

Roadside trees in Hamburg: Growth and vitality of *Tilia x vulgaris* (H.) and *Acer platanoides* (L.) along urban to rural gradients.



DISSERTATION

zur Erlangung des Doktors der Naturwissenschaften des Fachbereichs Biologie, der
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To whom it may concern,

As a native speaker of English, as well as an experienced editor and teacher of scientific writing, I confirm that the doctoral dissertation “Roadside trees in Hamburg: Growth and vitality of *Tilia x vulgaris* and *Acer platanoides* along urban to rural gradients” by Jessica Ehrhardt has been written in clear and correct English.

Sincerely,

A handwritten signature in black ink that reads "Esther Chang". The signature is written in a cursive style with a long horizontal stroke at the end.

Dr. Esther R. Chang

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ABSTRACT

Urbanisation is a key driver for global change. With an accelerated increase in world population, nearly 70 % of the global population is predicted to live in urbanized areas by 2050. Cities comprise densely built-up residential and business areas with traffic roads and regions of industry. Despite park sites with recreation value for citizens, sealing of soils is characteristic for many urban areas. Thus, higher atmospheric temperatures and CO₂ concentrations as well as air and soil pollution are factors that present challenges for citizens, animals and plants in cities.

Urban trees, which are often deliberately planted in urban parks and roadsides, are exposed to various stress factors. Although it is well known that trees in cities fulfil important ecosystem functions, such as improving air quality, providing shade and decreasing air temperatures, habitat conditions for them are often poor. Particularly roadside trees in cities suffer from deficiencies in their requirements for vital growth. Crowns of roadside trees in cities are continuously pruned for traffic and public safety demands, resulting in reduced leaf areas and photosynthesis in most cases. In addition, urban soils are very different from those found in natural stands, especially in roadsides, and are often polluted with heavy metals and de-icing salt, and lack water and nutrients due to sandy soil structure and lowered water levels. Further aggravating vital growth are management practices such as soil sealing, inadequate tree pit sizes, and damage or cutting of tree roots. Yet, planted trees in urban roadsides form a substantial part of the ecosystem of planted native and non-native species adapted to the local environment. In view of creating suitable habitat conditions for trees in densely built-up areas, it is important to provide at least the basic requirements that allow urban forestry to select well-suited species or lines. Keeping human-induced stress factors at low levels is vital for the health of urban roadside trees.

In this thesis, studies on roadside trees were conducted in the city of Hamburg in Northern Germany. The predicted regional climate change for Northern Germany includes higher temperatures with increasing risk of summer droughts and simultaneously warmer but wetter winters for the late 21st century. Sudden heat, drought and frost events are threatening future climate scenarios. Moreover, an increase in climatic extremes is expected and will most likely hamper the vitality of humans, animals and plants. These extremes in atmospheric climate conditions are especially challenging for sessile, long-lived organisms like trees, which cannot adapt to changing climate within one life-span. In Europe a northward shift of native trees adapted to cooler climates can be recorded already today.

The general aim of this thesis is to deepen the understanding of the effects of urban stress factors on the growth and vitality of native roadside trees in Hamburg. This metropolis contains a large number of park and roadside trees, making it a green city. The popular native roadside trees in North European cities *Tilia x vulgaris* (H.) (Lime tree) and *Acer platanoides* (L) (Norway maple), hereinafter named without acronym for the first descriptor were selected and studied along an urban-to-rural gradient within the boundaries of Hamburg. Three main research questions were addressed:

1. What are the roles of the atmospheric factors ambient air temperature and CO₂ content for the vitality and radial stem growth of the native species *Tilia x vulgaris* and *Acer platanoides* in urban roadside habitats?
2. How do soil parameters and crown volume affect growth of *Tilia x vulgaris* and *Acer platanoides* in urban roadside habitats?
3. How do atmospheric and urban climate factors affect the timing of bud burst in *Tilia x vulgaris* and *Acer platanoides* in urban roadside habitats?

To shed light on the influences of atmospheric shifts in air temperature and CO₂ content on stem growth of roadside trees, an urban-to-rural gradient was set up. Measurements of ambient air temperatures and CO₂ content at the selected study sites were used to characterise the atmospheric conditions along the gradient. Along this gradient from the city centre to the north-eastern outskirts of Hamburg, 40 roadside trees of each species were studied and stem increment was analysed over the period of two and a half years. Results showed increasing tree growth from urban to rural sites. The relationship between growth of tree stems, and increasing temperature and CO₂ content appeared to be negative. One way ANOVAs calculated significant differences in stem increment between the urban and rural sites in all examined years for *Tilia x vulgaris*. In *Acer platanoides*, however, significant differences only appeared in 2010.

As rural sites in both species differed in their degree of sealing from urban and suburban sites, and strongest growth was shown at rural sites that were the coolest in temperature, lowest in CO₂ but also the least sealed ones, the gradient in stem growth could not be related with certainty to temperature or CO₂ concentration. Therefore, two further sites at rural locations that differed little in the degree of soil sealing from the urban and suburban sites were selected for further study. When comparing sealed urban, suburban and rural locations, differences in stem growth were marginal in 2011 and 2012 for both species. Findings suggest that atmospheric temperature and CO₂ concentration were not the decisive factors for stem growth of urban roadside trees.

With respect to the second question, significant differences in stem growth between rural trees in sealed and unsealed sites appeared in 2011 and 2012 in *Tilia x vulgaris* but not in *Acer platanoides*. *Tilia x vulgaris* showed stronger growth at the unsealed than at the sealed sites, and a comparable trend was observed for *Acer platanoides*. Significant differences in plant-available soil nutrients were measured in K concentration between the sealed sites and the unsealed rural site for *Tilia*-sites, while differences between all *Acer*-sites were not significant. Potassium decreased gradually from the urban to the rural sites for both species. However, this decrease was not in the range of crucial nutrient supply. Lower C/N ratios from urban to rural locations were likewise observed. Findings rather suggest that soil sealing negatively affects the stem growth of trees and *Tilia* seemed to be influenced more strongly by soil sealing than *Acer*.

Observations of bud development were conducted in 2011 from early to late spring by taking pictures of branches of the studied trees during two- to three- day intervals at all sites for both species. Based on these pictures, a phenological index was defined by

classifying bud development for *Tilia x vulgaris* and *Acer platanoides*. Results verified that temperature influences the timing of full-spring leaf-bud development of *Tilia x vulgaris* and early-spring flower-bud development of *Acer platanoides*. In both species, full blooming and unfolding appeared significantly earlier at the urban than at the rural location.

Altogether, results of this thesis suggest that the influences of climate change, such as higher air temperature and CO₂ content on growth of urban roadside trees are smaller than the effects of edaphic site-characteristics. Limited water supply due to soil sealing, sandy urban soil characteristics in general, and limited tree pit sizes can be understood as proxies for the droughts expected in the future climate. The negative effects of urban stress factors, like high soil sealing and bulk densities of urban soils or limited space for tree root development, on vitality and growth of roadside *Tilia x vulgaris* and *Acer platanoides* in Hamburg were obvious, while the more subtle effects of atmospheric temperature and CO₂ content were probably masked by these urban stress factors. Regarding tree pit design, a sufficient size for tree pits and unsealed surfaces should be integrated into urban roadside planning.

With respect to tree phenology, budding of *Tilia x vulgaris* and *Acer platanoides* clearly indicated onset of native tree growth to be positively correlated to increasing atmospheric temperatures. Most probable, future air temperatures in Northern Germany will shift the onset of the vegetation cycle of native trees and will possibly affect the local ecosystems.

