp* the relation of g_s and SWP_{tot} was most accurately fitted by using equation (eq. 5.4), for *Ps* using equation (eq. 5.5) with VPD as second factor. For *Qc* and *Acer pseudoplatanus* (*Aps*), g_s was best explained by SWP from the planting pit (SWP_{PP}), for *Aps* using equation (eq. 5.4) and for *Qc* using equation (eq. 5.5) with VPD as second factor. For *Quercus robur* (*Qr*) we found the SWP data from the root ball (SWP_{RB}) to generate the most accurate correlation with g_s. However, for the sites of *Qr* (Y5 and Y6), the response of g_s in relation to SWP was not uniform. Thus, we analyzed the correlation of this *species x site combination* separately from each other (Table 5.3).

Table 5.3: Best fit results of the correlation analysis between tree species stomatal conductivity with soil water potential (SWP) and vapor pressure deficit (VPD). Displayed are the functions used to fit the data, the independent variables of the specifically used SWP (soil compartments in brackets: RB – root ball; PP – planting pit; Tot. – total soil volume), the p-value and the correlation coefficient (adjusted R^2).

Tree species	**Site**	**Fitted curve**	**Independent Variables (x)**	**p**	**Adj. R^2**
Qc	(Y2a-c)	Multi Linear (eq 5.5)	SWP (PP)	< 0.001	0.58
Apl	(Y3a-c)	Logarithmic (eq. 5.4)	SWP (Tot.)	< 0.001	0.66
Aps	(Y9, Y10)	Logarithmic (eq. 5.4)	SWP (PP)	< 0.001	0.63
Cb	(Y1)			ns	
Qp	(Y7, Y8)	Logarithmic (eq. 5.4)	SWP (Tot.)	< 0.001	0.88
Qr	(*Y5)*	Logarithmic (eq. 5.4)	SWP (RB)	< 0.01	0.55
Qr	(*Y6)*	Logarithmic (eq. 5.4)	SWP (RB)	< 0.05	0.64
Ps	(Y11)	Multi Linear (eq. 5.5)	SWP (Tot.)	< 0.05	0.92

For most of the *species x site combinations* a wide range of SWP (68 kPa to 271 kPa) and VPD (10.1 hPa, 29.6 hPa) was covered at the stomatal conductivity (g_s) measurements (10th percentile, 90th percentile). The daily mean g_s values varied considerably among the seven species ranging from 34.2 to 216.7 mmol CO_2 m^{-2} s^{-1}. The lowest and highest g_s rates of this range were measured for *Prunus serrulata* (*Ps*) and *Quercus cerris* (*Qc*), respectively.

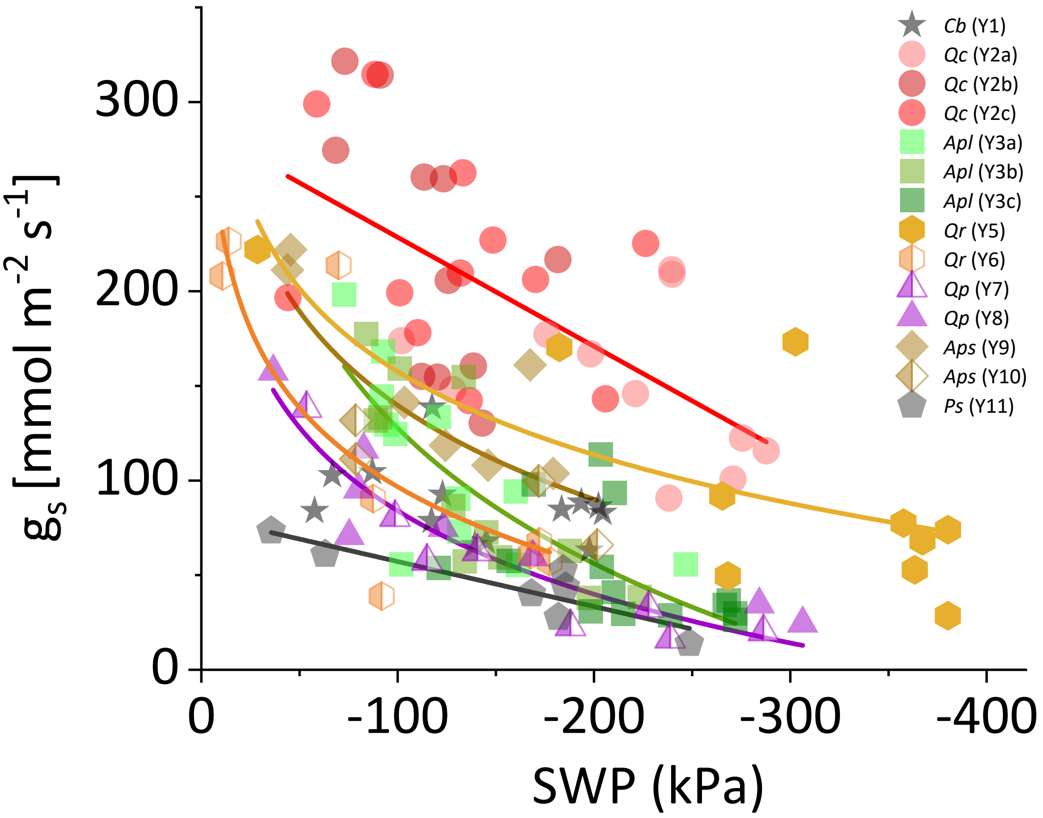

Figure 5.1: Absolute stomatal conductance (g_S) for CO_2 as a function of SWP for all tree species studied. According to Table 5.2, the SWP represented here corresponds to the soil compartment with highest R^2 for each *species x site combination*. Except for *Q. cerris* and *A. pseudoplatanus* (SWP of the planting pit) and *Q. robur* (SWP of the root ball), the total soil volume was the representative soil compartment for the relation of g_S and SWP. Colors distinguish between tree species, with light and dark shading indicating replicated sites for Y2 and Y3 (n=3). For the species *Q. robur*, *Q. palustris*, and *A. pseudoplatanus* (n=2), the two replicate sites per species were distinguished with fully and half-filled symbols. The presented curves according to the equations (5.5) and (5.6) were fitted as representatives for each species across their respective sites, excepting *Carpinus betulus* where no significant correlations was found and *Quercus robur* where one fit for each of the two sites was created.

5.3.3 Model based estimation of stomatal limited C-assimilation

Based on the linear and non-linear correlations of the measured g_s data (Table 5.2), we modelled daytime g_s ($g_{s\ \mathrm{mod}}$) (10 AM – 5 PM) for the growing seasons of the studied period 2018 – 2021 by using the species respective soil compartment SWP and the VPD data. The operational ranges of $g_{s\ \mathrm{mod}}$ (10th - 90th percentile) varied considerably across species (Figure 5.2 a-f, boxplots in the top). To determine whether and to which extent reductions in g_s affect the carbon uptake, we used the model of Farquhar et al. 1980. As the species specific variables $V_{c\ \mathrm{max}}$ and J_{max} (Table 5.1) were temperature dependent, we applied a temperature correction according to (Sharkey et al. 2007; Sharkey 2016). Thus, for each species the assimilation (eq. (5.6) and (5.7)) and its associated g_s (eq. (5.8)) was calculated for each full temperature step between 5 °C and 33 °C. In Figure 5.2 (bottom), three A_{OP} functions with different temperatures were displayed per species (15 °C, 20 °C, and 25 °C). For these representatives, the highest assimilation potential was given at high temperatures (25 °C). From all species, *Qc* can potentially reach the highest assimilation and *Qr* the lowest. The shape and positioning of the three A_{OP} curves of *Aps*, *Apl*, *Qp* and *Ps* were almost similar. By lowering g_S at high temperatures, the assimilation of all species might potentially be limited already at higher g_S in contrast to lowering g_S at low temperatures (15 °C).

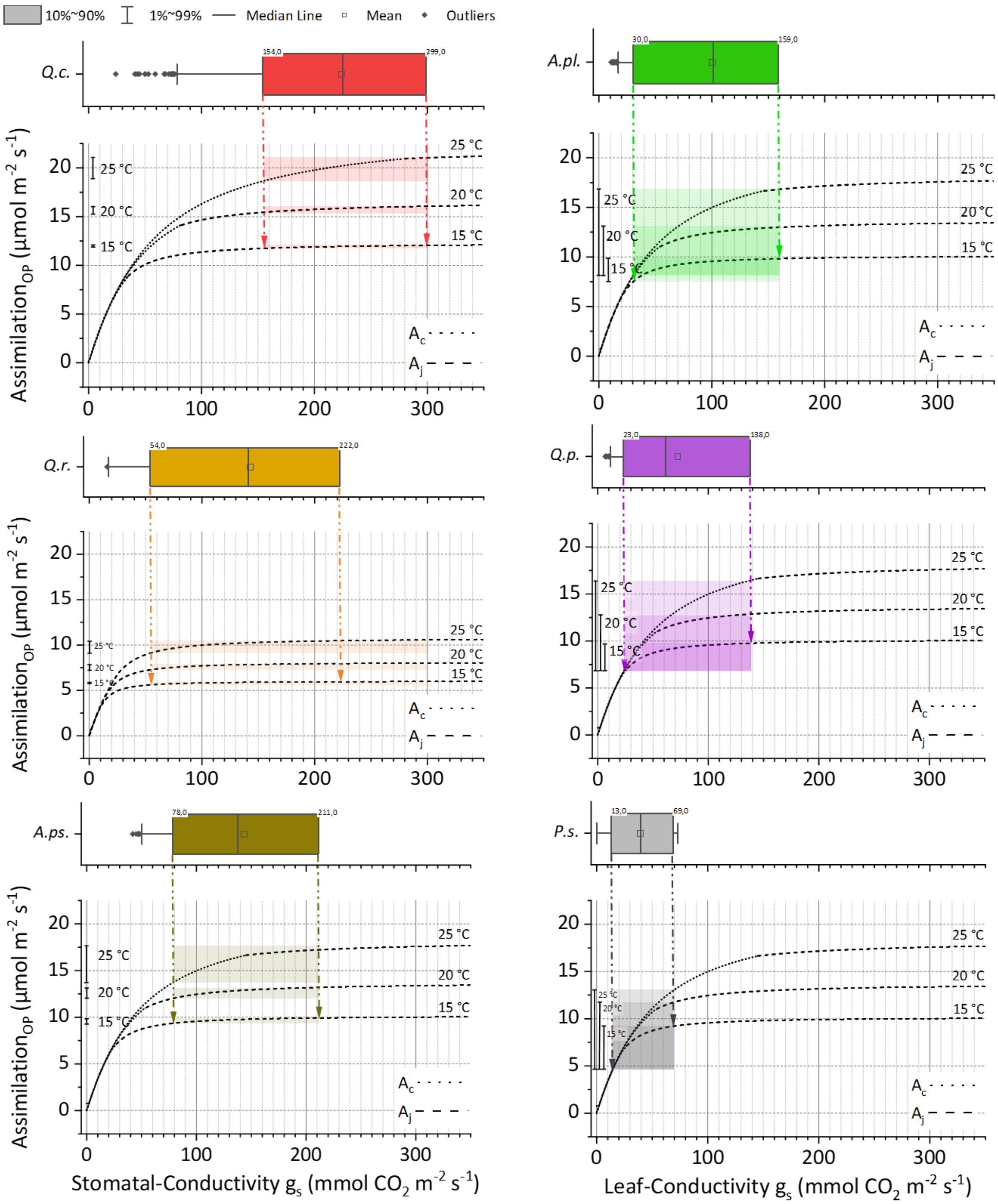

Figure 5.2: a-f top: Operation range of modelled stomatal conductivity ($g_{S\,\mathrm{mod}}$) for CO_2 of the investigated *species x site combination* (a-f) over the four growing seasons 2018-2021. a-f bottom: Temperature dependent operation range of assimilation (A_{OP}) as a function of stomatal conductivity displayed for the temperatures 15 °C, 20 °C and 25 °C . The dotted, colored arrows connecting top and bottom of each graph represent the 10th and 90th ($g_{S\,\mathrm{max}}$) percentile of modelled stomatal conductivity of each *species x site combination*. Parametrization of carboxylation capacity ($V_{c\ \mathrm{max}}$) in the CO_2 limited assimilation (A_c function; initial black line and dotted black line) and electron transport capacity (J_{max}) in the RubP limited assimilation (A_j function; initially broken and saturated part of the black line) were adjusted for each species. The whiskers close to the y-axis of the bottom graphs represent the 80% width of the species specific A_{OP} during the measurement period.

The stomatal conductivities ($g_{S\,\mathrm{mod}}$), modelled individually on the base of monitored SWP and VPD data of 4 years record, reveal distinct stomatal regulation ranges of the six tree species (horizontal box-whisker-plots in Figure 5.2). Whilst the absolute lowermost values of g_S only differ slightly between species (5-40 mmol m^{-2} s^{-1}), the regulation spans of g_S, in which stomatal apertures are tuning gas exchange during 80% of the days (10th-90th percentiles of all data points), differ strikingly. The extremes being *Qc* with 154-299 mmol m^{-2} s^{-1} and *Ps* with 13-69 mmol m^{-2} s^{-1}. These distinct regulation ranges of g_S in coordination with the CO_2 dependence of assimilation (deduced from V_{Cmax} and J_{max} for each species) result in evidently different pattern of stomatal limitation of A_{OP} (vertical bars Figure 5.2). For instance, the adjustment of stomatal conductivities to soil water availability ranging from 299 to 154 mmol m^{-2} s^{-1} in case of *Qc* (10th-90th percentiles, boxes in Figure 5.2) results in a range of assimilation A_{OP} between 12 und 21 µmol m^{-2} s^{-1}. Importantly, the degree of this stomatal limitation behavior is strongly controlled by temperature: At 25°C the down-regulation of stomatal conductivity from 299 to 154 mmol m^{-2} s^{-1} results in a reduction of A_{OP} by 11%, whilst at 15°C the same regulation resulted in a reduction of only 3%. As counterexample, the stomatal regulation range of *Qp* from g_S 138 to 23 mmol m^{-2} s^{-1} is accompanied by a limitation of A_{OP} by 59% at 25°C and by 33% at 15°C.