ZUSAMMENFASSUNG

Urbanisierung ist ein Schlüsselfaktor für den globalen Klimawandel. Mit dem exponentiell zunehmenden Wachstum der Weltbevölkerung, werden bis 2050 annähernd 70% der Menschheit in Städten leben. Städte umfassen sowohl dicht bebaute Wohn-, Arbeits- und Industriegebiete, die von einem Straßennetz durchzogen werden, als auch Regionen, die vor allem der Erholung dienen, wie z.B. Parks. Ein hoher Versiegelungsgrad ist charakteristisch in urbanisierten Gebieten. Hieraus resultierende wärmere Lufttemperaturen und CO₂-Gehalte wie auch Luft- und Bodenverschmutzung, sind drängende Probleme, denen die Stadtbewohner Mensch, Tier und Pflanze entgegentreten müssen.

Bäume werden meist gezielt in Parkanlagen und entlang von Straßen gepflanzt und sind vielen Stressoren ausgeliefert. Obwohl die positiven Eigenschaften von Bäumen in Städten seit langem bekannt sind – so erfüllen sie wichtige Ökosystemfunktionen, verbessern die Luftqualität, spenden Schatten und erniedrigen die Lufttemperatur – sind die Lebensbedingungen, denen sie ausgeliefert werden, häufig schlecht. Besonders Straßenbäume in Städten erleiden erhebliche Defizite in ihren Anforderungen an ein gesundes, wachstumsförderndes Leben: Die Photosynthese ist meist dadurch eingeschränkt, dass die Kronen von Straßenbäumen regelmäßig zurückgeschnitten werden und damit nur über eine reduzierte Blattfläche verfügen. Urbane Böden, besonders entlang von Straßenrändern, unterscheiden sich deutlich von natürlichen Wuchsorten für Bäume, sind oft durch Schwermetalle und Auftausalze verschmutzt und leiden an unzureichender Wasser- und Nährstoffversorgung aufgrund der meist sandigen Struktur und häufig abgesenkter Grundwasserstände. Darüber hinaus schränken Oberflächenversiegelung, beschädigte und bereits bei der Pflanzung stark reduzierte Wurzelmasse sowie reduzierte Wurzelausbildung und Ausdehnung aufgrund zu kleiner Baumgruben das vitale Wachstum ein. Dennoch bilden Straßenbäume in Städten einen bedeutenden Teil eines Ökosystems aus heimischen und nicht heimischen Arten, die sich besser oder schlechter an die lokalen Umweltbedingungen angepasst haben. Im Hinblick auf zukünftige Lebensbedingungen in dicht bebauten Räumen und dem steigenden Anteil der Weltbevölkerung in Städten, ist es von Bedeutung eine datengestützte Basis zu schaffen, die die Anforderungen an die Baumstandorte widerspiegelt und es Stadtbäumen ermöglicht, sich gesund zu entwickeln. Anthropogen verursachte Stressfaktoren sollten hierfür in ihrem Ausmaß auf urbanisierten Flächen gering gehalten werden.

In dieser Arbeit wurden Untersuchungen an Straßenbäumen im Stadtgebiet Hamburgs in Norddeutschland durchgeführt. Das vorhergesagte regionale Klima für Norddeutschland bis zum Ende des 21. Jahrhunderts deutet auf höhere atmosphärische Temperaturen und damit auf ein höheres Risiko von Sommerdürren bei gleichzeitig wärmeren und feuchteren Wintern. Darüber hinaus wird eine Zunahme von klimatisch bedingten Katastrophen erwartet, die besonders für sessile und langlebige Pflanzen, wie Bäume, lebensbedrohlich werden können. Der beschleunigte Wandel der atmosphärischen Klimabedingungen stellt eine besondere Herausforderung an diese dar, da sie sich binnen einer Lebensspanne nur bedingt anpassen können.

In Europa wird die Verlagerung heimischer Baumarten, die an kühlere Klimate angepasst sind, in Richtung nördlicher gelegener Regionen bereits heute beobachtet.

Generelles Ziel dieser Arbeit war es, das Verständnis der Einflüsse urbaner Stressfaktoren auf das Wachstum und die Vitalität heimischer Baumarten zu vertiefen. Die Metropole verfügt über sehr viele Park- und Straßenbäume, die sie zu einer grünen Stadt machen. Die in nordeuropäischen Städten beliebten heimischen Baumarten *Tilia x vulgaris* (H.) und *Acer platanoides* (L.), nachfolgend ohne Namens Kürzel des Erstbeschreibers genannt, wurden für Untersuchungen ausgewählt und entlang eines Stadt-Land Gradienten innerhalb der Stadtgrenzen Hamburgs untersucht. Die Untersuchungen umfassten dabei drei Ziele:

1. Welche Rolle spielen Umgebungstemperatur und Luft-CO₂-Konzentration in Bezug auf Vitalität und radiales Stammwachstum von urbanen Straßenbäumen der heimischen Arten *Tilia x vulgaris* und *Acer platanoides* in Hamburg?
2. Wie beeinflussen ausgewählte Bodenparameter und das Baumkronenvolumen die urbanen Straßenbäume der Arten *Tilia x vulgaris* und *Acer platanoides* in Hamburg?
3. Wie beeinflussen atmosphärische und stadttypische Klimafaktoren die urbanen Straßenbäume der Arten *Tilia x vulgaris* und *Acer platanoides* in Hamburg?

Um den möglichen Einfluss von steigenden Lufttemperaturen und CO₂-gehalten auf das Stammwachstum von Straßenbäumen zu beleuchten, wurde ein urban-ruraler Gradient innerhalb der Stadtgrenzen von Hamburg gelegt. Daten zu den Messungen der Umgebungstemperaturen und CO₂-Gehalte an den ausgewählten Untersuchungsflächen dienten dazu, die atmosphärischen Bedingungen entlang des Gradienten zu charakterisieren. Entlang dieses Gradienten wurden vom Stadtzentrum bis zu den nordöstlich gelegenen Randgebieten der Stadt jeweils zehn Straßenbäume pro Art an vier Untersuchungsgebieten untersucht. Der jährliche Stammzuwachs wurde von 2010 bis 2012 beobachtet und dokumentiert.

Die Ergebnisse zeigen eine graduelle Zunahme des Stammzuwachses von urban nach rural in allen Jahren und für beide Arten. Stammwachstum und Lufttemperatur und CO₂-Gehalte waren offenbar negativ miteinander verbunden. Einfache ANOVAs berechneten signifikante Unterschiede im Stammzuwachs in allen Untersuchungsjahren zwischen den urbanen und ruralen Standorten für *Tilia x vulgaris*. Bei *Acer platanoides* jedoch wurden signifikante Unterschiede nur für 2010 berechnet. Weil sich die ruralen Standorte beider Arten in ihrem Versiegelungsgrad von den urbanen und suburbanen unterschieden und stärkstes Stammwachstum nicht nur an der kühlssten ruralen Lokalität gemessen wurden, sondern eben auch an den Standorten, die offensichtlich weniger stark versiegelt waren, konnte ein negativer Bezug zwischen Stammwachstum und Umgebungstemperaturen nicht sicher festgehalten werden. Deshalb wurde ein weiterer Untersuchungsstandort für jede Art an der ruralen Lokalität herausgefiltert, der sich in geringerem Maße von den urbanen und suburbanen Standorten unterschied. Im Vergleich der versiegelten urbanen, suburbanen und ruralen Flächen waren die Wachstumsunterschiede bei *Tilia x vulgaris* und *Acer platanoides* gering in den Jahren 2011 und 2012.