The stomatal limitation of A_{OP} *per se* and its dependence on temperature show a certain regularity with regard to stomatal regulation pattern: Species with the widest regulation ranges, expressed as delta of conductivities between 90th and 10th percentiles of observations in Figure 5.3, are less affected by stomatal limitation, and additionally stomatal limitation is less temperature dependent (*Qr*, *Qc*, *Aps*). Stomatal limitation is most pronounced and most temperature sensitive in case of *Qp*, *Apl* and *Ps*. These species regulate stomatal conductivities on only narrow regulation ranges at lower absolute range (Figure 5.2). This is also indicated by lowest conductivity values at the lower 10th percentile of modelled g_S during the 4 years record (Figure 5.4). The low assimilation values and the low temperature dependence of *Qp*, *Apl* and *Ps* at the lowermost 10th percentile (Figure 5.4) point to the fact that these species regulate the stomatal conductivities down to ranges that intercellular CO_2 partial pressures become reduced to values where CO_2 dependences of assimilation show strong initial slopes (Figure 5.2). In case of *Qr*, the low (but temperature-dependent) assimilation rates at 10th percentile are not due to stomatal limitation as consequence of low stomatal conductivities; it is the consequence of the low assimilation potential of this species as documented by literature values of V_{Cmax} and J_{max}.

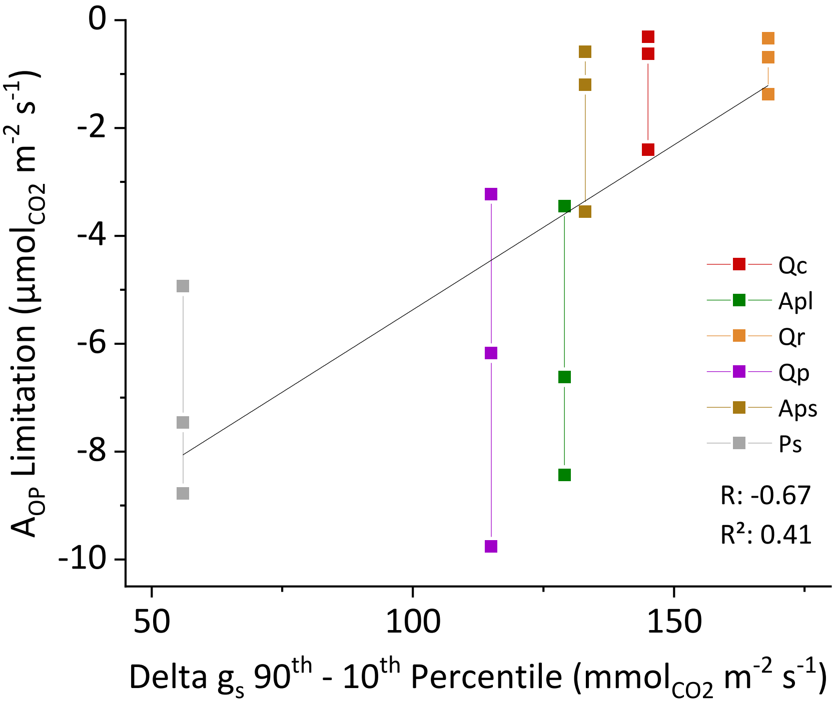

Figure 5.3: Limitation of potential assimilation (A_{OP}) by reducing the stomatal conductance across the range from higher to lower g_S (90th percentile to 10th percentile of 4 years record, respectively) for each tree species.

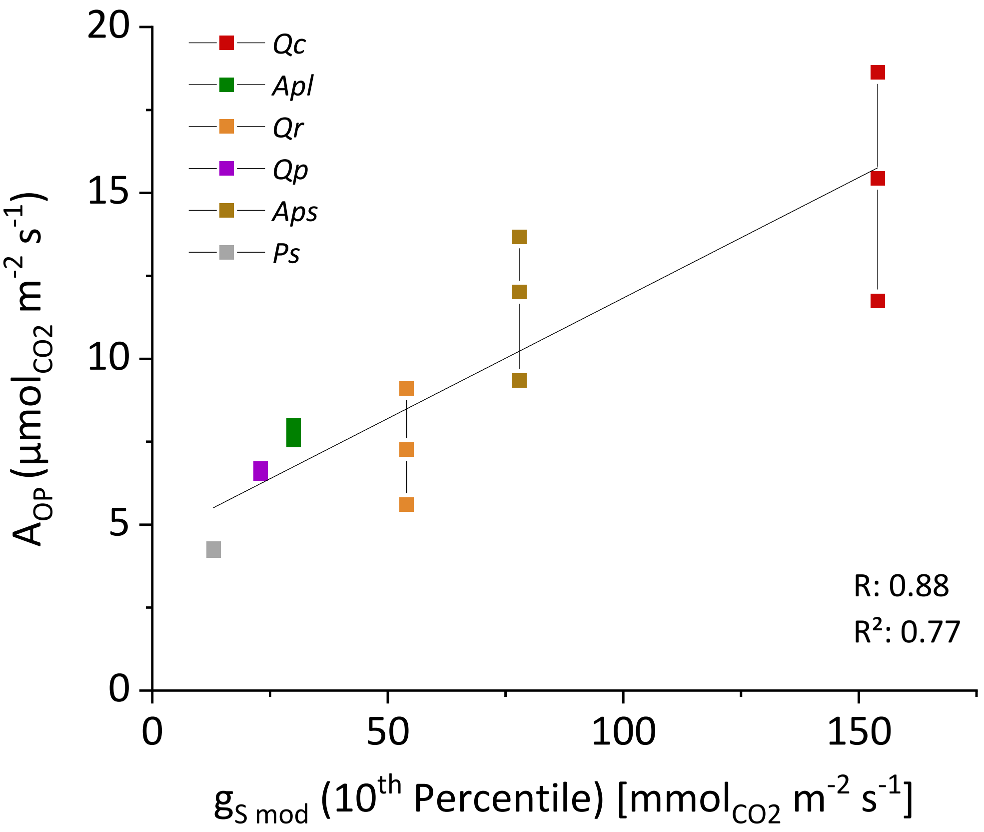

Figure 5.4: Potential assimilation (A_{PO}) at the lower bounds of the stomatal regulation range (lower g_S) (lower 10-percentile of 4 years record) for each tree species.

The time courses of the actual assimilation A_{OP} (considering actual values of dynamic model parameters: actual mean temperature (10 AM – 17 PM) and $g_{S\,mod}$ by actual SWP values) show for each *species x site combination* widely varying dynamics and strong differences regarding the total assimilation as an annual mean throughout the 4 years record (data not displayed). However, only a separation of stomatal limited assimilation by dividing the maximum assimilation (setting actual g_S as species specific $g_{S\,max}$) by the actual assimilation, reveals information about stress incidences that occur under *in situ* conditions (Figure 5.5). Compared to the dynamics of the actual assimilation, also the dynamics of the stomatal limited assimilation shows widely varying dynamics between the years and the *species x site combinations*, however with different patterns. With exception of site Y6 in 2018, the stomatal limited assimilation of the species *Qc*, *Aps* and *Qr* at their respective sites was on average across the 4 years record less pronounced with values > 94% of maximum assimilation. Thereby the stomatal limitation of assimilation was most pronounced in 2018, as the lower limit of the range containing 80% of the data lowered down to 59%, 69% and 81% for *Qr*, *Aps* and *Qc*. For the following years 2019 – 2021 this lower limit never fell below 86%. In contrast, the species *Qp*, *Apl* and *Ps* show in all years strongly pronounced variations and thus low total values representing a strong stomatal limited assimilation. Thus, the stomatal limited assimilation of the species *Qp*, *Apl* and *Ps* at their respective sites was on average of the 4 years record strongly pronounced with values of 80%, 85% and 72% of maximum assimilation, respectively.

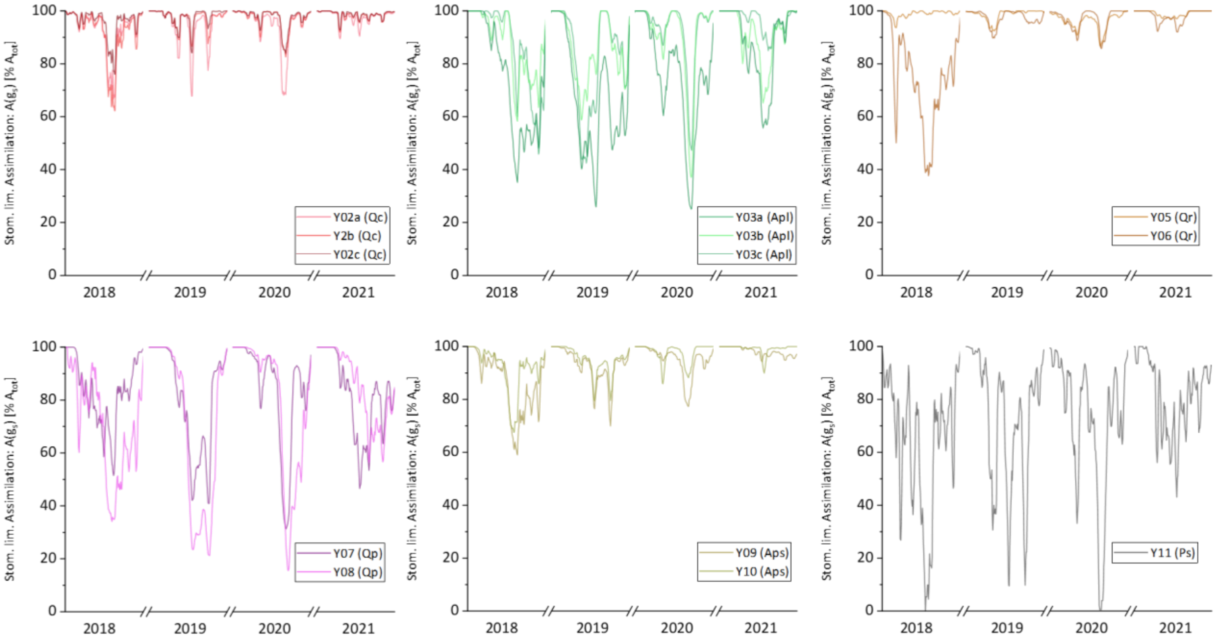

Figure 5.5: Species specific time courses of the 5 day average relative stomatal limited assimilation ((A_{lim}) as a percentage of A_{max}) modelled by the individual tree parameters, SWP and the VPD (only for *Qc* and *Ps*) during the growing seasons of a four years record (2018 – 2021).

5.3.4 Relations between stress incidences, growth and carbon balance

We found that average relative basal area increment (rBAI) was reasonably correlated with the modeled annual mean operational range of assimilation ($R^2 = 0.56$, Figure 5.6). Intensity of stomatal regulation i.e. width of g_S regulation range and the percentage of stomatal limited assimilation compared to assimilation with $g_{S\ max}$ had no consistent effect on growth rates: those species with broadest regulative span of stomatal conductivities (Figure 5.2) and lowest stress incidences (A_{lim}) showed highest (*Qc*), intermediate (*Aps*) and lowest (*Qr*) relative basal area increment (Figure 5.6). A similar pattern can be derived when considering the stable carbon isotope values of the biomass ($\delta^{13}C$) (Figure 5.7). Variation of carbon isotope composition can be mainly explained by the annual mean value of A_{lim} (% of A_{max}). Throughout the $\delta^{13}C$ data range, species with higher incidences of stomatal CO_2 limitation of assimilation, indicated by more negative values (*Ps*, *Qp* and *Apl*), show lower ^{13}C discrimination, indicated by less negative values, whilst species with lower incidences (less negative values; *Qc*, *Qr* and *Aps*) show higher ^{13}C discrimination (more negative values). Furthermore, a clustering, that approximately separated the previously described group of tree species around a $\delta^{13}C$

value of -26‰ was visible (Figure 5.7). This indicates that the limitation of assimilation by regulating stomatal apertures (Figure 5.2) was decisive for CO_2 availability, which underlines the plausibility of the modelled values of A_{lim}.

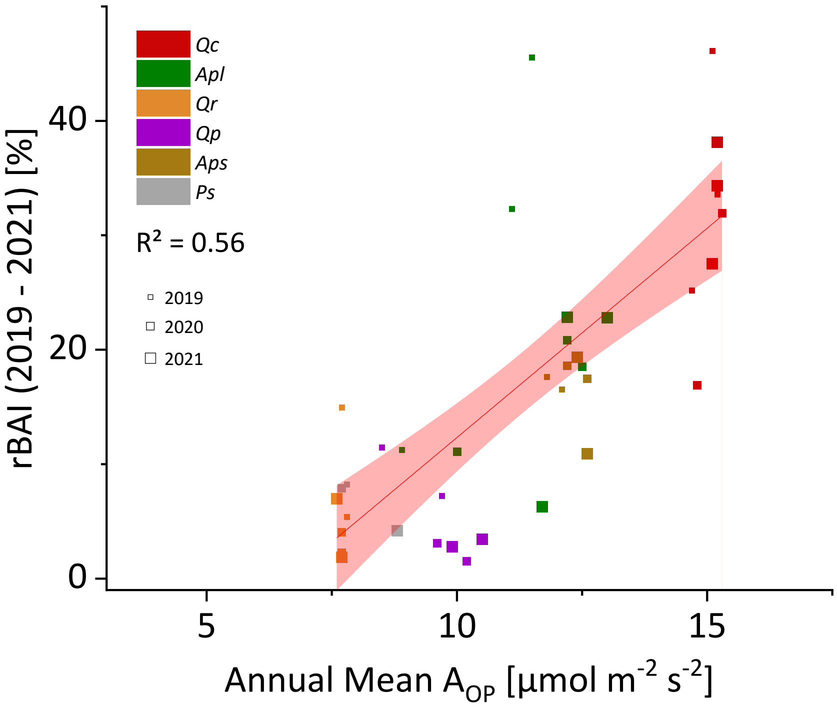

Figure 5.6: Relationship of the annual mean A_{PO} [µmol m^{-2} s^{-1}] the relative basal are increment during 2019 – 2021. The symbol size shows the year of record for the data pairs of each site. The confidence band shows the range where 95% of the data were expected.

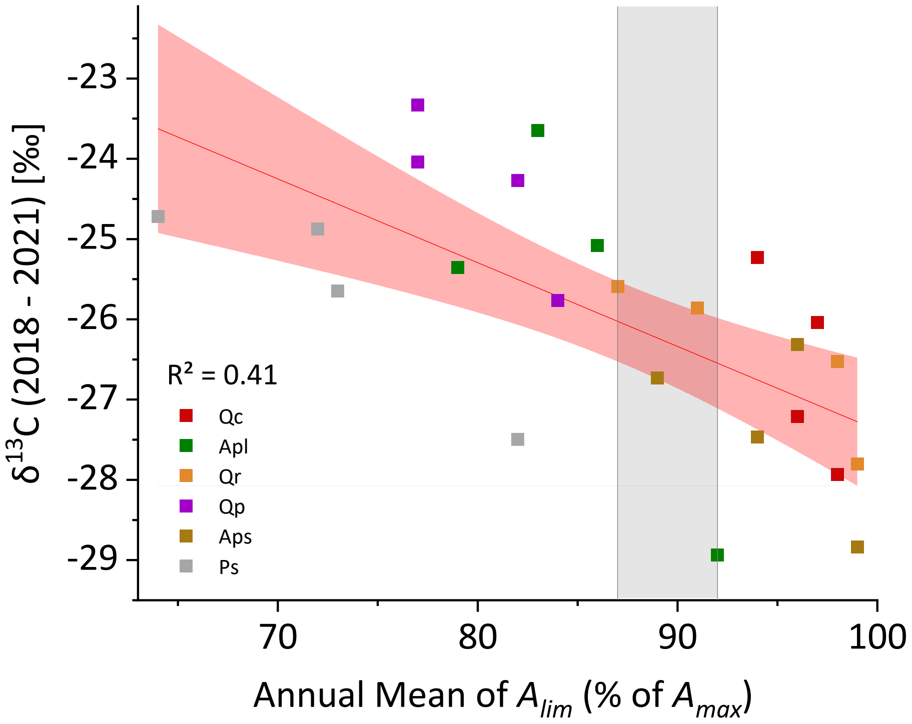

Figure 5.7: Relationship of the annual mean of A_{lim} as a percentage of A_{max} during the 4 years record with the stable carbon isotope values of the biomass ($\delta^{13}C$). The red confidence band bordering the linear regression line ($R^2 = 0.41$) shows the range where 95% if the data were expected. The grey shaded area marks a potential threshold range describing the intersection of the lower clustering border of the tree species group *Qc*, *Qr*, *Aps* (87%) and the upper clustering border of the tree species group *Qp*, *Apl*, *Ps* (92%).

5.4 Discussion

5.4.1 Response of young urban street trees to soil hydrological dynamics

For urban sites the effect of soil water availability on tree physiology and C balance has been studied insufficiently as soil water measurements are challenging, time consuming and expensive due to urban infrastructures, necessities of permissions and securing of equipment. We studied young street trees of seven different species located randomly at urban sites with typical soil characteristics i.e. high sand content and high sealing degree (Table 5.1). On the base of stomatal reaction patterns (g_s) and continuously monitored soil water availability, we modelled for each *species x site combination* within a four years growing season record their g_s. Based on a biochemical model of photosynthetic CO_2 assimilation (Farquhar et al. 1980) we deduced over a broad temperature range the species specific operational range of assimilation. Applying the dynamic input parameters (g_S and T), we extracted from the modeling output the periods of stomatal limited assimilation, i.e. the extent to which primary production became limited by stomatal diffusion resistance.

The stomatal conductance (g_S) of leaves is a key variable that regulates the gas exchange between the intercellular space of plants and the atmosphere in response to environmental parameters as soil water availability and vapor pressure deficit (VPD). Thus, one can assume from g_S data a provision of insights into stomatal limitation of assimilation and, hence, into the stress incidence of trees (Flexas & Medrano 2002). Therefore, many studies that aim to identify strategies of urban trees coping heat, drought and site conditions rely on g_S measurements (Osone et al. 2014; Gillner et al. 2017a; Caplan et al. 2019). However, continuous direct monitoring of g_S is not realizable particularly on urban sites. Thus, an integrational view on stomatal limitations of assimilation over larger time spans is missing. We approached this challenge by modelling A_{lim} by combining g_S data measured at varying situations of SWP and VPD, high resolution monitored SWP data, VPD and temperature records, with temperature dependent A/g_S relationships following Farquhar et al. 1980; Sharkey et al. 2007.

The range of g_S regulation measured between different *species x site combinations* in this study (Figure 5.1) has been reported in studies on commonly used urban tree species (Fini et al. 2009; Osone et al. 2014; Gillner et al. 2017a; Caplan et al. 2019). The g_S of almost all *species x site combinations* was correlated significantly negative with the soil water available in different soil compartments (Table 5.2 and Appendix Table 5.1) of the rooting zone which is also indicated in other studies (Gao et al. 2023). However, the trend of reducing stomatal aperture with increasing VPD (Klein 2014; Gillner et al. 2017a) was, in interaction with SWP, only visible for *Quercus cerris* (*Qc*) and *Prunus serrulata* (*Ps*). *Carpinus betulus* 'Lucas' (*Cb*) showed at its respective site (Y1) in this study no significant correlations of g_S with neither SWP nor VPD. We suggest a potential interaction of g_S with SWP to be diminished by the comparatively narrow SWP data range (-60 to -210 kPa; Figure 5.1) captured during the g_S

measurements. Furthermore, the site Y1 was highly shaded, which resulted hypothetically in a less dramatic g_S respond to decreased soil water availability (Siegert & Levia 2011) comparable to the significant but only moderate g_S response of Ps at site Y11, where shading also prevailed.

In response to soil water availability, influenced by site conditions (e.g. soil composition) (Schütt et al. 2022a) and soil sensitivity for intensive drying (Schütt et al. 2022b), trees are likely able to adapt their root growth and their root architecture individually (Larcher 2001). However, those strategies exhibited by specific species are yet not clear (Yang et al. 2023), particularly not for young urban street tree species (Becker et al. in prep. ; Zhang et al. 2020). Therefore, we aimed to obtain this important information about the ability to explore the root zone from correlations (R^2) between stomatal conductivity and SWP of the four soil compartments (root ball, planting pit, surrounding urban soil, and total soil volume) assuming that high R^2 indicate the respective soil compartment to be highly critical for adequate soil water supply for the respective *species x site combinations*. We found that the root distribution patterns are reflected in the four years' operation ranges of stomatal conductivities: the g_S of *Acer platanoides* (*Apl*), *Quercus palustris* (*Qp*) and *Ps*, representing those tree species with the lowermost range of g_S values, are mainly correlated with SWP of the total soil volume, indicating an even root distribution throughout the three laterally adjacent soil compartments. For *Qc*, *Acer pseudoplatanus* (*Aps*) and *Quercus robur* (*Qr*), representing the tree species with higher total g_S and wider ranges of stomatal regulation, stomatal reaction was found to be mainly controlled by the SWP of the planting pit and the root ball (*Qr*), and less by the surrounding urban soil. Contrary than expected, the species whose roots may not reached the surrounding urban soil had the highest absolute g_S values, suggesting a more efficient exploration of soil water by fine roots that sustained higher transpiration demands. In case of *Qr*, water uptake obviously has been ensured by a relevant amount of fine roots within (and deeply below) the root ball (Danner & Knapp 2001), which is indicated by the significant but comparatively low R^2 between g_S and the SWP (Table 5.1). For *Qc* and *Aps* the high R^2 between g_S and SWP in the planting pit on the one hand and the highest and respectively relatively high g_S values on the other hand, indicate that higher densities of fine roots in the planting pit, i.e. a preference of intensive root branching (Yang et al. 2023) in the respective soil substrate, supported the trees' water balance better than lateral soil exploration. These results are supported with the assumption that water spending species (as revealed for *Qc*, *Qr* and *Aps* (Figure 5.1)) have better access to soil water due to a better developed root system (Levitt 1980; Mediavilla & Escudero 2004). However, due to the comparatively weaker R^2 of *Qc*, *Qr* and *Aps* (Table 5.2), we suggest these species produced rapidly sink roots in the early stage after planting (Danner & Knapp 2001 for Oak seedlings) which tapped soil water outside the monitored soil volume (Figure 3.1). As g_S were measured only during the seasons of 2019 and 2020 and thus in the middle of the study period, no conclusions can be drawn about a change/adaptation of the root system over time and thus a change in the preferential soil compartment for water uptake.

5.4.2 Stomatal reaction patterns as determinants for limitation of assimilation

For our estimates how different stomatal reaction patterns could have caused limitation of assimilation, we used a photosynthesis model (Farquhar et al. 1980) parametrized by the values of Γ^*, K_m and R_d as described by (Sharkey et al. 2007; Sharkey 2016). The CO_2 demand functions are based on literature values for $V_{c\ max}$ and J_{max} and partly on calculated values for $V_{c\ max}$ and J_{max} following gas exchange measurements of young *Qc* and *Qp* trees growing in an experimental field near Hamburg (experimental field study described in (Schütt et al. 2022a)). All parameters were adjusted to the respective mean temperature of each day during the study period following Sharkey et al. 2007 in order to include the temperature effects on potential assimilation rates before calculating the stomatal limitation.

This study is a first conceptual approach with a high number of assumptions that have to be further evaluated in future studies. The time course of g_S modelled on the base of soil water data and VPD must be considered as rough estimate. Alike the parametrization of the photosynthesis model and the deduced values of assimilation must be taken with caution, since $V_{c\ max}$ and $J_{\ max}$ can vary throughout the growing season particularly in response to drought (Grassi & Magnani 2005; Pilon et al. 2018). Thus, the data on stomatal limitation revealed in this study might not be considered as highly exact values in absolute terms, but nevertheless, they evidence that stomatal limitation and consequently stress incidence varies considerably as function of the temperature dependence of assimilation due to enzyme kinetics. Additionally, this leads to the expectation that higher leaf temperatures should result in higher stomatal conductivities, when higher assimilation rates cause lower intercellular CO_2 partial pressure and, thus, stomatal opening. This thermal opening response of stomata has been reported in only a few studies, which might be due to the problem to dissect between the effects of temperature and of VPD on stomatal regulation (Urban et al. 2017; Marchin et al. 2022).

To evaluate the effect of particular stomatal limitation patterns in terms of *in situ* stress incidences, we assumed that at a reduction of assimilation must affect both, C investments into stress reactions and lack of assimilates. During the course of the four years record, the derived assimilation data of the investigated tree species fluctuate between the calculated operational ranges depending on the temperature sensitivity of $V_{c\ max}$ and J_{max} as well as the g_S affected by SWP. However, as the stomatal limitation of assimilation is pivotal for stress reactions (coping with consequences of excess energy) (Pilon et al. 2018; Kullberg et al. 2023) whilst thermal limitation due to enzyme kinetics is not, we approached stress incidences by the quotient of maximum assimilation (at $g_{S\ max}$) and actual assimilation (at $g_{S\ mod}$) (Figure 5.5). We found for the species with the widest range of stomatal regulation (*Qc*, *Qr* and *Aps*) the assimilation to be limited by a comparatively small proportion ranging on annual average between 86% and 99% of maximum assimilation (Figure 5.7). On the other hand, the species with the narrowest range of stomatal regulation (*Qp*, *Apl* and *Ps*) were most severely affected by stomatal limitation of assimilation ranging on annual average between 64% and 92% of maximum assimilation (Figure 5.7).

The extent to which primary production became limited by stomatal diffusion resistance depended on the interaction of two factors: 1. the range of stomatal regulation and 2. the parametrization of the photosynthesis model and its temperature dependence: Regulation ranges at higher conductivities led to lower incidences of stomatal limitation of assimilation particularly at lower temperatures (15-20°C), since stomatal regulation takes place in the saturation range of the curve describing the conductivity dependence of assimilation. Higher individual V_{cmax} values as well as increased V_{cmax} values at higher temperatures stretch this curve and cause an expansion of the curved range in which changes of the stomatal aperture have a stronger effect on assimilation.

The interaction between regulative ranges of stomatal conductivity and temperature dependence of assimilation is most pronounced with trees that combine narrow g_S ranges at absolute lower conductivities with medium V_{cmax} values. This is the case for *Qp*, *Apl* and *Ps*: trees of these species show both, a relevant diffusional limitation of assimilation at moderate temperatures and a strong increase of limitation with rising temperatures. In case of Aps the interaction is intermediate: medium regulative ranges of conductivity combined with medium V_{cmax} lead to almost no diffusional limitation at lower but relevant limitation at higher temperatures. At low overall V_{cmax} as with *Qr*, the potential assimilation is rarely affected by regulation of stomatal aperture even at higher temperatures. At extremely high ranges of stomatal regulation combined with high V_{cmax} as in case of *Qc*, diffusional limitation of assimilation remains low even at 25° C. Hence, this combination might reflect mechanisms of constrictive adaptation to warm and dry climates, since *Qc* is the only one of the six studied species whose native distributional range is restricted to warm and dry climate (from South Central over South Europe to Turkey (Jalas & Suominen 1988; EUFORGEN 2023)).

These findings seem to be in conflict with the postulation, that C*3*-plants utilize their inherent resources most effectively when they operate at or close to the point where CO_2 and RubP are co-limiting, i.e. when the supply function at maximum stomatal conductivity intersects the demand function at the intersection point of (A_c) with (A_J) (Lambers & Olivera 2019). Our observations reveal that particularly at lower temperatures some trees frequently regulate their stomatal aperture in a higher range of conductivities than photosynthetic CO_2 demand would necessitate. On the one hand this strategy means excess transpiration at lower temperatures i.e. an ineffective utilization of a resource, but on the other hand, at high temperatures, the stomatal limitation of assimilation would remain at low levels. Hence, stress reactions necessary to dissipate excess energy, detoxify ROS, and protect, repair or replace damaged proteins and cell components (Wujeska et al. 2013) are not triggered at higher temperatures unless soil water becomes a limiting factor. Furthermore, when soil drought affects leaf conductivity at higher temperatures, the stomatal limitation of assimilation and hence the stress reactions do not rise as progressively as it is the case for trees that regulate their stomatal aperture at lower conductivity ranges. Thus, we propose as a possible explanation that the detected high conductivity ranges of stomatal regulation reflect a margin of safety corresponding to the temperature regime of hot and dry natural habitats. Thereby, the magnitude of stomatal reaction patterns and margin of safety seem obviously persisting also when grown in cooler and wetter climates (*Qc*). However, the physiological properties behind temperature dependence of assimilation of trees from temperate climates have a certain phenotypic plasticity. For instance, Kattge & Knorr 2007 demonstrated for 36 species a general tendency for an acclimation response of optimum temperature of $V_{c\ max}$ and J_{max} to plant growth temperature, whereas Kullberg et al. 2023 found stomatal limitation rather than an acclimation of optimum temperature of $V_{c\ max}$ and J_{max} most important for a limitation of assimilation. To what extent these drought responsive physiological properties can persist in nursery grown trees reproduced from plants of different proveniences (e.g. hot, dry, sandy soils – urban like) (Hannus et al. 2021) or can be trained in nurseries by pre-conditioning tree species under harsh, urban like growing conditions (Dreßler 2019; Roloff 2021b), should be part of future studies.