Die Ergebnisse lassen vermuten, dass weder die Unterschiede in der Lufttemperatur noch die in den CO₂-Gehalten einen entscheidenden Einfluss auf das Stammwachstum urbaner Straßenbäume haben.

Bezug nehmend auf die zweite Frage, den Einfluss von Bodenfaktoren auf das Wachstum der Untersuchungsbäume, konnten signifikante Unterschiede zwischen den ruralen Standorten unterschiedlichen Versiegelungsgrades in den Jahren 2011 und 2012 bei *Tilia x vulgaris*, nicht jedoch bei *Acer platanoides* festgehalten werden. *Tilia x vulgaris* zeigte ein stärkeres Wachstum an der unversiegelten Fläche. Zwar ähnlich, aber doch weniger deutlich, verhielt es sich bei *Acer platanoides*.

Signifikante Unterschiede zwischen den pflanzenverfügbaren Nährstoffen konnten bei der Kalium-Konzentration festgestellt werden. K⁺ sank graduell von den urbanen zu den ruralen Lokalitäten, jedoch lagen selbst die geringsten Gehalte nicht in einem, die Vitalität der Bäume beeinflussenden Versorgungsbereich. Engere C/N Verhältnisse von urban nach rural wurden außerdem gemessen. Die Ergebnisse lassen eher vermuten, dass vor allem Bodenversiegelung das Wachstum der Baumstämme beeinflusst und *Tilia* hierbei offenbar stärker negativ als *Acer*.

Insgesamt lassen die Ergebnisse dieser Arbeit vermuten, dass negative Einflüsse des Klimawandels durch Lufttemperaturerhöhungen und erhöhte CO₂-Konzentrationen das Stammwachstum von Straßenbäumen in der Stadt nur wenig beeinflussen, direkt wirkende Faktoren wie edaphische Charakteristika, die Vitalität und das Wachstum der Bäume jedoch stärker prägen. Auswirkungen atmosphärischer Temperaturen und CO₂ Gehalte auf das Wachstum von *Tilia x vulgaris* und *Acer platanoides* wurden höchstwahrscheinlich von Faktoren wie hoher Bodenversiegelung und –verdichtung als auch dem sandigen Substrattyp der häufig zu kleinen, das Wurzelwachstum einschränkende Baumgruben, an Straßenrändern in Hamburg überdeckt. Bezug nehmend auf die Gestaltung von Baumgruben sollte eine ausreichende Dimensionierung in Breite und Tiefe sowie möglichst gering versiegelte Oberflächen Eingang in die Planung von Straßenbaum-Pflanzungen finden. Ein weniger sandiges Bodensubstrat sollte darüber hinaus Basis für die Gestaltung von Baumgruben sein.

Mit Blick auf die Fragestellung nach dem Einfluss atmosphärischer und stadttypischer Klimafaktoren auf die Phänologie von *Tilia x vulgaris* und *Acer platanoides* im Hamburger Straßenraum, deuten die Beobachtungen klar darauf hin, dass der Vegetationsbeginn der heimischen Bäume auch im stadtgeprägten Straßenraum positiv mit den Lufttemperaturen korreliert ist. Ich vermute, dass die zukünftig weiter steigenden Lufttemperaturen in Norddeutschland den Beginn des Vegetationskreislaufs heimischer Bäume verschieben werden und so möglicherweise die lokalen Ökosysteme längerfristig beeinflussen.

1 INTRODUCTION

Trees in urban areas are exposed to challenging environmental conditions. Roadside trees do not result from spontaneous establishment under appropriate conditions but are planted into an ecosystem that only satisfies their requirements to a limited degree. In cities, an inherent complexity of microclimatic components, including the urban atmosphere, is evident. Urban areas are characterized by a heterogenic pattern of residential areas, zones of industry, recreation areas and regions with a high density of traffic. Urban greening plays a significant role in the urban climate, and especially trees affect the urban climate beneficially in many ways: trees store carbon by assimilation of CO₂ and produce O₂, function as air filters, reduce the ambient temperature on warm days and provide shade (Meyer 1993, Balder 1998). However, a multitude of directly and indirectly human-induced factors harm tree vitality in cities and negatively affect growth of roadside trees including elevated atmospheric temperatures, deficient water and nutrient supply, soil sealing and compaction, pollution of ambient air and soils, pruning of tree crowns, vandalism and damage through traffic, and building activities (e.g., Balder 1998).

Atmospheric CO₂

On a global scale (IPCC 2007) as well as for urbanized areas (e.g., Berry and Colls 1990a, 1990b, Ziska et al. 2004, Zhang and Lin 2012), concentrations of CO₂ in the atmosphere have continuously increased since the beginning of industrialization, and affect the growth and vitality of trees. CO₂ is a vital gas for the metabolism of photosynthesis and, thus, for tree growth. By the end of the 21st century, higher atmospheric temperatures and CO₂ concentrations are expected to shift the physiological limitations for photosynthesis, especially for C3 plants. Today, photosynthesis of C3 plants is mainly limited by the capacity of ribulose-1.5-bisphosphate carboxylase/oxygenase (RuBisCo). With a rise in atmospheric CO₂, plants will shift their thermal optimum for maximum rates in photosynthesis so that carbohydrate production will most likely be limited by electron transport capacity. Moreover, the capacity of RuBisCo activase might acclimate to higher, supraoptimal temperatures (Sage and Kubien 2007).

In FACE (free air CO₂ enrichment) experiments, which have been conducted since the beginning of the 1990s, scientists found that highly elevated CO₂ concentrations increased plant biomass by augmenting rates of photosynthesis. Higher CO₂ contents in the ambient air foster the efficiency of net carbohydrate production clearly through a disproportional gain in photosynthesis against losses through photorespiration. Using an urban to rural CO₂ gradient of only 66 ppm, Ziska et al. (2004) were able to show that only slightly higher CO₂ concentrations correlate with higher productivity of *Chenopodium album* in Maryland (MD), USA. The authors, however, concluded that several factors besides CO₂ influence biomass production of urban plants.

Experiments within the FACE-program also demonstrated that elevated CO₂ reduced stomatal conductance. In studies on *Arabidopsis thaliana*, Dow et al. (2014) found a clearly negative correlation between atmospheric CO₂ concentrations and stomata

conductance. Besides these direct influences on plant growth, CO₂ also indirectly influences vitality of plants as it is also a major driver of atmospheric temperatures (Idso et al. 2001).

Atmospheric temperature

Usually, temperature decreases simultaneously with the decreasing CO₂ concentration from urban to rural locations. In cities, temperature gradients occur worldwide and are known as the urban heat island effect (UHI) (Oke 1982). With regard to plant phenology, atmospheric temperature plays a key role because the timing of the annual cycle of most trees in cold temperate regions is controlled by photoperiodic constraints (Heide 1974, Juntilla 1982, Heide and Prestrud 2005, Heide 2008, 2011). Hänninen and Tanino (2011) outline the prolonged growth period coupled with climate warming for boreal and temperate trees but also point to species-specific responses. Observations of Hasenauer et al. (1999) and Dobbertin and Giuggiola (2006) also indicate a positive correlation between prolonged vegetation periods and elevated tree growth due to higher atmospheric temperatures. Likewise, analyses of tree rings from oriental beech (*Fagus orientalis*) by Kose and Guner (2012) support this assumption. If so, the rise of ambient temperatures might, on the one hand, minimize the number of early autumn and late spring frost events in the temperate zone over time (Häkkinen and Hari 1988). On the other hand, earlier bud burst of plants may also increase the risk of frost damage, and late winter frosts might become a new danger for earlier breaking buds. Fitter and Fitter (2002) showed a rapid change in flowering time of British plants within a time span of 47 years. They found the date of flowering to be sensitive to the temperature during the previous month, particularly for early-spring blooming and insect-pollinated annuals. In contrast, Heide (2003) stated that higher autumn temperatures are more important for budding than higher temperatures in early-spring.