5.4.3 Reproducibility of the modeled stress incidences

The so far drawn conclusions were based in majority on modelling data based on a more generalized parametrization of literature values. Therefore, we aimed to check if the findings such as different patterns of assimilation between the *species x site combinations* and a strongly different limitation of assimilation by stomatal regulation between the *species x site combinations* are reproduced in tree attributes such as the relative growth of stem basal area and the stable carbon isotope values of the biomass ($\delta^{13}C$). Tree growth is a typical and widely used parameter to cumulatively assess trees physiological and morphological vigor (Gillner et al. 2017a; Móricz et al. 2021; Hirsch et al. 2022; Schütt et al. 2022a). We found that the annual relative basal area increment of the *species x site combinations* was reasonably correlated with the modeled annual mean A_{OP} ($R^2 = 0.56$, Figure 5.6). Data of annual relative growth rates were fluctuating on a wider range than the mean assimilation which is reasonable. Compared to growth, assimilation is in the same tendency, but not in the same extent influenced by environmental parameters and the specific assimilate distribution and the typical growth behavior, divided in above- (stem and branches) and belowground growth (root) (Larcher 2001; Barbaroux & Breda 2002), must be considered.

The obtained data for *Qr* and *Qc* show clearly, that high stomatal conductivity ($g_{S\,\mathrm{max}}$) in combination with a wide range of stomatal regulation and less stomatal limited assimilation can result in both, comparatively decreased and increased tree growth, respectively, as also the enzyme kinetics (individual $V_{c\ \mathrm{max}}$ and $J_{\ \mathrm{max}}$) contribute to total carbon assimilation. These observations provide evidence, that pronounced stomatal regulation (i.e. isohydric reaction type) is not coupled with higher incidences of stomatal limitation of assimilation and, hence, with growth depression due to lack of reduced carbon. However, current studies often use the sensitivity or the regulation width of stomatal conductivity as a criterion for reduced assimilation to describe the vitality or growth behaviors of trees e.g. (Jonard et al. 2011). Depending on the underlying definitions, often inconsistencies occur, and species were characterized as both isohydric and anisohydric (Moser-Reischl et al. 2019; Hirsch et al. 2022; Marchin et al. 2022). Therefore, it is recommended to use alternative, quantitative parameters, e.g., the measure of stomatal limitation of assimilation as modeled in this study or e.g. the leaf water potential at 50% of the maximum g_S ($\Psi g_S 50$) as introduced by Klein 2014 to compare strategies of different tree species in coping with soil drought by avoiding the current, yet biased, distinction between isohydric and anisohydric species (Klein 2014).

Our suggestion, that stomatal regulation in relation to assimilation rather than only stomatal regulation width is of importance to evaluate stress incidences, is further supported by the integration of the stable carbon isotope values of the biomass ($\delta^{13}C$) (Figure 5.7). Contrary to the general evidence that wide stomatal regulation range results in more positive $\delta^{13}C$ values as a consequence of lower ^{13}C discrimination, we found no such correlation (data not shown). Instead, species with higher incidences of stomatal CO_2 limitation of assimilation and the lowermost regulative width of stomatal conductivities (*Ps*, *Qp* and *Apl*) (Figure 5.2), show lower ^{13}C discrimination. Furthermore, the species with lower incidences and the wider range of conductivities (*Qc*, *Qr* and *Aps*) show higher ^{13}C discrimination i.e. these species experienced less situations of reduced intercellular CO_2 partial pressure resulting from reduced stomatal conductivities.

Regarding the findings that reduction of assimilation by regulating stomatal apertures (Figure 5.2) follows a certain gradient represented by increased $\delta^{13}C$ values (Figure 5.7) and that two groups of tree species with different stomatal regulative strategies clustered, an estimation of a quantitative threshold range i.e. critical reduction of assimilation by stomatal regulation, seems plausible. By combining results of stomatal limited assimilation with simultaneously measured soil water availability (i.e. SWP), a threshold range might increase the indicative power of monitored soil water data. Yet, threshold values indicating increased stress based on limited soil water availability are generalized (von Wilpert 1991; Bréda et al. 1995) and not available for specific species, particularly under consideration of stomatal effect on assimilation (Emanuel et al. 2007). In a previous study, Schütt et al. 2022b quantified the extent and intensity of critical soil water availability at the herein studied trees sites using a common threshold value (von Wilpert 1991; -120 kPa SWP) to assess potential implications for trees vitality. Contrary to this threshold value, which describes beginning stomatal regulation of *Picea abies*, we found in this study that stress is only inaccurately explained by only studying stomatal closure. Furthermore, we revealed that the biochemical consequences for the trees, i.e. stomatal limited assimilation, from lowering the stomatal conductance were in addition to SWP highly dependent on a wide range of parameters such as temperature, $V_{c\,max}$, J_{max} and VPD. Taking potential occurring co-correlations into account, as g_S was part of the photosynthesis model and modeled from SWP data, we used the herein gathered data for rough estimations of species specific relations of A_{lim} with SWP (Figure 5.8). With exception of *Ps*, *Qc* and *Qr*, we found very close relationships ($R^2 > 0.85$) described as exponential decay functions (*Apl* and *Qp*) and linear functions (*Qc*, *Qr*, *Aps*, *Ps*). Applying the upper border of the described threshold range of stomatal limited assimilation, the tree species were affected by lowering SWP starting from 25 kPa (*Ps*), 100 – 150 kPa (*Qp* and *Apl*) to 160 – 250 kPa (*Qr* and *Aps*). According to this calculation, the assimilation of *Qc* will only be affected critically by stomatal regulation when SWP decreases below approximately 340 kPa.

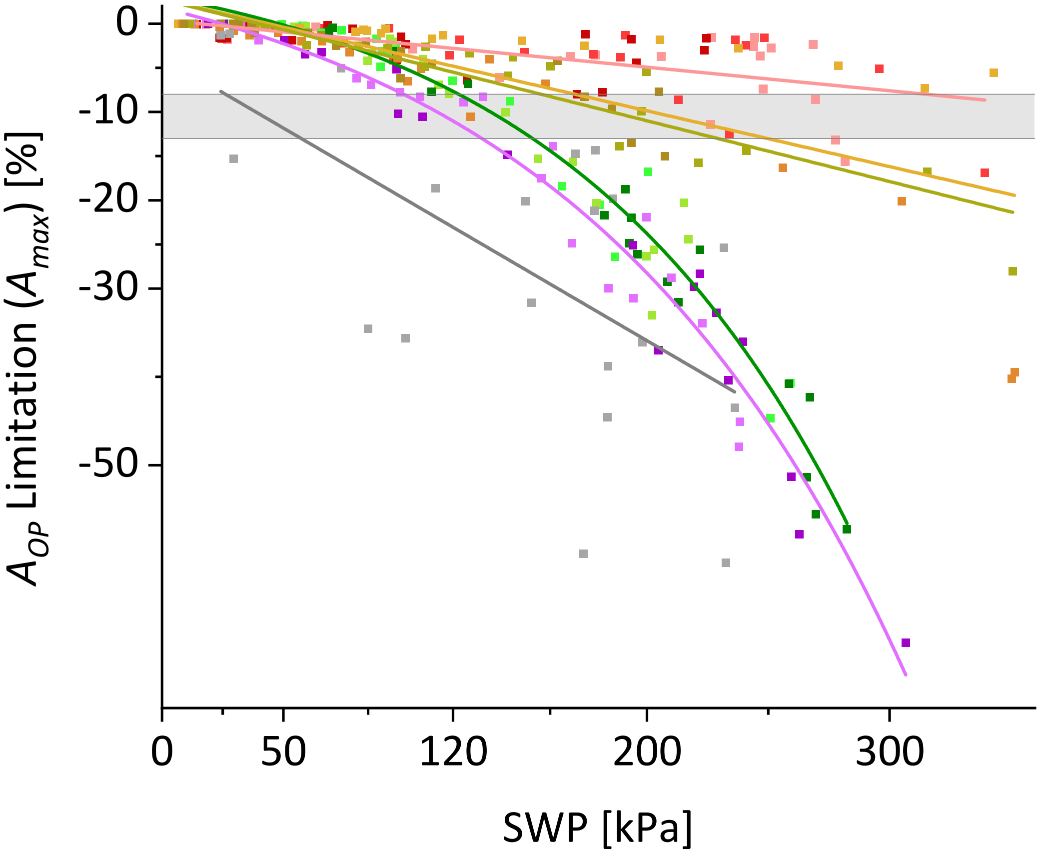

Figure 5.8: Relation of stomatal limited assimilation, displayed as negative percentages of A_{max}, to soil water potential. The regressions consist of linear and exponential functions. The grey shaded area indicates the threshold range derived from Figure 5.6.

5.5 Conclusion

Most tree species regulate their stomatal conductivities highly sensitive in response to soil water availability, however likely less dramatically depending on site characteristics (i.e. shading). We further suggest the water availability in specific soil compartments to be highly critical for the regulation of stomata and thus revealing indications about the efficiency of root zone exploration. The regulation range differs strongly between the species (wide regulation: *Qc*, *Qr*, *Aps*; narrow regulation: *Apl*, *Qp*,*Ps*). Temperature sensitivity of assimilation due to enzyme kinetics in interaction with regulative ranges of stomatal conductivity are highly relevant for trees with narrow regulation and low assimilation operation ranges, as these were limited in carbon assimilation due to stomatal regulation earlier and already at low temperatures. The assimilation of species that regulate their stomata strongly in combination with high assimilation is less sensitive to stomatal regulation also with increasing temperatures. Although this study is a first conceptual approach, the observations provide evidence against the generic assumption that broadly ranged stomatal regulation (i.e. isohydric reaction type) be coupled with higher incidences of stomatal limitation of assimilation.

We suggest the frequency of events with stomatal limited assimilation during the course of the growing season to be an indicator for individual stress incidences (% of reduced assimilation by stomatal limitation). Therefore, *Qp*, *Ps* and *Apl* are expected to have experienced by far more days stress by stomatal limitation of assimilation than *Qc*, *Qr* and *Aps*. Particularly $\delta^{13}C$, comparatively less complex to gather, has proven to approximate these stress incidences and thus might be an applicable parameter for future investigations at urban tree sites.

6 Conclusions, Practical Recommendations and Outlook

6.1 Conclusions drawn from research results

In this thesis, two differing experimental approaches were carried out to investigate the development of soil hydrological deficiencies in the root zone and its physiological and morphological effect on recently planted urban tree species: (i) a long-term *in situ* soil water monitoring in the urban environment and (ii) a large-scale experimental field study in a complete block design with different soil substrates, representative for young urban street tree sites, and commonly used urban street tree species.

Under *in situ* conditions at urban street sites, the dynamics of soil water availability were monitored in a six year period during tree establishment after planting. On this basis my specific attempt was to determine the extent of critical soil water availability, and further, to derive from those data a ranking of different meteorological, site and soil variables that reflects their predictive importance for critical soil water availability to occur. To specifically identify and assess physiological responses, adaptation strategies, and suitability of trees during critical periods of soil water availability, I extended monitoring with tree physiological and morphological measurements implemented in a photosynthesis modeling approach. Focusing specifically on soil hydrological properties of representative substrates of root zone compartments (i.e. planting pit and urban surrounding soil), I aimed to identify in the experimental field study if and to what extent different tree species are affected in growth and vitality when planted into these substrates. Therefore, the dynamic of soil water availability, development of tree growth and tree vitality were monitored over a three years record in comparison to a naturally loamy-silt reference soil.

In general, the site characteristics of urban trees identified and evaluated in this thesis mainly confirm the results of previous studies. Regarding investigated site- and soil parameters having a direct impact on the hydrological status of a tree site it can be concluded that:

(1) Urban street tree sites tend to comprise high contents of sandy textures due to past and present anthropogenic activities such as construction- and infrastructure work (Craul & Klein 1980; Craul 1985; Gilbertson & Bradshaw 1990; Greinert 2015). In this thesis, sandy textures were found to account on average for > 85 Vol. % in both, planting pit- and surrounding urban soils. This findings are in line with other investigations. In the city of Hamburg soils at vegetation-sites along roads (n = 62) composed to more than 80% of pure sands with simultaneously high percentages of rubble and coarse stones (“Stadtbodenkartierung Straßenbegleitgrün” (FHH 2012)). Furthermore, at 26 established urban street tree sites (6 actual tree sites, 20 felled tree sites) the soils contained on average 86 Vol. % sandy textures (Schaaf-Titel 2019; Thomsen et al. 2020). Comparatively high sand contents were also

found at other and diverse tree sites settings e.g. in Hongkong (Jim 1998; Jim & Ng 2018; Jim 2019b). Therefore, the selection of the two urban substrates for the experimental field study was representative ('Sand': 95% and 'FLL': 93% sand content, respectively). However, the intention was to reflect extreme conditions likely to occur in the artificially and densely build up urban area ('Sand') and to reflect a sand dominated but regarding the official recommendations i.e. FLL (2015) permitted structural soil substrate, originally intended to improve site soil conditions ('FFL'). Low plant available water holding capacities of sand-dominated soils and substrates is of common soil scientific knowledge (Blume et al. 2009) and additional gravel, stones or rubble results volumetrically, if these are non-porous, (Benk et al. 2020), also to lowered plant available water content. However, high sand and stone contents are so far required to meet common recommendations of street tree planting substrates (Bassuk et al. 2015; FLL 2015; ZTV-Vegtra-Mü 2016; Embrén et al. 2017). E.g. the FLL (2015) recommendation is based on minimum rather than maximum required amounts of sandy textures displayed in their substrate grading curves and the content of stone fraction (> 2mm) is also recommended to reach high percentages (FLL 2015; Embrén et al. 2017). Due to the macro pore structure created between the coarse sandy and stony particles, the determined plant available water holding capacities of the 'Sand' and 'FLL' substrate were reduced by -75% to -50%, respectively, compared to the 'Loamy-Silt' reference and are in its total amount in line with findings of (Grabosky et al. 2009). Furthermore, these predominantly sandy-textured planting soils were restricted in terms of hydraulic conductivity under soil drying conditions. The extent of limited unsaturated water conductivity (ku) of the different soil substrates was confirmed by lab experiments (Figure 4.1). However, this finding, is described in few forest and ecological studies and lectures rather than in association with trees at harsh urban sites (Hacke et al. 2000; Blume et al. 2009; Schulze et al. 2019; Abdalla et al. 2021). Nevertheless, it is likely a crucial limitation in terms of water supply with increasing urban infrastructure densification and climate change. Due to the increasing percentage of air-filled macro-pores, the pore space becomes on the small scale non-conductive for water transport and thus, the amount of water quantitatively available for the tree roots decreases locally rapidly although the total amount of water in the soil stagnates. Therefore I hypothesize that a sufficient adaptation of trees towards drought in the sand dominated urban belowground environment include, in addition to lower the root potential, also a strategy of bypassing soil non-conductivity by investments into a tightly branched fine root system.