Changes in phenological responses like budburst or leafing of woody and herbaceous plants have been documented in phenological gardens and in the field for a long time in many European regions (Roetzer et al. 2000, Chmielewski and Rotzer 2001, Bruns et al. 2003). In Hamburg, site-specific observations for the date of blooming of *Forsythia* by Carl Wendorf and Jens Iska-Holz have been carried out since 1945 and document a slight shift to earlier phenology (Jensen et al. 2011).

Indeed, phenological traits of plants can be responsive to various factors, and biotic factors can also act as triggers that break down dormancy and initiate growth. However, temperature is understood to be the main cause that breaks dormancy and initiates growth (e.g., Rathcke and Lacey 1985, Bowers and Dimmitt 1994, Neil and Wu 2006).

Regardless of time, the fulfilment of chilling requirements plays the most important role in regulating bud burst of trees in the temperate-zone. The sum of low temperature is crucial to satisfy the chilling requirements for bud burst of temperate-zone trees. It has been the focus of diverse studies during the past years. Murray et al. (1989), for example, found that the date of bud burst following climate warming depended on chilling requirements for different tree species in Britain. They stated that trees with low chilling requirements thrive earlier in spring due to climate warming and benefit from longer growing seasons.

However, these trees are also exposed to higher risk of early frost damage. Trees with high chilling prerequisites most likely would not bud earlier in spring due to warmer winters. Overall, they suggest that climatic warming will not lead to strong shifts in the date of budburst for most woody species growing in Britain at lowland sites. For predicting phenological changes due to a warmer climate, the date of flowering and the beginning of leafing have also often been documented for urban plants (e.g., Häkkinen et al. 1998, Lovett et al. 2000, Iakovoglou et al. 2001, Donnelly et al. 2004, Caffarra and Donnelly 2011) along urban-to-rural gradients. Gregg et al. (2003) compared phenological responses of Eastern cottonwood (*Populus deltoides*) to ozone along an O₃ gradient in the vicinity of New York and found reduced growth of trees exposed to higher ozone concentrations at the rural sites. Studies of Berland (2012) showed differences in canopy cover of trees along an urban-to-rural gradient but also between different microhabitats. Indeed, canopy cover of urban trees in densely built-up regions is lower than in more rural areas. However, it cannot be adequately characterized by linear distance along the urban to rural gradient, but by a patchy pattern of microhabitats within cities.

Soil

Urban soils are often split into anthropogenically modified soils comprising the upper layer and the subjacent original soils. In situ parent soils in Hamburg were generated from the glacial periods Saale (~ 300 000-130 000 years ago) and Weichsel (~ 115 000-11 700 years ago). Holocene sediments from the Elbe formed the valley of the river Elbe (Miehlich 2010). Land-use has changed drastically with human activity, and urbanization has had severely negative influences on soils. Natural soils have been excavated or compacted for building works for thousands of years. Furthermore, since the rise of industrialization, the practice of compaction and dislocation or removal of the original soil has been expanded for use in road works and industrial areas. In view of an increasing world population and accompanying increase in demand to live in a place of high economic value (Niemelä 2011) urbanization and subsequent soil sealing will possibly also increase rapidly in the future.

Soils in urban areas often show small-scale heterogeneity due to impacts on formation and development by anthropogenic activities. Therefore, physical and chemical properties can strongly differ within short distances and form a mosaic of different soils (e.g., Burghardt 1994, Pouyat et al. 2002, 2007, Scharenbroch et al. 2005). Excavation pits for buildings, streets or trees are often backfilled with sandy substrates and building waste. Besides, pollutants like heavy metals or de-icing salt are washed into soils close to streets and, hence, into the substrates of tree bases. High content of contaminants like heavy metals or de-icing salt impedes tree vitality due to the activation of free O₂ radicals or hinders the absorption of nutrients (e.g., Cakmak 2000, Doichinova et al. 2014). The osmotic value of the soil is elevated when NaCl is used for street de-icing and reduces the availability of water for roadside trees. Moreover, the soil structure can be severely disrupted leading to nutrient leakage. Mechanical disturbances provoke changes in soil chemistry (pH, mobility of nutrients), physics (water- and air conditions), and biology (flora and fauna). Fellenberg (1984) describes urban soils as matter sinks for mainly human-produced waste.

By providing anchorage, water and nutrients, soil is essential for the growth and vitality of plants. To maintain fixation in the substrate, trees develop root systems that can extend to a size comparable to their leaf crown. Trees try to ensure a sufficient supply of water and nutrients by spreading their roots into the soil as far as possible to maximize the surface area available for nutrient exchange and water supply (e.g., Meyer 1993, Kutschera and Lichtenegger 2013).

Roots are highly flexible and can adapt to their environment by changing the direction and shape of growth in response to barriers (e.g., Balder 1998, Kutschera and Lichtenegger 2013). High plasticity of tree root systems was proven by Bauerle and Centinari (2014), who documented species-specific strategies of root systems to occupy the limited space of soil, available in containers. Nevertheless, limited space in soil is a severe stress factor for roadside trees in cities. Tree pits are often narrow and hardly allow trees to grow in depth. The natural rooting depth and width of a tree in most cases exceeds the space that is provided for roadside trees in their tree pits. Pauleit (2003) claims for tree pits of at least 3-4 m width in urban environments. Furthermore, physical damage of roots through road works and utility trenching impacts water and nutrient supply (e.g., Balder 1998, Pauleit 2003). However, not only water and nutrient content in the soil affect the vitality of root systems (Bijoor et al. 2011) but also physical soil conditions are important factors (e.g., Balder 1998, Pauleit et al. 2002, 2003, Pouyat et al. 2007).

Impermeability and compaction of soil substrates severely impede percolation of water and prevents sufficient nutrient supply for plants. Moreover, soil compaction leads to minimal soil aeration. Reduced aeration possibly leads to dysfunctions in the root system resulting in overall smaller or less developed root systems and, thus, to increased stress during periods of drought. Weltecke and Gaertig (2012) found aeration deficiencies in the soil lead to a decrease of fine root density and tree vigour in urban soils. Finally, effects of insufficient water, nutrient and O₂ supply also affect the crown structure of trees (Roloff 1989).

Pruning

Other human activities related to tree care are also stress factors for plants: crowns of urban trees have to be pruned constantly to maintain safety for traffic and pedestrians. As a consequence, however, the net primary production of assimilates is lessened due to a reduced photosynthetic area. Moreover, pruning of tree crowns always means wounding the tree and can create opportunities for pathogens, which can in turn increase insect calamities for trees. Martin and Stutz (2013) compared pruned and non-pruned trees of *Quercus rubra* in Phoenix (AZ), USA. Pruned trees were more often negatively affected by disease and pest problems than non-pruned ones, especially by wood decay, *Verticillium* wilt, sooty canker, and ash decline. They suggest that extensive wounding of trees, possibly caused by excessive crown manipulation through pruning, may be the reason for high numbers of negatively impacted urban trees.

Urban environment and scientific research

The UHI is often used in so-called space-for-time substitution experiments in order to estimate future environmental conditions for plants from their recent urban living situations. Observations on CO₂ and temperature gradients stretching from urban to rural areas have already been conducted for decades (e.g., Berry and Colls 1990a, 1990b, Ziska et al. 2004, George et al. 2007). Pataki et al. (2007) compared forecasts of the IPCC from 2007 on the global climate to their own measurements along an urban-to-rural CO₂ and temperature gradient in Maryland (MD), USA. The results proved the suitability of dense urban areas for studying reactions of plants to future conditions of the global climate in 2100.

However, using the city as a laboratory for analyses on ecological responses of perennials to higher ambient temperatures or CO₂ is risky. Carreiro and Tripler (2005) described the advantages and disadvantages of experiments where trees function as “bio-indicators” for global warming. Indeed, long-lived organisms like trees are suitable for observations on plant reactions to a changing climate in particular, as the environmental influences on growth can be mirrored by tree-rings over their whole life-span. However, as trees do not only display reactions to climatic shifts, but also incorporate the influences of microclimatic conditions simultaneously, relating responses of tree vitality and growth to a single factor is challenging or even impossible. Long and Smith (1990) underlined the importance of including the interplay of factors contributing to plant vitality already in the 1990s. Iakovoglou et al. (2001) separated abiotic from biotic factors in their studies on parkland and roadside trees, and found the interplay of various factors (like site conditions, placement, land use and age of trees) to be the most important for variable tree growth. Also, the results of Gregg et al. (2003) suggest that the interplay of various urban parameters and their variable loading influences growth of trees.

Factors that generally influence the growth of roadside trees in cities most likely also influence the vitality and growth of urban trees in Hamburg. The second largest city in Germany is regarded as a very green metropolis with more than 410 000 trees within its boundaries. The city state holds a large data set of trees within a register, where more than 180 000 roadside trees have been documented with individual-level data regarding species, location, age, crown volume, stem diameter and damages (www.GALK.de, Status 2005). The most abundant roadside trees in Hamburg are *Tilia x vulgaris*, *Quercus robur* and *Acer platanoides* (Doobe 2004). All three species are native and are among the most often planted roadside trees in north European cities (Sukopp and Wittig 1998, Sæbø et al. 2003, Sjöman et al. 2012, Roloff 2013). In the current list of the GALK (Gartenamtsleiterkonferenz) for roadside trees, *Tilia x vulgaris* as well as *Acer platanoides* are classified as suitable for lining streets as they are able to cope with the city climate. Roloff et al. (2008a, 2008b) studied roadside trees from the point of view of climate change. Resistance to drought and winter hardiness were calculated with the so-called KLAM (KLimaArtenMatrix). While their resistance to frost is well above critical levels for *Tilia x vulgaris* and *Acer platanoides*, the tolerance to drought stress is a more critical factor for both species. *Acer platanoides* is more likely to withstand longer periods of drought than *Tilia x vulgaris*.

Aim of studies

In order to avoid crossing or displacing native with non-native species, which might trigger a shift from original ecosystems to novel ecosystems, maintaining native species over their natural geographic distribution is of exceeding importance. To gain insight into the physiology and phenology of the native trees *Tilia x vulgaris* and *Acer platanoides*, roadside individuals of these species were investigated within the city boundaries of Hamburg along an urban-to-rural temperature-gradient from 2010 to 2012. The major aim of the thesis is to deepen our understanding of the effects of urban stress factors on the growth and vitality of native roadside trees. As many roadside trees hardly reach 25% of their natural life span (Roloff 2013), data on growth and vitality may support the development of a sustainable roadside tree program that encompasses the choice of native species and optimizes aspects like tree pit size or site- and species-specific tolerances to urban stress factors. I specifically address the following research questions:

Which factors influence stem growth and vitality of Tilia x vulgaris and Acer platanoides roadside trees along urban-to-rural gradients in the city of Hamburg?

Do increasing atmospheric temperatures and CO₂ concentrations have a beneficial or detrimental effect on the growth and vitality of roadside trees under exposed urban conditions?

Besides stem growth of street trees along a temperature-gradient from urban to rural, differences in stem growth were also documented for trees planted into differently sealed sites. Moreover, volume of tree crowns (as a proxy for the photosynthetic active area), soil nutrients (P, K, and C/N ratio) as well as soil moisture, and pH were measured. The content of de-icing salt was derived from soil conductivity values. Sites with different levels of soil sealing but equivalent climatic situations were chosen at the rural location to compare stem growth of trees with respect to the conditions of their tree pits.

With regard to phenology, buds of *Tilia x vulgaris* and *Acer platanoides* were photographed in spring 2011. Comparable to stem growth measurements, timing of leaf and flower budding was documented for sites along the temperature-gradient with similar levels of soil sealing, and for sites with similar ambient temperatures but different levels of soil sealing of tree bases. In order to answer whether changes in timing of leafing and flowering can be predicted from temperature or soil sealing differences between the sites, the following question was raised:

Is budding in Tilia x vulgaris and Acer platanoides affected by differences in temperature along urban-to-rural gradients and/or affected by differences in the degree of soil sealing in Hamburg?

The data obtained in this study may lead to insights regarding the interplay and relative importance of factors affecting the growth and vitality of urban roadside trees. In addition, reactions of native trees to climate change might be derived from the results.

2 MATERIAL AND METHODS

2.1 Site description

The investigations were conducted in the city of Hamburg (53° 33'N, 10° 0' E) in Northern Germany. With about 1.75 million citizens and an approximate area of 700 km², this city is the second largest in Germany. Hamburg is closely located to the North Sea and the Baltic Sea. Therefore, the city lies under temperate coastal climatic influences, and precipitation reaches approximately 770 mm per year. The annual mean temperature rose from 8.8° C (1961-1990) to 9.2° C in the reference period 1971-2000. The annual mean temperature between 2001 and 2010 was 9.7° C. Temperature data of the German meteorological centre (DWD) for the reference period 1971-2000 displays a temperature gradient of approximately 1.1° K from the centre to the outskirts of the city, comparable to the urban heat island (UHI) of London (Watkins et al. 2002).

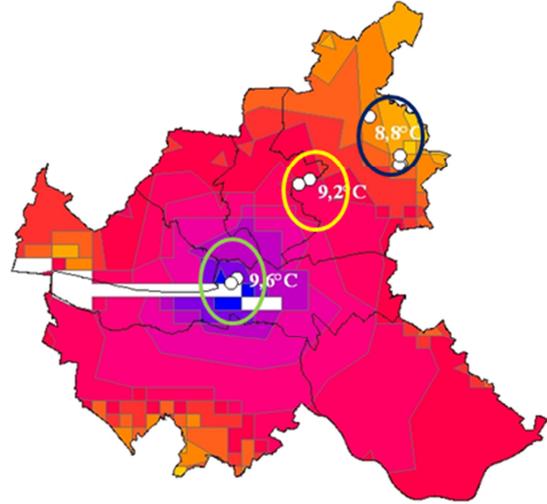


Fig. 1: City of Hamburg with interpolated temperature data for the time period 1971-2000. White dots show geographical position of study sites. Ellipsoids display locations: green: 'urban', yellow: 'suburban', blue: 'rural'.