(2) High percentages of the soil surfaces can be sealed within or around the crown projection area. The site characterization at the street tree sites shows that sealing (impervious or pavement) can occur within 25 m² around the tree stem in a wide range from 0 - 100 %. In a survey on established trees the sealed surface within a 20 x 20 m area around the tree accounted for 81% (Schaaf-Titel 2019). Such sealing degrees can significantly contribute to lowered growth rates due to decreased water supply

and oxygen content in the soil pore space (Weltecke & Gaertig 2012; Gaertig & Schönemann 2015; Sand et al. 2018; Johnson et al. 2019). By using the data-driven model approach (*randomForest* model; chapter 3), I was able to show that the parameter soil sealing was of medium importance for critical soil water availability conditions to occur. However, the study design of both experimental approaches was not designed to derive more detailed findings such as the influence of the type/permeability of sealing or to prove its impact on tree growth.

(3) The infiltration capacity of surface water can be significantly increased by the preparation of planting pits with structural soil substrates and unsealed surfaces compared to the prevailing surrounding soils. Infiltration measurements on the surfaces of planting pit substrates in the *in situ* approach as well as in the experimental field study revealed significantly higher capacities compared to the urban soil (*in situ* approach) (Ow & Ghosh 2017; Bretzel et al. 2020), caused most likely by compaction due to past construction works and foot- and car traffic. However, to solve the dilemma that higher sand contents lead to higher uncompacted infiltration capacities (proved by results of the experimental field study (Moll 2021)) and to less susceptibility towards over-compaction that simultaneously lowers infiltration capacities extremely (Lusk & Toor 2017), the open soil surfaces in general but at least in the tree crown projection areas have to be protected better to maintain high infiltration capacities also in improved substrates with reduced sand contents.

During the first two of four years of measurements at all 17 *in situ* soil water monitoring sites (2016 – 2019) the extent of critical soil water availability, based on a threshold value, found to be differently expressed in the investigated soil compartments. In the last two years, with extreme and also moderate meteorological conditions (2018 and 2019, respectively)) the critical soil water availability of SWP -1200 hPa lasted in all soil compartments for three to five months. Thereby, the water extraction from the highly sand dominated urban soils, indicated by the calculated drought intensity, was lower compared to the root ball (mainly composed of fertile nursery top soil horizons) and the planting pit (Figure 3.2). I suggest, that the water extraction was most likely diminished due to reasons of low hydraulic conductivities with decreasing soil water availability as given above. The site selection in the *in situ* approach aimed to represent a wide range of tree- and site characteristic variability. By adding these to the adapted *randomForest* model, their interacting processes responsible for a certain predictor variable i.e. status of soil water availability were incorporated and evaluated (Carranza et al. 2021). The plausible conclusions drawn from the analysis results demonstrated the capability of such data-driven methods to predict the occurrence of critical soil water availability with high accuracy. Although one might assume that the soil water availability at urban tree sites is less influenced by meteorological parameters than at natural sites, the model results proved meteorological variables to have high predictive importance for the status of soil water availability. In particular, the specific results indicate the importance of precipitation in general and the accumulation of succeeding summertime precipitation events, which are projected to decrease in frequency with climate change (Schlünzen et al. 2010; Meinke et al. 2018). Furthermore, it can be suggested that the effect of increasing soil water availability in response to single, sufficient precipitation to be still delayed due to limited amount of unsealed soil surfaces available for infiltration and in general low infiltration capacities of the soils. In turn, the latter were also as single input parameters confirmed to be of medium importance. A similar pattern was found for the irregular application of irrigation at some sites during the monitoring. While an improved site design might increase the accessibility of the soil also for short-term precipitation, long-term irrigation strategies covering a greater soil surface could likely have a more lasting effect on reducing the SWP in the whole root zone sufficiently instead of only in the root ball. In accordance, differences in the extent and development of critical soil water availability between the sites indicated the interactive importance of other, site and tree related parameters and characteristics. The measurements in the first two years after planting revealed the trees being mainly determinant for the reductions soil water availability in the planting pit and in the urban soil and thus may control the degree soil water remaining in the soil. With the soil water measurements in the experimental field study I was able to reproduce this finding, as only from the second year on a sufficient decrease of the soil water availability in the respective substrates and soils was evident. The described pattern was most likely suitable to generate information about the ability of developing freshly grown roots i.e. it is likely that reductions of soil water availability indicate the presence of water consuming tree roots. Therefore I suggest roots of the recently planted trees of both experimental approaches to have fully penetrated the planting pits during the first two to three growing seasons after planting. Different than expected, the roots of the trees in the *in situ* approach also expanded into the urban soil, which was also reflected by decreasing soil water availability in this soil compartment later on. The measurements of the stomatal conductivity and the subsequent correlations with the SWP data divided among the soil compartments (by utilizing R^2 as quality criterion) even enabled a species specific suggestion about the soil compartment mainly utilized for water supply (Table 5.2). Interestingly, *Quercus cerris*, *Quercus robur* and *Acer pseudoplatanus*, the species with highest measured values of stomatal conductance (Figure 6.1), mainly utilized soil water in the root ball (*Quercus robur*) and in the planting pits at their respective sites, whereas the other tree species i.e. *Quercus palustris*, *Prunus serrulata* and *Acer platanoides* utilized soil water in the total soil volume including all soil compartments. For the *randomForest* model input parameter tree age, which was of very high importance it can be suggested that the high predictive importance results of both: (1) site establishment by root zone development, as revealed by the annually stepwise increase of critical soil water availability (root ball > planting pit > urban soil) and (2) the increasing amount of aboveground biomass (i.e. leaf area index), revealed by the annually increasing drought intensity. Taken together, the aging of the recently planted trees simultaneously increases the access to water and the demand for water and thus influences the availability of soil water strongly. The identification of the higher importance of soil temperature than air temperature based on the model results suggests soil temperature serving as an index variable for tree sites susceptibility for soil drought, as it integrates site-specific characteristics affecting water- and energy balance (e.g. the degree and type of soil sealing, the presence or absence of herbaceous soil covering vegetation and the degree of shading through tree canopies or buildings). Soil properties like soil texture were only of medium predictive importance. However, the advantage of measuring SWP instead of VWC was that SWP can be applied to estimate soil water availability independent of soil properties and was therefore expectable. Furthermore, different to the experimental field study in the nursery revealing the importance of textural differences for the water supply and growth of trees separated between substrates, the soil compartments planting pit and urban soil at all sites of the *in situ* were composed mainly by sandy soil textures with low variability and thus represented only a narrow range of data. The applicate model was able to verify the main determinants of soil water dynamics and can potentially be applied to predict soil water availability in uncontrolled experimental setups and heterogeneous environments such as cities. Based solely on the investigations of soil water availability measurements it can be concluded, that periods of long lasting critical soil water availability, according to the threshold value applied, increases the probability of lasting growth- and vitality losses and likely endangers the development of young street-trees to mature trees.

To verify if and how the measured extent of critical soil water availability increases water stress for the investigated tree species at their respective sites in fact, supplementary tree physiological measurements were conducted. I revealed that most of the investigated tree species regulate their stomatal conductivities highly sensitive in response to soil water availability, however, likely less dramatically depending on site characteristics (i.e. shading). Thereby, the regulation range differs strongly between the species (wide regulation: for *Quercus cerris*, *Quercus robur* and *Acer pseudoplatanus* and narrow regulation for: *Quercus palustris*, *Acer platanoides* and *Prunus serrulata*). Temperature sensitivity of assimilation due to enzyme kinetics in interaction with regulative ranges of stomatal conductivity are highly relevant for trees with narrow regulation and low assimilation operation ranges, as these were limited in carbon assimilation due to stomatal regulation earlier and already at low temperatures. The assimilation of species that regulate their stomata on a wide range in combination with high assimilation operation range is less sensitive to stomatal regulation also with increasing temperatures. The observations provide evidence against the generic assumption that broadly ranged stomatal regulation (i.e. isohydric reaction type) be coupled with higher incidences of stomatal limitation of assimilation. It can be hypothesized that the frequency of events with stomatal limited assimilation during the course of the growing season can act as an indicator for individual stress incidences (% of reduced assimilation by stomatal limitation). Therefore, *Quercus palustris*, *Prunus* *serrulata* and *Acer platanoides* are expected to have experienced by far more days stress by stomatal limitation of assimilation than *Quercus cerris*, *Quercus robur* and *Acer psuedoplatanus*. Although this study is a first conceptual approach, particularly $\delta^{13}C$ has proven to approximate these stress incidences and thus might be an applicable parameter for future investigations at urban tree sites as it is comparatively less complex to obtain. Tree growth on the other hand represented the modeled annual mean A_{OP}. However, to derive further conclusions about inter- and intraspecific variations of water stress reactions regarding different site hydrological characteristics such as soil textural composition, a characterization was derived from growth and tree vitality measurements of different tree species in the standardized experimental field study.

In general, tree growth of almost all species was significantly constrained on the artificial urban soils 'Sand' and 'FLL'. The average growth of the two similar tree species *Quercus cerris* (highest) and *Quercus palustris* (lowest) was in line with the findings of the *in situ* approach. Compared to the growth in the reference 'Loamy-Silt' soil, growth of *Quercus palustris* was strongly restricted in both urban representative soils. Significant differences in growth occurred for *Tilia cordata* 'Greenspire' and *Quercus palustris* between all three planting soils. *Quercus cerris*, *Carpinus betulus* 'Lucas' and *Gleditsia triacanthos* 'Skyline' showed no differences between the urban representatives but significantly less growth compared to the reference. Amazingly, *Ostrya carpinifolia*, *Liquidambar styraciflua* and *Amelanchier lamarckii* did not differ in growth between the 'FLL' and the 'Loamy-Silt', however strong restrictions were apparent in 'Sand'. No differences between all planting soils were only observed for *Koelreuteria paniculata*. Thus, with a few exceptions, the selected artificial planting soils were sufficient to survive, however, most likely they did not encourage the trees to sufficiently build up above ground biomass and to increase the assimilation of carbohydrate reserves, or to provide effective ecosystem services in the long term. To successfully grow and thrive in artificial urban sandy soils and soil substrates, trees that invest more in the fine root system to bypass soil non-conductivity (e.g., *Tilia cordata* 'Greenspire' and *Liquidambar styraciflua*) might be more suitable than trees that are able to lower their root water potential to very negative values, which might be successful in fine-textured drying soils (e.g., *Koelreuteria paniculata, Quercus cerris*; (Sjöman et al. 2018)).

6.2 General conclusion and practical implications

Research on urban green in general and on the vitality, lifespan, soil conditions, hydrology and management strategies of urban trees started already decades ago (Farkas et al. 2023). Before and at the same time that climate change has been scientifically proved, scientists observed the ongoing urbanization to affect tree performance as a consequence of e.g. artificial soil properties and soil treatment, particle composition, soil compaction, lowered pore space, suppressed gas diffusion, soil sealing, pollutants and the supply with soil water (e.g. Patterson 1977; Craul & Klein 1980; Craul 1985;

Leh 1989; Clark & Kjelgren 1990; Gilbertson & Bradshaw 1990). Despite of still valid findings, research on urban green has significantly increased only during the last decade. As the trend to further densify urban infrastructure at cost of former urban green spaces prevails (Schetke et al. 2016), peoples demand for healthy and livable urban environment has increased simultaneously. Yet, pressure to the urban green is caused by both, ongoing urbanization and climate change (i.e. lack of urban green spaces in quality and quantity, limited accessibility of urban green spaces, increasing heat island, air pollution, climate extremes. As indicated by a keyword network map provided by Farkas et al. 2023). However, keywords defined in the three manuscripts of this study such as street trees, tree planting, drought, tree growth, urban soils, climate change were in this keyword network map still more or less comparatively underrepresented in actual research on urban green (Farkas et al. 2023). Therefore, the findings of this study will increase the awareness about the fundamentals for a successful and sufficient development of the yet to be planted street tree population.

To derive small scale data of soil water availability on individual tree level, sensor based measurements, as provided in this thesis, are of high resolution and applicability. Other sources to approximate or calculate information about soil water supply were remote sensing data on soil moisture (Liu et al. 2023) and drought indices derived from meteorological data (Vicente-Serrano et al. 2010; Paton et al. 2021). Those data were, when detailed data of the past were lacking, suitable to compare and classify long-term data of e.g. dendrochronological studies e.g. Moser et al. (2017). However, particularly for the urban environment, those data were lacking in small-scale resolution regarding heterogeneous site conditions and characteristics. A further, yet not widely used method to predict the water supply and to calculate the evapotranspirational potential of trees in the urban environment, is the application of Hydro-Pedo-Transfer-Functions parametrized from a set of site-, soil- and meteorological data (Wessolek & Kluge 2021). As this newly developed tool has to be further adapted and evaluated regarding representability of small scale varying urban soil conditions (Wiesner et al. 2016) and interregional applicability, data on soil water availability under *in situ* conditions as measured and processed in this thesis could be used to further calibrate those predictions. Yet, a variety of companies offer complex services including sensor installation, soil water monitoring and irrigation recommendations. However, the determination of soil water availability of single tree sites is primarily suitable to determine the actual state of soil water availability. Shortcomings in general tree site design affecting tree's water supply and causing regular irrigation needs can result in a significant staffing effort that is not feasible with public funding. Therefore, such high resolution data of soil water availability as obtained in this thesis should additionally be used to identify variables that affect water availability at tree sites. In this thesis, the data-based *randomForest* model was successfully adapted to conditions of and at young urban street tree sites. With increasing amount of response data, supplemented with further predictor variables such as high-resolution tree physiological data (e.g. dendometer measurements or sap flow), and a more detailed analysis on influencing parameters such as irrigation schemes, soil water availability could be predicted also for non-instrumented sites in the future. A further promising tool to model the water balance of recently planted urban trees was presented by Schreiner et al. (2022). Contrary to the approach used in this study, those authors applied a water balance model (AMBAV; (DWD 2022)) from the agricultural sector validated by various sensor based measurements regarding soil water availability and tree physiology. The validation of modeling results at *in situ* urban tree sites in the City of Berlin showed, that estimations on soil water status and thus irrigation recommendations were plausible for recently planted trees in defined soil substrates and similar site characteristics. However, next to the validity of those modellings results and results of this thesis for aging and established urban trees, a further challenge in data handling will be the integration of water logging as a consequence of heavy precipitation events during more frequent summer storms. Decreasing oxygen supply can lower growth and vitality of trees sufficiently, which is highly correlated by top-soil gas diffusivity (Weltecke & Gaertig 2012). Independently of the degree of soil sealing or extreme precipitation events, soil oxygen concentrations below a critical threshold value (e.g. 10% (Blume et al. 2009)) could so far not be detected by soil aeration investigations at selected sites within the *in situ* monitoring (Lisitano 2021). However at sites with densely packed water-bound covers and at sites with freshly mixed and backfilled structural soil substrates, the soil oxygen concentration tended to be impaired critically.