In order to select trees for the proposed study on growth of urban street trees along the urban-to-rural gradients, the *Hamburger Baumkataster* was used. Two sites per location (i.e. 'urban', 'suburban', and 'rural' shown as ellipsoids in Fig. 1), one each per species, were searched to establish the above-mentioned temperature gradient. In winter and summer 2010, six sites with roadside trees of the species *Tilia x vulgaris* and *Acer platanoides* were selected. Site location ranged from the city centre to the north-eastern outskirts. Requirements of the sites were: comparably high soil sealing of tree bases, proximity to streets and planting of trees during the time span from 1970-1979. Within the city-boundaries and only about 10 kilometres from the urban sites ("Neustadt"), a residential area ("Steilshoop") was used as the suburban location. Farthest from the urban location (15-19 km), two sites ("Rahlstedt" and "Bergstedt") that were about 4 kilometres apart from each other but showed the same mean temperatures in interpolated data were selected to represent the rural location. With regard to urban soils, identifying sites with a similar degree of soil sealing was difficult, because the register for urban trees does not contain information on soils and their degree of sealing. Therefore, in late summer of 2010, two additional sites were selected at the rural location. These sites showed more similar soil sealing to the urban and suburban sites than the initially chosen rural sites. At these additionally chosen sites, *Tilia* trees were planted in 1978, while the trees of the *Acer*-site were planted in 1980-1982 and, thus, somewhat later than trees at all other sites (1970-1979). Aiming to contrast growth and vitality of *Tilia x vulgaris* and *Acer platanoides* between sites differing in soil sealing but not in climatic conditions, the rural sites chosen in 2010 were retained for the purposes of this study.

2.2 Temperature measurements

From July 17th 2010 to March 2012, temperature measurements were taken at the study sites over 30 minute intervals. Instruments used were temperature loggers with a measuring range from minus 20° C to plus 60° C (*Ebi 20 T*). Before using the instruments, loggers were 2-point calibrated by the manufacturer. One temperature logger was fixed per site in a small white wooden house that allowed for air flow through the slat-walls but kept instruments dry from precipitation. Houses were fixed in the tree crowns at a height of approximately 3 m. In order not to damage the bark of tree stems, rubber straps were used to fasten the houses. Using a corresponding interface, data from loggers were uploaded regularly in situ to a Laptop with the software program *Winlog.basic* (*Ebro 2008*).

2.3 CO₂ measurements

Atmospheric carbon dioxide in heavy traffic regions is higher than in the surrounding, less urbanized areas. Consistent with this, a gradient in CO₂ content of ambient air was assumed for the locations representing the urban-to-rural gradient. For comparison of atmospheric CO₂ concentrations between the city centre and the more rural outskirts, measurements were conducted from April 2010 to November 2011 using a portable photosynthesis system LC pro+ (*ADC Bioscientific Ltd.*) directly at the study sites. For field work, reference data of the ambient air as well as analyzed data of the vacant leaf chamber were used. First values were recorded at the earliest after five minutes of instrument warming and when the difference between reference and analyzed data were not higher than 4 ppm. Ten CO₂ measurements were recorded consecutively at two minute intervals for each month at each study site.

Due to heavy traffic within the city, data collection spanned from 08:30-12:00. To assure comparability of measured CO₂ data in spite of the time difference, a correction value was calculated. Measurements at each location were taken in April 2011 on three consecutive days at one site from 08:30-12:30 at 30 minute intervals. Approximated values documented for each location were subtracted from the location-specific CO₂ value that was measured at 08:30, when measurements started. Thus, to adjust CO₂ values for each site to the same time of the day (08:30), the correction value (2-15 ppm) was added to the originally measured CO₂ values.

2.4 Stem circumference

As an indicator of tree vitality, stem growth was measured throughout the growing seasons of 2010, 2011 and 2012. Stem circumferences were measured with non-invasive permanent tree diameter cords (*DI* by *UMS*). Ten trees per site were equipped with measuring tapes, shortened to overlap no more than 10 cm and fixed at a height of 2.60 m to protect them from damage, displacement or removal. The number of cords fixed in early spring 2010 was 60. In late summer 2010, a further 20 cords were installed at *Tilia* and *Acer* trees of the newly chosen 'rural sealed' sites. Thus, a total of 80 tree diameter cords were installed. Despite fixing cords at a height safe from vandalism, three

cords were lost during the period of measurement. Four additional cords were rendered useless in 2012 as they were forced open most likely due to stem growth.

From April to October 2010, stem growth measurements were taken monthly at six sites (urban sealed, suburban sealed, rural unsealed). For sealed sites at the rural location, observations and measurements were conducted at eight sites from April to October 2011. In 2012, all remaining tapes at the eight sites were monitored from July to October. Diameter data were converted into circumferences and translated into percentage of monthly and annual stem growth for each tree.

2.5 Crown plumbing

Tree crowns of both species were studied in early spring of 2012. For plumbing, crowns of eight trees per site were measured for total height and the radius at 45° intervals of the cardinal directions around the tree stem (North, Northeast, East, Southeast, South, Southwest, West, and Northwest). One mean averaged over all eight radii was used as a proxy for the crown radius in the volume formula of a paraboloid, which is the geometric figure most likely to approximate the shape of the studied tree crowns. Volumes of crowns were estimated without measuring leaf sizes or leaf density and by assuming comparable crown characteristics at all sites within species.

2.6 Soil analyses

Substrate and type of soil as well as physical and biological traits (soil fabric, content of building rubble, visible carbonate or humus, soil fauna content) were identified by establishing one flat excavation at each site based on the German soil survey mapping method (Ad-Hoc-Arbeitsgruppe Boden 2005). Soil profiles were excavated with due prudence to a depth of approximately 40 cm after checking the latest conduit plans of sites from each of the concerned building companies. Thereafter, deeper soil for chemical soil analyses was extracted cautiously using a “Pürckhauer-borer” (*Eijkelkamp, Agrisearch Equipment*).

For measurements of soil moisture, soil samples were collected five times from May 2011 to May 2012 from the bases and grass strips surrounding the studied trees. Except for May/June 2011, all samples were taken over five consecutive days after at least three days without precipitation. At each site, the bases of five trees were chosen for soil extraction. Holes were arranged circularly around each tree stem at various distances and dug with help of an “Edelman-borer” (*Eijkelkamp, Agrisearch Equipment*). Borings were taken to a depth of 30 cm at least five times and divided into depth increments of 0-10, 10-20 and 20-30 cm. As far as possible (when no barriers due to underground sealing or rubber waste occurred), soil extraction was taken out of the same drill. Soil samples were deposited in air- and water-proof plastic bags, separated for each depth interval, to produce representative samples for each tree base. Filled plastic bags were stored in a cooling-chamber until analysis (up to one week from time of soil excavation).

Soil moisture was determined gravimetrically in the laboratory: approximately 5 g of the pooled samples were weighed before and after drying a soil sample in an oven for 24 hours at 105° C. Analysis of nutrient contents was carried out with the remaining pooled

samples. Soil pH was determined with part of the soil sample using a pH-Meter and a CaCl₂ solution. For analyses of soil conductance, samples were dissolved in H₂O and measured with a conductivity-Meter.

2.7 Budding

From March 21st to April 25th 2011, crowns of five trees per site were photographed twice a week using a digital camera (model Panasonic Lumix DMC-FZ 38). Pictures were taken with the same camera settings between 09:00 and 12:00 of the south-facing branches. As no tripod was used, photographs were taken by the same person, which allowed for an approximately uniform height.

Analysis of photographs was carried out with the graphic software program Windows Paint. Buds of a whole picture section, containing at least 120 buds, were counted and set as 100 %. Bud stages were assigned only after completing this initial step for all photographs. This was necessary to get an overview of all the bud phenophases and to identify five stages. In order to minimize conflicting estimation of bud stages by individual errors, pictures were analyzed by the same person on successive days. Buds that were not swollen yet (P1) were assigned to the dormant winter stage and not counted or included in the analysis. Thus, counting started when most of the buds were already in the swollen stage (P2) and ended when fully developed flowers or leaves (P5) were visible. In order to compare the tree crowns with each other, a phenological index (PI) was calculated for which percentage shares of each relevant stage (P2-P5) were added together and divided in the following way:

$$PI[\%] = P5 \% + (P5 \% + P4 \%) + (P5 \% + P4 \% + P3 \%) + (P5 \% + P4 \% + P3 \% + P2 \%) / 4 \quad (1)$$

Tab. 1: Exemplary numerical data for the calculation of the Phenological Index (PI [%]).

	P1	P2	P3	P4	P5	Σ / Ø
N	0	45	59	25	17	146
% of 146	0	30.8	40.5	17.1	11.6	100
PI [%]	0	100	69.2	28.7	11.6	52.4

2.8 Data analyses

All statistical analyses were conducted and figures were generated with the statistic program STATISTICA (*Statsoft*, version 9). All graphs show one-way ANOVA's, whiskers display standard errors (coefficient=1), outliers and extreme values are not shown. For all statistical analyses, location (urban, suburban, or time (year, month, and day) was chosen as the independent variable. Assumptions of normality were tested by

the Shapiro-Wilk test and accepted if p-values were > 0.05 . Where required, original data were log-transformed.

In generalized linear models, repeated-measures ANOVAs were calculated to clarify the effect of the current temperature gradient along the sites from urban to rural over the period of 20 months (July 2010 - February 2012). In order to display differences in temperature between the locations at different times of the day, temperature data were split into four 6-hour time zones per day (0:00-06:00, 06:00-12:00, 12:00-18:00 and 18:00-24:00). For corrected atmospheric CO₂ data, a one-way ANOVA and a post hoc test (Tukey HSD) could be conducted as assumptions were met.

Stem growth rates were calculated using relative values in percent [%] generated from diameter values in centimetre [cm]. Cessation of stem growth was defined as an incremental growth of < 0.1 %. As neither normal distribution nor homogeneity of variance could be reached for monthly stem circumference data, and the loss of some dendrometer cords led to an unbalanced design, differences between locations were tested with the Kruskal-Wallis test. Instead of using a post hoc test for differences between two groups at a time, Mann-Whitney-U-tests were used for each site. For annual stem growth data and tree crown measurements, assumptions for ANOVA were met and a one-way ANOVA with the Tukey HSD test were calculated for each species.

For analyses of budding, statistical analyses were conducted for both species when the majority of buds of at least one studied tree had entered stage P2. This was approximated by using photographs taken on April 4th for *Acer* and April 15th for *Tilia*. The bud development, as expressed by the "PI", was used for both species as the dependent variable, and sites as the independent variables.

The normal distribution was not found in the budding records and even transformed data (arcsin square root) did not show normal distributions. As Lindman (1974), however, describes the F-Test (ANOVA) to be remarkably robust to deviations from normality and homogeneity in variances matched with budding data, a one-way ANOVA was calculated.

To calculate linear correlations between interval-scaled temperature and bud burst or soil moisture and bud burst, daytime temperatures were averaged over single months from November 2010 to March 2012. Because data violated parametric assumptions as they were not normally distributed, the Spearman's correlation coefficient (r) was calculated. For both species only graphs with the highest correlation coefficients between PI and temperature, and PI and soil moisture, are shown. Differences in soil moisture between the sites of *Tilia x vulgaris* and *Acer platanoides* were calculated separately for each species, with one-way ANOVAs and subsequent post hoc tests (Tukey HSD).

In order to find significant differences in soil nutrients between the sites, one-way ANOVAs followed by Tukey HSD tests were calculated for each species to show heterogeneity of urban soils.

3 RESULTS

3.1 Temperature

Measurements of temperature from summer 2010 to the end of winter 2012 verified the gradient from urban to rural sites. Significantly different temperatures occurred between the locations in all seasons from summer 2010 to March 2012 (Fig. 2) although the seasonal and annual temperatures in 2010-2011 and 2011-2012 differed clearly: Seasonal temperatures diverged between the years by up to 3.1° C (autumn 2010 vs. autumn 2011). Temperatures in summer 2011 were approximately 1.1-1.5° C lower than in 2010, while temperatures of ambient air in autumn 2011 and winter 2011/2012 were noticeably higher than in autumn and winter of 2010/2011. However, significantly highest temperatures were continuously documented for the urban location compared to the other locations in all seasons. Differences in ambient air temperature were highest between 0 and 6 o'clock and then decreased in the course of the day. In spite of that, differences in atmospheric temperatures between the locations were still significant in most cases. From 18-0 o'clock temperatures at the rural sites hadn't fallen as much as those at the suburban and rural sites. Thus, differences in atmospheric temperature between the urban and all other study sites increased again. For the whole time span highest temperatures at the urban location were followed by temperatures at the suburban and finally the rural sites. Although in the beginning of studies interpolated atmospheric temperatures at the rural location were assumed to be equal for all rural sites, data showed significantly higher atmospheric temperatures at the sealed sites in both years almost continuously.

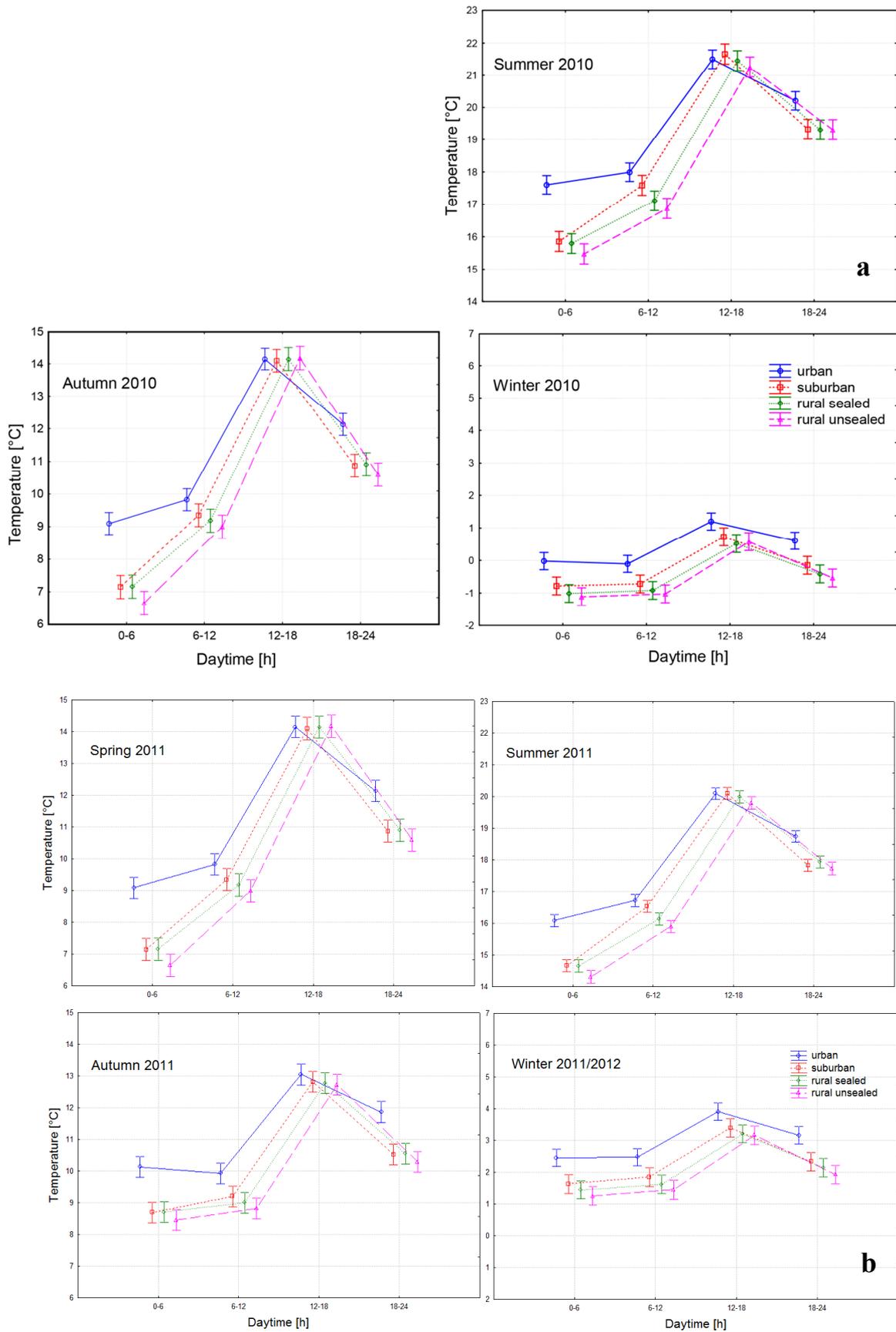


Fig. 2: Approximated ambient air temperatures at studied sites in 2010/2011 (a) and 2011/2012 (b). Error bars show mean standard error. Note different scaling of temperatures for seasons.