Despite of long lasting critical soil water availability (up to 5 months per year), the tree species investigated under *in situ* conditions in this study showed distinct variation in tree growth and carbon assimilation. Due to the experimental study design of the *in situ* monitoring, distinguishing between the adaptability of respective tree species and the impact of respective site characteristics as reason for these variations was not possible. However, to maintain or even increase the tree species and genetic diversity within the urban tree population, which ensures e.g. a diverse wildlife and insect habitat, a continuous pollen supply and a resilience against disease and pests, tree sites should be planned, prepared and managed to be suitable for any tree species within the limits of the future urban climate. Therefore, based particularly on the results of the large-scale experimental field study with different urban soil substrates, I recommend to improve the tree site soil conditions and -dimensions to improve the water storage capacity and the total amount of water storage. Compared to the plant available water content of the reference soil (‘Loamy-Silt’), the urban soil substrates ‘Sand’ and ‘FLL’ had plant available water contents of -75% and -50%, respectively. Taking the advantage of sufficient air capacity of the urban soils into account, which was accordingly lower in the reference soil and caused most likely a post-flooding vitality decline of *Quercus cerris* and *Koelreuteria paniculata*, tree growth and tree vitality were on average still significantly restricted. Though, the coarse particle size of the urban soils resulted in addition to the sufficient air capacity to significantly higher infiltration rates, enabling a fast and deep water resupply after precipitation events, and to a very low unsaturated conductivity, restricting water loss from evaporation (Moll 2021). However, during the vegetation period, when the water consumption of the tree roots increased, very low unsaturated conductivity becomes a constraint, as it restricts lateral water resupply from moist, non-rooted soil areas (Hacke et al. 2000; McDowell et al. 2008). Differences in the aboveground tree growth and -vitality indicate, that the tree species followed contrasting strategies to cope with the restricted water resupply, which was also proved for the fine- and coarse root development within 'Sand' compared to uniform growth in 'Loamy-Silt' (Ocker 2022; Musal 2022). As the addition of a certain proportion of skeletal fractions > 10 mm is necessary to provide structural stability of planting pit soil substrates, it can therefore be recommended to generally increase the share of medium to fine pores in the fine soil fraction by decreasing the share coarse sand and gravel (1 mm – 10 mm) in the grading curves provided by the FLL (2015) and other recommendations (Bassuk et al. 2015; Embrén et al. 2017). In order to guarantee environmental compatibility, regionally sourced or produced components should be identified, sourced and used as a priority.

Currently investigated substrates additives with promising properties were wood chips and compost (Scharenbroch & Watson 2014; Somerville et al. 2019), as well as regional harvested porous bricks from demolitions (Nehls et al. 2013; Bauer et al. 2023) and biochar (Abel et al. 2013; Lo Piccolo et al. 2022). Despite of structural-components (up to 35%) that prevent over compaction and thus sufficient gas exchange- and infiltration capacity of the soil material, improved soil substrates, that have to be further developed based on findings of this thesis and other studies e.g. (Loh et al. 2003; Riikonen et al. 2011; Pregitzer et al. 2016; Yilmaz et al. 2018; Bretzel et al. 2020; Bauer et al. 2023) have to permit sufficient water supply and capillary water transport during hot and dry summers, e.g. 2018, 2019 and 2020 in northern Europe. To evaluate the hydrological quality of improved substrates prior to backfilling appropriately, manufacturers should be committed in future to provide the plant-available water capacity (pore space of medium to fine pores) instead of the maximum water holding capacity (total pore space) as actually recommended by FLL (2015) recommendations. Furthermore, to increase the availability of soil water in the root zone on the long-term, the recommended planting pit dimensions (12 m^3 (FLL 2015)) should at least be strictly adhered or even extended. However, at the investigated tree sites in the *in situ* approach, soil material of the surrounding urban soil was during sampling detected to be consistently bordering close by the trunks of the respective trees (Figure 3.1). Thus one might hypothesize that planting pits of not newly build up sites e.g. re-planting after felling, are likely to be under dimensioned. As recently planted trees are able to develop available root space (in this study 7,5 m^3) already within two years (Musal 2022), growth depressions or reduced vitality might consequently be likely the earlier the tree roots reach the surrounding urban soil. To minimize these risks, the FLL (2015) specifications regarding the recommended planting pit design are already more and more implemented in the practice. The city of Munich is currently even aiming to plant new trees exclusively in planting pits of even 36 m³ and to fill them with defined municipal planting pit substrates (oral communication from Peter Schlinsog (Baureferat Gartenbau München), 2022).

Following planting, I identified for nine tree species reaction patterns in terms of above- and belowground growth and vitality within a three year study period, respective to each of the three planting soils. Contrary to studies of Stratópoulos et al. (2019a); Stratópoulos et al. (2019b); Zhang et al. (2020), where drought was created artificially by preventing water infiltration using rain-out-shelters on loamy soils (focusing on temporary drought), the trees at the experimental site were exposed to permanent water limiting conditions without rain exclusion by using sandy textured substrates representative for urban roadside conditions. Depending on the study design, one can identify tree species advanced to deeply lower their root water potential (Sjöman et al. 2018) or tree species advanced to escape dry spots by growing deep and widely branched roots (Hacke et al. 2000). Amazingly, all individuals of the nine tree species planted in the urban soil substrates with low unsaturated hydraulic conductivity, survived throughout at least three growing seasons and thus coped with different strategies against limited amount and availability of soil water. From the investigated tree species, *Quercus palustris* and *Amelanchier lamarkii* were most severely restricted in growth and vitality, whereby the latter failed to spread its roots successfully into the planting pit (Ocker 2022; Musal 2022). For planting those tree species in the dense urban environment or along roads it can be particularly recommend to prepare the designated sites with ameliorated soil substrates in sufficient dimensions (Table 6.1) which is in case of *Quercus palustris* in line with recommendations of the GALK (https://strassenbaumliste.galk.de/sblistepdf.php). Although *Koelreuteria paniculata* was vigorous growing in both ‘Sand’ and ‘FLL’ substrate, the vitality and the appearance were on average lowest of all species on these substrates. Furthermore, the vitality of *Koelreuteria paniculata* was by far lowest of all species in the reference soil, which is likely be related to a general sensitivity towards limited oxygen supply (citree 2015) and was amplified by an unplanned flooding of the experimental site in 2020. In case of vitality, a similar tendency was found for *Quercus cerris* (citree 2015). Planting of *Koelreuteria paniculata* and *Quercus cerris* at sites which highly tend to compose of stagnant soil water, high soil sealing degrees or compact and fine porous surrounding soils, can therefore not being recommended and is not yet included in the recommendations of the GALK (Deutsche Gartenamtsleiterkonferenz e.V.). Despite of the flooding event at the experimental study site, the remaining tree species were very vital, which further improved by 2021 with overall best ratings for *Tilia cordata* ‘Greenspire’, *Liquidambar styraciflua, Carpinus betulus* ‘Lucas’ and *Quercus cerris*. In terms of growth, *Tilia cordata* ‘Greenspire’ and *Ostrya carpinifolia* were least impaired by the urban substrates ‘Sand’ and ‘FLL’.

Table 6.1: Summary and interpretations of the growth and vitality data of the nine tree species investigated during the establishment phase (up to 3 years after planting) in three planting soil substrates: 'Sand', 'FLL' and 'Loamy Silt'.

Species	**Growth-Response**	**Vitality**	**Recommendation**
Quercus cerris	Highest stem growth overall, responds to substrates in 'Loamy-Silt' significantly stronger than in 'FLL' and 'Sand' but comparatively less restricted in the latter.	Average in 'Sand and 'FLL', below average in 'Loamy-Silt' in the second year.	Suitable, adaptable to sandy conditions, likely sensitive to stagnant water and oxygen deficiency.
Quercus palustris	Responds strongly to substrates, strong growth in 'Loamy-Silt', restricted in 'Sand' and 'FLL'. Across all species strongest restricted in 'Sand'.	Average to high vitality in 'Loamy-Silt' and 'FLL', very weakened with chlorosis and light green leaves in 'Sand'.	Demanding on the substrate and its water availability, low suitability for sandy sites.
Carpinus betulus ‚Lucas‘	Responds to substrates, higher growth in 'Loamy-Silt' than in 'Sand' and 'FLL' and comparatively stronger restricted in both. Medium-residual growth in all planting soils.	Within species vitality graded according to substrates. Between species comparatively high vitality in 'FLL' and 'Sand'.	Suitable, stronger in growth with increasing substrate quality in terms of water supply.
Ostrya carpinifolia	Reacts particularly to 'Sand' substrate, strongly restricted growth in 'Sand'. Almost no restrictions in 'FLL'.	Within species vitality graded according to substrate quality. Reduced vitality in 'Sand' compared to other species.	Overall suitable, weaker in growth and vitality at sandy sites
Tilia cordata ‚Greensp.‘	Responds to substrates, however, comparatively strongest and less restricted growth in 'Sand' and 'FLL'.	Highest vitality in 'Sand' and 'FLL'.	Overall suitable
Liquidambar. styraciflua	Responds with restrictions on 'Sand'. Least restricted on 'FLL' and overall lowest growth of all species.	Compared to strong growth restrictions, very high vitality in 'Sand'.	Suitable. Despite of lowest growth high vitality particularly at sandy sites.
Gleditsia triacanthos ‚Skyline‘	Responds to substrates. Overall average growth rates. In clay stronger growth than in 'Sand'. Striking is the overall comparatively higher invest in crown growth.	Vitality improves with the years, in the third year vitality in all substrates above average.	Suitable. Harmless in sandy locations.
Koelreuteria paniculata	Hardly reacts to substrates in the test. Thus, comparatively high growth in 'Sand', medium in 'FLL' and low in 'Loamy-Silt'.	Weakened in all soils, especially in loam, lowest vitality scores compared to the other species.	Limited suitability independent of site soil conditions and high sensitivity to stagnant water or oxygen deficiency.
Amelanchier lamarckii	Responds to substrates. Strong restrictions in 'Sand', no restrictions in 'FLL'. Lowest growth rate in 'Sand' compared to other tree species.	High vitality score in 'FLL' and 'Loamy-Silt', in sand extremely weakened.	Suitable in ameliorated sandy substrates such as 'FLL'. Sufficient provision of structural soil regarding dimension of planting pit is recommended.

At tree sites that were restricted in topsoil or bottom-soil dimensions, tree species should be individually selected according to their specific adaptations of root system architecture towards soil substrate supplied. At sites with near-surface vertical restrictions (Figure 6.2a), *Quercus cerris* can be suggested to be suitable from the set of tree species we investigated, as it develops in 'Sand' deep reaching roots originating from the root ball. At sites with belowground restrictions (Figure 6.2b), *Tilia cordata* 'Greenspire' is expected to suit to such conditions (Ocker 2022; Musal 2022), as long as horizontal root spreading is ensured.

Taken together, in addition to protecting and preserving mature, established trees (Thomsen et al. 2020), the results of this study clearly indicate the need of improving soil conditions at yet to be planted trees to increase their resilience and longevity towards climate extremes in an even denser urban environment than their predecessors faced. The findings and conclusions of this thesis contribute therefore mainly to the understanding of the fundamentals required for successful establishment of recently planted trees in urban areas. As a result, a knowledge-based, individual selection of tree species depending on soil properties and root zone dimension needs to be the future objective in the practice and however also in science, as it represents the basis for an effective urban tree management that promotes the resilience and longevity of trees in an increasingly densely populated urban environment, especially in the face of climate change and extreme weather events.

6.3 Outlook

In addition to the important findings by studying the water availability in the root zone of various urban tree species, this study has raised important questions to be addressed and methodological adaptations to be implemented in future research. Considering the potential longevity of trees, the value of long-term studies and surveys were highlighted to be of outstanding importance, particularly, when the study area is a heterogeneous urban environment. Additionally, under the aspect of strongly varying meteorological conditions during the monitoring period (e.g. 900 mm and 527 mm annual precipitation in 2017 and 2018, respectively), the investigation of trees with different planting years proved to be of great value. To answer until when tree development and vitality is dependent on the soil water availability in the initially investigated soil volume and how soil water depletion differs between vigorous and non-vigorous trees in the future and whether potential tree mortality can be predicted empirical, data comparable to the herein obtained, should continuously collected in future. To gain further insights into the impact of site characteristics i.e. the sealing degree, soil characteristics as structural soil type and planting pit dimension on the soil water availability and the establishment of young urban street trees, *in situ* study sites should be planned within long-term projects, to ensure the compliance of the complex scientific design to be integrated in urban planning. By integrating those sites, the practicability of the developed data-driven statistical model can be tested and further improved to more accurately determine the impact of site- and tree-specific predictor variables on the dynamic of soil water availability. To do so, the accuracy, resilience and the optimal installation conditions of the used low-cost SWP point measurement sensors (Watermark) in coarse porous and stony substrates (low unsaturated conductivity) must be further evaluated, to prevent within site heterogeneity of data.

The large-scale experimental field study in a complete block design offered an important opportunity to investigate the interaction of soil physical- and hydrological properties with different preselected tree species, to characterize their growth behavior and, emerging from this, to evaluate their suitability to thrive under soil conditions representative for the urban environment. As each tree species was thus three years exposed to three different soil water availabilities, one might expect the species developing individual strategies to overcome limitations of soil water availability and thus increase in drought tolerance (Dreßler 2019; Roloff 2021b) respectively a tolerance to cope with coarse porous soil conditions in the long run. To determine the practical benefits of preconditioning and to address the feasibility of its implementation in nursery production, the trees of the experimental field study should be uniformly planted along a typical urban roadside. A long-term monitoring to record site establishment, growth and vigor should be conducted as part of a follow-up study. Further, the unique nursery experimental study design should be continuously used to evaluate the suitability of other promising tree species and cultivars that are not in the focus yet.

Another promising concept to reproduce tolerant and drought adapted tree species is to acknowledge possible genetic variations and -adaptations within one species, which in fact means the selection of propagation material (i.e. seeds and scions) from particular provenances (Hannus et al. 2021). Thereby, the selection of provenances that combine drought, naturally coarse porous and low organic soils (Weigel et al. 2023) could provide suitable sources for growing urban trees. As knowledge on the general practicability is scarce, the urban forestry industry has not embraced the differentiation between properties of the same tree species of different ecotypes (Hannus et al. 2021) and the integration of different soil types has not yet received attention, future research should point in that direction.

At least, future surveys on the availability functional of soil substrates that combine soil water- and oxygen availability, structure stability and regionality of the component sources are necessary. To generate an overview on the state of the art, these soil substrates should be investigated regarding plant available water content under varying compaction rates, unsaturated conductivity, and degradability of organic components and production of CO_2. Thereafter, the soil substrates should tried to be optimized by the integration of innovative and regional available additives such as biochar or fine porous crushed bricks.

As climate change in northern Europe will intensify summer droughts and the occurrence of extreme precipitation events, the great value of applying and protecting sufficient amounts of soil mixed according to create a well-balanced water- and air content ratio can provide a vigorous and fast development of recently planted urban trees. Given the importance of the ecosystem functions provided by well-established, mature trees to human well-being (Salmond et al. 2016; Marselle et al. 2020), it is vital to ensure that the fundamentals of appropriate tree site design and its protection, based on the findings and recommendations of this thesis and future studies, can be translated into practice through an adequate financial budget, and a strongly encouraged research and staff training.

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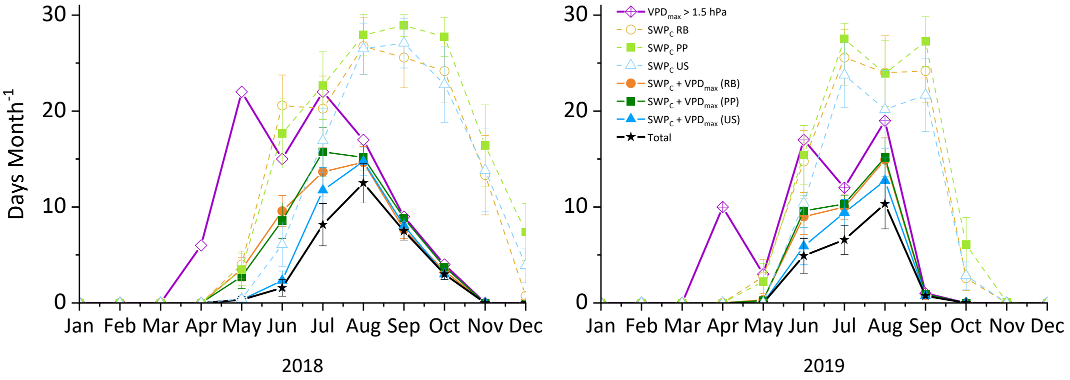
List of Figures

List of Tables

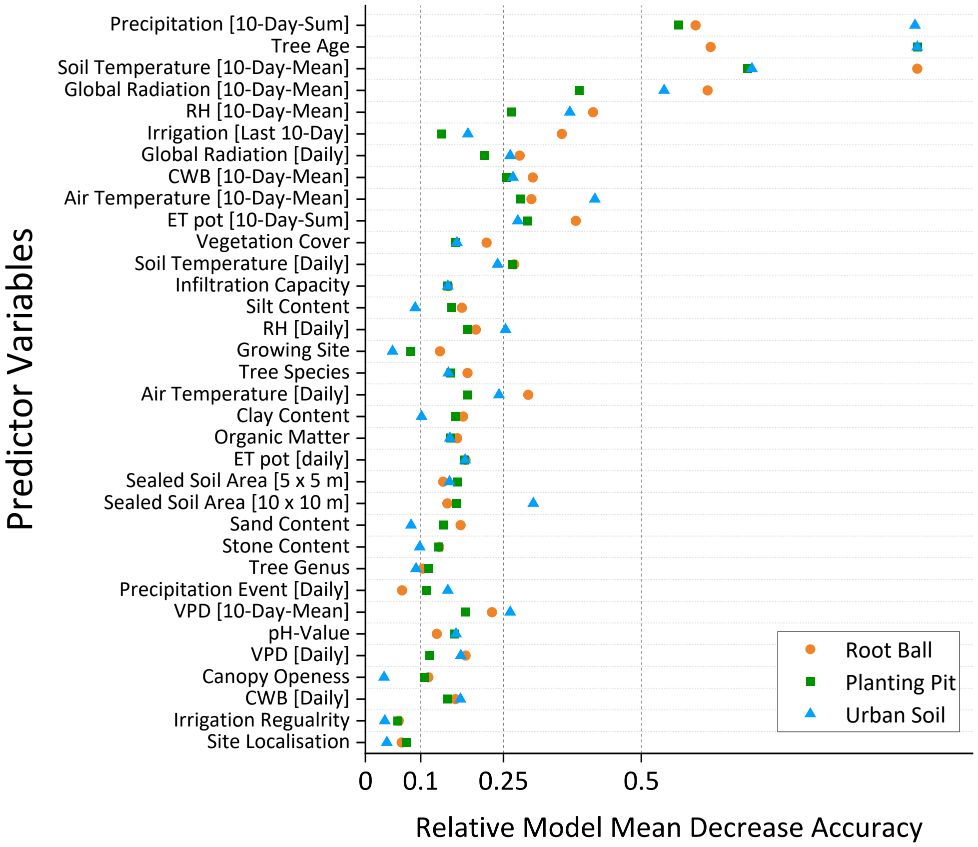
Appendix

Appendix Table 3.1: Table of the three response- and 50 predictor variables used for the *randomForest* approach.

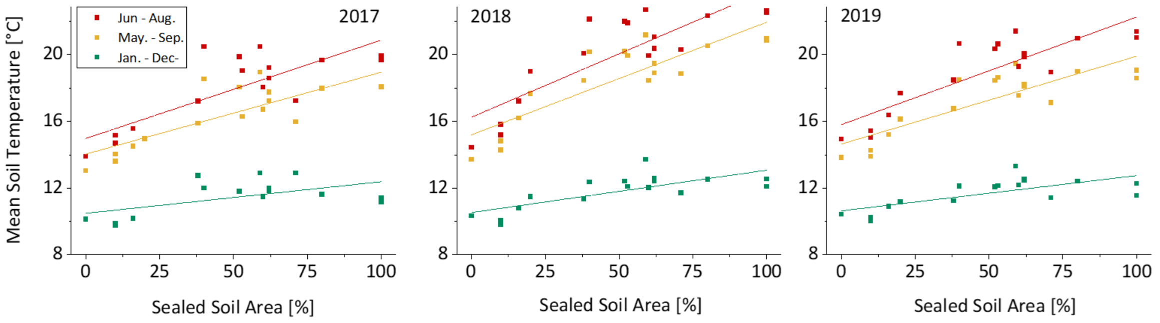
Variables	Unit			No.	Definition in Model	Data Source	Y1 2016- 2019	n=3 Y2 2016- 2019	n=3 Y3 2016- 2019	n=3 Y4 2016- 2019	Y5 2017- 2019	Y6 2017- 2019	Y7 2017- 2019	Y8 2017- 2019	Y9 2017- 2019	Y10 2017- 2019	Y11 2018 - 2019
Response Variables																	
Soil water availability																	
Drought Day Occurence		> 1200 hPa	Root Ball	1	Daily Dynamic Category	SWT Monitoring											
Drought Day Occurence		> 1200 hPa	Planting Pit	2	Daily Dynamic Category	SWT Monitoring											
Drought Day Occurence		> 1200 hPa	Urban Soil	3	Daily Dynamic Category	SWT Monitoring											
Predictor Variables																	
Meteorological Variables																	
Precipitation	mm		Event Sum	1	Daily Dynamic Integer	HUSCO Meteo											
	mm/d		Intensity	2	Daily Dynamic Integer	HUSCO Meteo											
	mm		10-day Sum	3	Daily Dynamic Integer	HUSCO Meteo											
Climatic Water Balance	mm		Daily Sum	4	Daily Dynamic Integer	HUSCO Meteo											
	mm		10-day Sum	5	Daily Dynamic Integer	HUSCO Meteo											
Air Temperature	°C		Daily-Mean	6	Daily Dynamic Integer	HUSCO Meteo											
	°C		10 day-Mean	7	Daily Dynamic Integer	HUSCO Meteo											
VPD	kPa		Daily-Mean	8	Daily Dynamic Integer	HUSCO Meteo											
	kPa		10 Day-Mean	9	Daily Dynamic Integer	HUSCO Meteo											
Pot. Evaporation	mm/d		Daily-Mean	10	Daily Dynamic Integer	HUSCO Meteo											
	mm/d		10 Day-Mean	11	Daily Dynamic Integer	HUSCO Meteo											
Global Radiation	W/m²		Daily-Mean	12	Daily Dynamic Integer	HUSCO Meteo											
	W/m²		10 Day-Mean	13	Daily Dynamic Integer	HUSCO Meteo											
Relative Humidity	%		Daily-Mean	14	Daily Dynamic Integer	HUSCO Meteo											
	%		10 Day-Mean	15	Daily Dynamic Integer	HUSCO Meteo											
Vapor Pressure Deficit	kPa		Daily-Mean	16	Daily Dynamic Integer	HUSCO Meteo											
	kPa		10 Day-Mean	17	Daily Dynamic Integer	HUSCO Meteo											
Site characterisitcs																	
Soil Temperature	°C	Depth specific	Daily-Mean	18	Daily Dynamic Integer	SWT Monitoring											
	°C	Depth specific	10 Day-Mean	19	Daily Dynamic Integer	SWT Monitoring											
Sealed Surface Area	%	5 x 5 m Grid		20	Static Integer	Own Survey	*16,00*	*61,67*	*61,33*	*6,67*	*59,00*	*40,00*	*100,00*	*100,00*	*71,00*	*38,00*	*20,00*
	%	10 x 10 m Grid		21	Static Integer	Own Survey	*41,25*	*77,25*	*59,83*	*12,50*	*80,75*	*71,00*	*100,00*	*100,00*	*92,75*	*74,50*	*44,75*
Soil Properties																	
Planting Pit and used for Root Ball	%	Sand	Depth Weighted	21a	Static Integer	Mixed Sample Soil Analysis	*87,90*	*83,17*	*86,87*	*83,20*	*92,00*	*87,70*	*82,20*	*82,20*	*77,20*	*84,30*	*NaN*
	%	Silt	Depth Weighted	22a	Static Integer	Mixed Sample Soil Analysis	*5,40*	*10,53*	*7,70*	*11,23*	*4,90*	*7,30*	*13,50*	*14,10*	*11,70*	*9,00*	*NaN*
	%	Clay	Depth Weighted	23a	Static Integer	Mixed Sample Soil Analysis	*6,70*	*6,30*	*5,47*	*5,57*	*3,10*	*5,00*	*4,20*	*3,60*	*11,10*	*6,70*	*NaN*
		pH	Depth Weighted	24a	Static Integer	Mixed Sample Soil Analysis	*6,60*	*6,70*	*6,60*	*5,90*	*6,71*	*6,90*	*7,20*	*7,20*	*6,40*	*6,80*	*NaN*
	%	Carbon Content	Depth Weighted	25a	Static Integer	Mixed Sample Soil Analysis	*4,10*	*7,63*	*5,47*	*1,63*	*1,30*	*4,44*	*1,90*	*2,30*	*9,57*	*4,03*	*0,83*
	%	Stone Content	Depth Weighted	26a	Static Integer	Mixed Sample Soil Analysis	*52,80*	*35,07*	*32,20*	*9,10*	*12,30*	*29,40*	*56,40*	*43,20*	*36,00*	*29,40*	*48,00*
Urban Soil	%	Sand	Depth Weighted	21b	Static Integer	Mixed Sample Soil Analysis	*1,00*	*2,00*	*2,00*	*4,00*	*4,00*	*2,00*	*3,00*	*3,00*	*2,00*	*2,00*	*NaN*
	%	Silt	Depth Weighted	22b	Static Integer	Mixed Sample Soil Analysis	*73,80*	*81,10*	*87,20*	*86,73*	*93,20*	*97,00*	*82,20*	*82,20*	*87,60*	*90,50*	*84,20*
	%	Clay	Depth Weighted	23b	Static Integer	Mixed Sample Soil Analysis	*13,90*	*11,30*	*8,47*	*9,00*	*4,90*	*1,50*	*13,50*	*14,10*	*9,40*	*5,80*	*9,30*
		pH	Depth Weighted	24b	Static Integer	Mixed Sample Soil Analysis	*12,20*	*7,60*	*4,33*	*4,27*	*1,90*	*1,50*	*4,20*	*3,60*	*3,00*	*3,70*	*6,40*
	%	Carbon Content	Depth Weighted	25b	Static Integer	Mixed Sample Soil Analysis	*6,90*	*6,43*	*6,23*	*5,73*	*7,29*	*6,80*	*7,20*	*7,20*	*6,40*	*7,10*	*7,30*
	%	Stone Content	Depth Weighted	26b	Static Integer	Mixed Sample Soil Analysis	*1,80*	*1,50*	*2,33*	*0,93*	*0,62*	*0,30*	*1,90*	*2,30*	*1,20*	*0,80*	*0,00*
Vegetation Cover		2 Levels		27	Annual Dynamic Category	Own Survey	*16 no veg.; '17-'19 herabaceous*	*16 no veg.; '17-'19 herabaceous*	*16 no veg.; '17-'19 herabaceous*	*herbaceous*	*herbaceous*	*herbaceous*	*no veg.*	*no veg*	*herbaceous*	*16-'17no veg. '18-'19 herbaceous*	*no veg.*
Irrigation			Event	28	Dynamic Category	Data Estimation	1,00	1,00	0,67	1,00	13,00	0,00	8,00	3,00	0,00	0,00	1,00
		2 Levels	Regular/No Irr.	29	Static Factor	Data Estimation	0,00	0,00	0,00	0,00	1,00	0,00	1,00	1,00	0,00	0,00	0,00
Infiltration Rate	cm/d	PP		30	Static Integer	Own Measurement	*2630,00*	*3640,00*	*3621,67*	*4464,00*	*3446,00*	*6048,00*	*427,00*	*1282,00*	*806,00*	*5472,00*	*1166,00*
	cm/d	US		31	Static Integer	Own Measurement	*628,00*	*1016,00*	*1146,67*	*569,67*	*2512,00*	*2112,00*	*NaN*	*NaN*	*533,00*	*2274,00*	*144,00*
Canopy Openess		3 Levels		32	Static Factor	Estimation	*2,00*	*0,00*	*1,00*	*2,00*	*0,00*	*0,00*	*0,00*	*1,00*	*1,00*	*1,00*	*2,00*
Tree Genus		7 Genus		33	Static Factor	Street Tree Cataster	*Beech*	*Oak*	*Maple*	*Oak*	*Oak*	*Oak*	*Oak*	*Oak*	*Maple*	*Maple*	*Cherry*
Tree Species		1-3 Species per Genus		34	Static Factor	Street Tree Cataster	*C. betu.*	*Q. cerr.*	*A.plat*	*Q. cerr.*	*Q. robu*	*Q. robu*	*Q. palu*	*Q. palu*	*A. pseu*	*A. pseu*	*P. serr*
Tree Age	Years (starting with Plantation)			35	Annual Dynamic Integer	Street Tree Cataster	*Table1*	*Table1*	*Table1*	*Table1*	*Table1*	*Table1*	*Table1*	*Table1*	*Table1*	*Table1*	*Table1*
Growing Site		3 Site Types		36	Static Factor	Estimation	Park	Street canyon	Street canyon	Park	Street canyon	Street canyon	Street canyon	Public Square	Street canyon	Street canyon	Public Square
Site Localisation		2 Types		37	Static Factor	Estimation	urban	sub-urban	sub-urban	sub-urban	urban	urban	urban	urban	urban	urban	urban



Appendix Figure 3.1: Water demanding conditions in the soil and the atmosphere in monthly comparison for the years 2018 and 2019. Light, dashed lines show the monthly average sums of days below SWP$_C$ in the soil compartments root ball (orange), planting pit (green) and urban soil (blue). The pink line shows the monthly number of days on which the daily maximal VPD values exceeding 15 hPa. The bright, coloured lines show the monthly number of days on which simultaneously SWP fell below SWP$_C$ and daily VPD$_{max}$ exceeded 15 hPa (colours with the same assignment as for the dashed lines). The black line shows the monthly number of days when SWP in all soil compartments fell below SWP$_C$ and daily VPD$_{max}$ exceeded 15 hPa.



Appendix Figure 3.2: Raw output of the *randomForest* model displayed by the means of the mean decrease accuracy for each predictor variable. The input data were delimited to the growing season (May – September). The ranking is based on the mean values of the root ball in ascending order. Error bars represent the standard deviations of five model runs with randomly selected seed numbers.



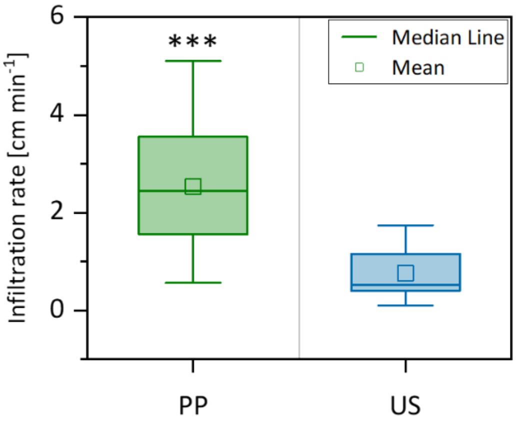
Appendix Figure 3.3: Scatter Plot of depth weighted mean soil temperature and sealed soil area (5 x 5 m Grid) in 2017, 2018 and 2019. Soil temperatures are presented as means of different time spans: whole year (green), growing season May to September (yellow) and July to September (red). The associated R^2 and p-values are listed in Appendix Table 3.

Appendix Table 3.2: Dimensions of investigated soil volume per soil compartment by planning. Vol_{tot} is the cumulative soil volume at each monitored site starting with the root ball, Vol_{corr} is the raw soil volume of each soil compartment.

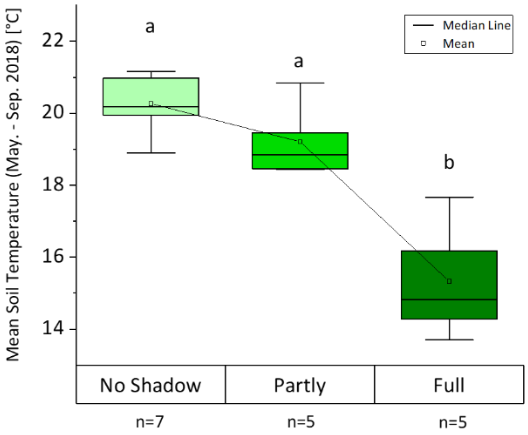
Soil compartment	Body	Dimensions			$Vol._{tot}$	$Vol._{corr}$
		Height [m]	Length [m]	Depth [m]	[m³]	[m³]
Root Ball	Ellipsoid	0.55	0.60	0.60	0.10	**0.10**
Planting Pit	Cuboid	0.95	1.50	1.50	2.14	**2.03**
Urban Soil	Cuboid	1.2	2.40	2.40	6.91	**4.77**

Appendix Table 3.3: R^2 and p-values of the scatter plots of Appendix Figure 5.3.

	2017			2018			2019		
	Year	Apr. - Oct.	Jul. - Sep.	Year	Apr. - Oct.	Jul. - Sep.	Year	Apr. - Oct.	Jul. - Sep.
R^2	0.34	0.61	0.64	0.55	0.72	0.74	0.49	0.69	0.74
p	0.017	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.00167	< 0.001	< 0.001



Appendix Figure 3.4: Comparison of soil infiltration capacity (n=15) in the planting pit (PP) and the urban soil (US). Means were significantly different (*** = p < 0,001).

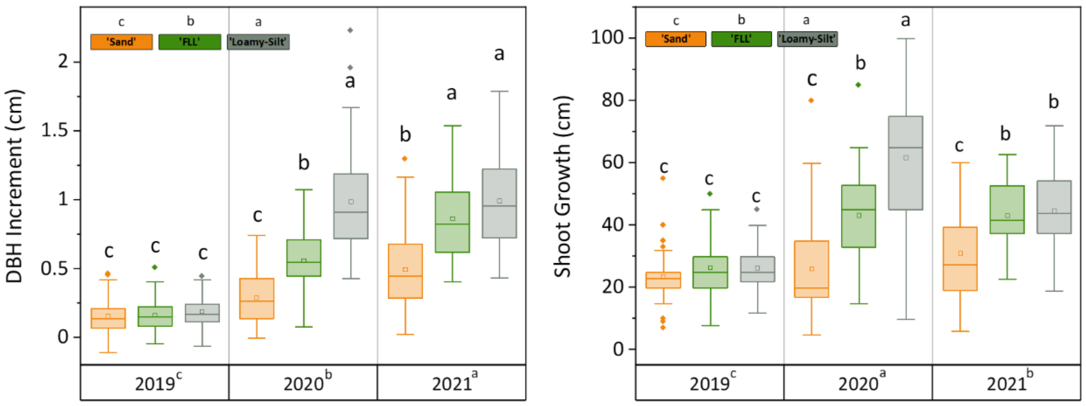


Appendix Figure 3.5: Dependency of three canopy openness categories (estimated degree of daily shadow) and depth weighted mean soil temperature during the growing season of 2018 displayed by a box-plot. 'No shadow' (n=7), 'partly' (n=5) and 'full' (n=5). Statistical analysis was performed using a one way ANOVA. Boxes with the same letters indicate no significant differences at the p < 0.05 level. Mean comparisons were performed by post-hoc procedure based on the Bonferroni-test.

Appendix Table 3.4: Quality assessment of the *randomForest* model approach.

	Overall OOB estimate of error rate			OOB error estimation for days > SWP_C		
	[%]	[%]	[%]	[%]	[%]	[%]
Seed No.	RB	PP	US	RB	PP	US
31	2.88	1.88	1.64	6.82	4.43	5.46
59	3.02	1.90	1.54	6.93	4.50	5.17
72	2.84	1.79	1.57	6.46	4.21	4.82
197	1.79	1.87	1.54	6.64	4.35	5.28
146	2.85	1.79	1.65	6.71	4.10	5.28
Mean	2.68	1.85	1.6	6.71	4.32	5.21
SE	0.50	0.05	0.05	0.18	0.16	0.27

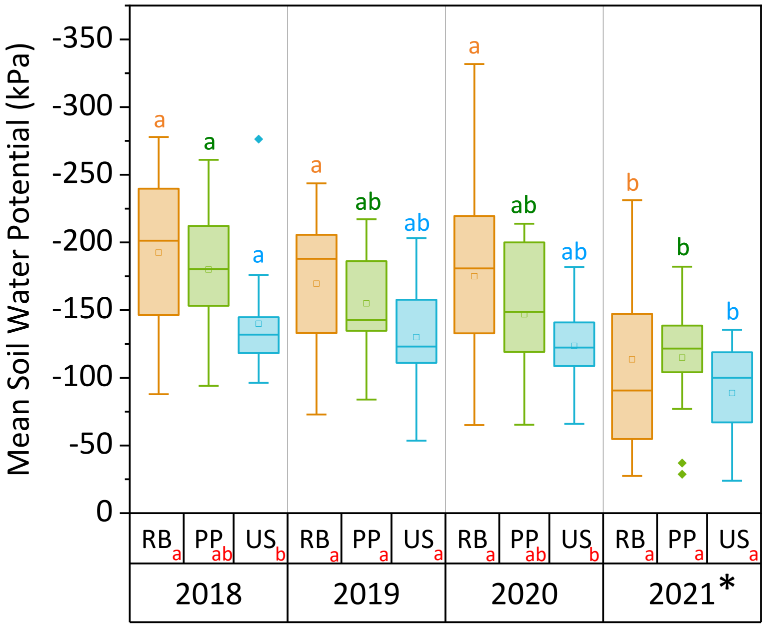
Appendix Figure 4.1: View on the experimental site in western direction in June 2019. The three planting soils are clearly visible (light = 'Sand'; dark = 'FLL', brown = 'Loamy-Silt'). Watering bags were removed after 2019.



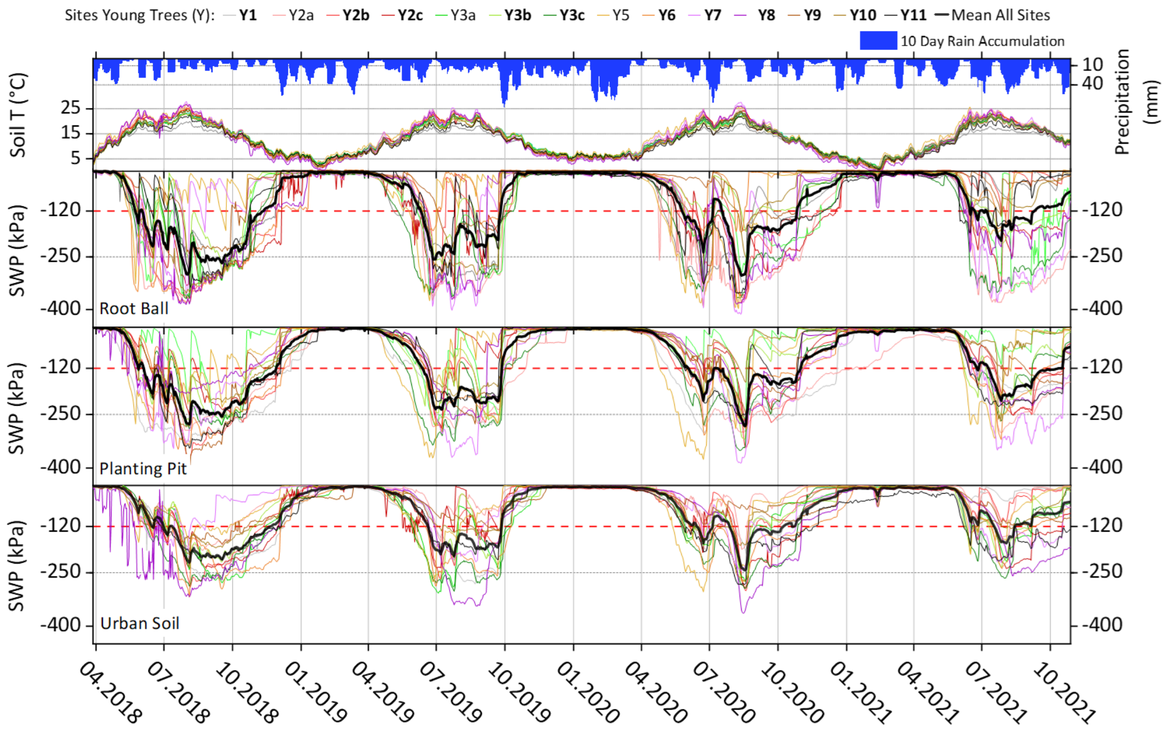
Appendix Figure 4.2: Annual DBH- and shoot growth in each investigated year as a mean of all species (n=9) in the planting soils (n=3). Statistical analysis were performed by using a one-way ANOVA. The same letters indicate no significant differences at the p ≤ 0.05 level provided separately for overall growth (boxes), growth in substrates across all years (legend) and growth in the years across all substrates (x-axis). Mean comparisons were performed by Tukey post-hoc comparisons.

Appendix Table 5.1: Supplementary regression analysis data for Table 5.2 from g_S with SWP (of all soil compartments) and VPD according to equations (5.4) and (5.5).

	Tree species	*Cb*		*Qc*		*Apl*		*Qr*				*Qp*		*Aps*		*Ps*	
	Site	Y01		Y02a-c		Y03a-c		Y5		Y6		Y7+Y8		Y9+Y10		Y11	
Reg. Func.	Soil comp.	Sig.	R²	Sig.	R²	Sig.	R²	Sig.	R²	Sig.	R²	Sig.	R²	Sig.	R²	Sig.	R²
(4)	RB	ns		***	0.28	***	0.24	**	0.55	*	0.64	***	0.60	ns		*	0.68
	PP	ns		***	0.35	***	0.48	*	0.53	ns		***	0.86	**	0.67	*	0.60
	US	ns		ns		***	0.65	ns		ns		***	0.80	ns		*	0.70
	Tot.	ns		ns		***	0.69	ns		ns		***	0.88	ns		*	0.68
(5)	RB + VPD	ns		** |**	0.55	***|**	0.42	ns		ns		** |ns	0.62	ns		* |*	0.91
	PP + VPD	ns		***|***	0.58	***|*	0.60	ns		ns		***|ns	0.76	* |ns	0.52	* |*	0.92
	US + VPD	ns		***|ns	0.38	***|*	0.61	ns		ns		** |ns	0.59	ns		* |*	0.90
	Tot. +VPD	ns		***|ns	0.37	***|*	0.65	ns		ns		***|ns	0.72	ns		* |*	0.92



Appendix Figure 5.1: Means of measured soil water potentials (kPa) in all soil compartments of all sites (n=14) subdivided to each year. Different red letters indicate significant differences (p > 0.05) between the soil compartments in the respective year. Stars indicate significant differences (* = p > 0.05 between the years.



Appendix Figure 5.2: Dynamics of depth-weighted soil water tensions within the soil compartments root ball, planting pit and urban soil over the course of four years. Data are displayed for all sites (Y1-Y11) except for sites Y4 and with three replicates each at Y2 (red) and Y3 (green). Black dynamic line shows the overall mean SWT across al sites. The mean soil temperature per site (colors match with SWT lines) and in dark blue the 10-day precipitation sum (radar based DWD RADKLIM data (DWD 2022) of site Y5) were displayed at the top of the graph. Red dashed line in the SWT-graphs shows the critical SWT-value used (-120 kPa). Violet point-line shows the limit of raw data range (-250 kPa). Exceeding values were generated through temperature correction. The figure is altered and extended according to Figure 3.1 (Schuett et al. 2022).