Tab. 2: Significant differences in atmospheric temperatures between the locations and differently sealed sites calculated by Tukey-HSD-tests. Abbreviations and symbols: *** = $p < 0.001$, ** = $p < 0.01$, * = 0.05, n.s. = not significant.

Daytime	Location	2010-2011				2011-2012			
		Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	
0-6	u-su	***	***	***	***	***	***	***	
	u-rs	***	***	***	***	***	***	***	
	u-rus	***	***	***	***	***	***	***	
	su-rs	n.s.	***	***	n.s.	n.s.	n.s.	***	
	su-rus	***	***	***	***	***	***	***	
	rs-rus	***	***	***	***	***	***	***	
6-12	u-su	***	***	***	***	***	***	***	
	u-rs	***	***	***	***	***	***	***	
	u-rus	***	***	***	***	***	***	***	
	su-rs	***	***	***	***	***	***	***	
	su-rus	***	***	***	***	***	***	***	
	rs-rus	***	***	***	***	***	***	***	
12-18	u-su	**	***	***	n.s.	***	***	***	
	u-rs	n.s.	***	***	n.s.	***	***	***	
	u-rus	***	***	***	n.s.	***	***	***	
	su-rs	***	n.s.	***	n.s.	***	n.s.	***	
	su-rus	***	***	***	n.s.	***	n.s.	***	
	rs-rus	***	**	*	n.s.	***	n.s.	n.s.	
18-24	u-su	***	***	***	***	n.s.	***	***	
	u-rs	***	***	***	***	***	***	***	
	u-rus	***	***	***	***	***	***	***	
	su-rs	n.s.	***	***	***	***	n.s.	***	
	su-rus	n.s.	***	***	***	***	***	***	
	rs-rus	n.s.	***	***	n.s.	***	***	***	

3.2 CO₂

In atmospheric CO₂ concentrations along the urban-to-rural gradient, a difference of approximately 25 and 23 ppm CO₂ was documented in 2010 and 2011, respectively. For both years, data of *Tilia*- and *Acer*-sites were lumped together as differences between the sites of the same location were marginal. Figure 3 visualizes the gradient in bar charts: Significantly higher CO₂ contents were measured for the urban location compared to the unsealed rural sites in 2010 (398 vs. 374 ppm) and 2011 (406 vs. 384/383 ppm). Significant differences in atmospheric CO₂ contents also occurred between the urban and suburban location in both years. In 2011, CO₂ contents were measured at sealed and unsealed rural sites. Here, differences were low and not significant.

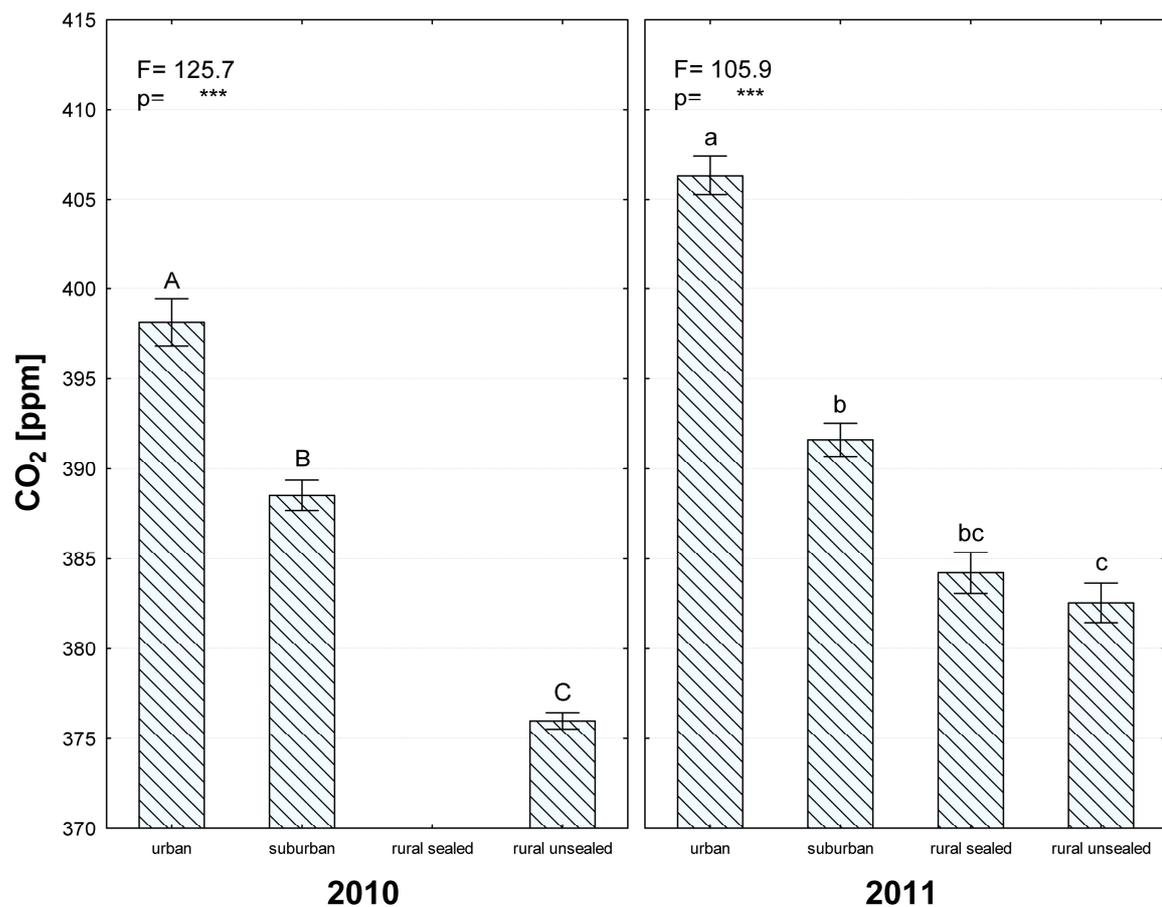


Fig. 3: Atmospheric CO₂ contents in 2010 and 2011 measured at study sites at the urban, suburban and rural location. Whiskers show mean standard error. Letters above bars indicate significances between locations calculated by a post hoc Test (Tukey HSD) after one-way ANOVAs, *** = $p < 0.001$.

Figure 4 visualizes differences in monthly taken data of atmospheric CO₂ contents at urban, suburban and rural sites in 2010 and 2011. Clearest differences appeared between urban and rural sites at the beginning (April) and the end (September) of the vegetation period in both years. In June, differences in atmospheric CO₂ concentration were small, but still differed significantly from each other. Comparison of CO₂ concentration between all sites of the rural location showed no significant differences.

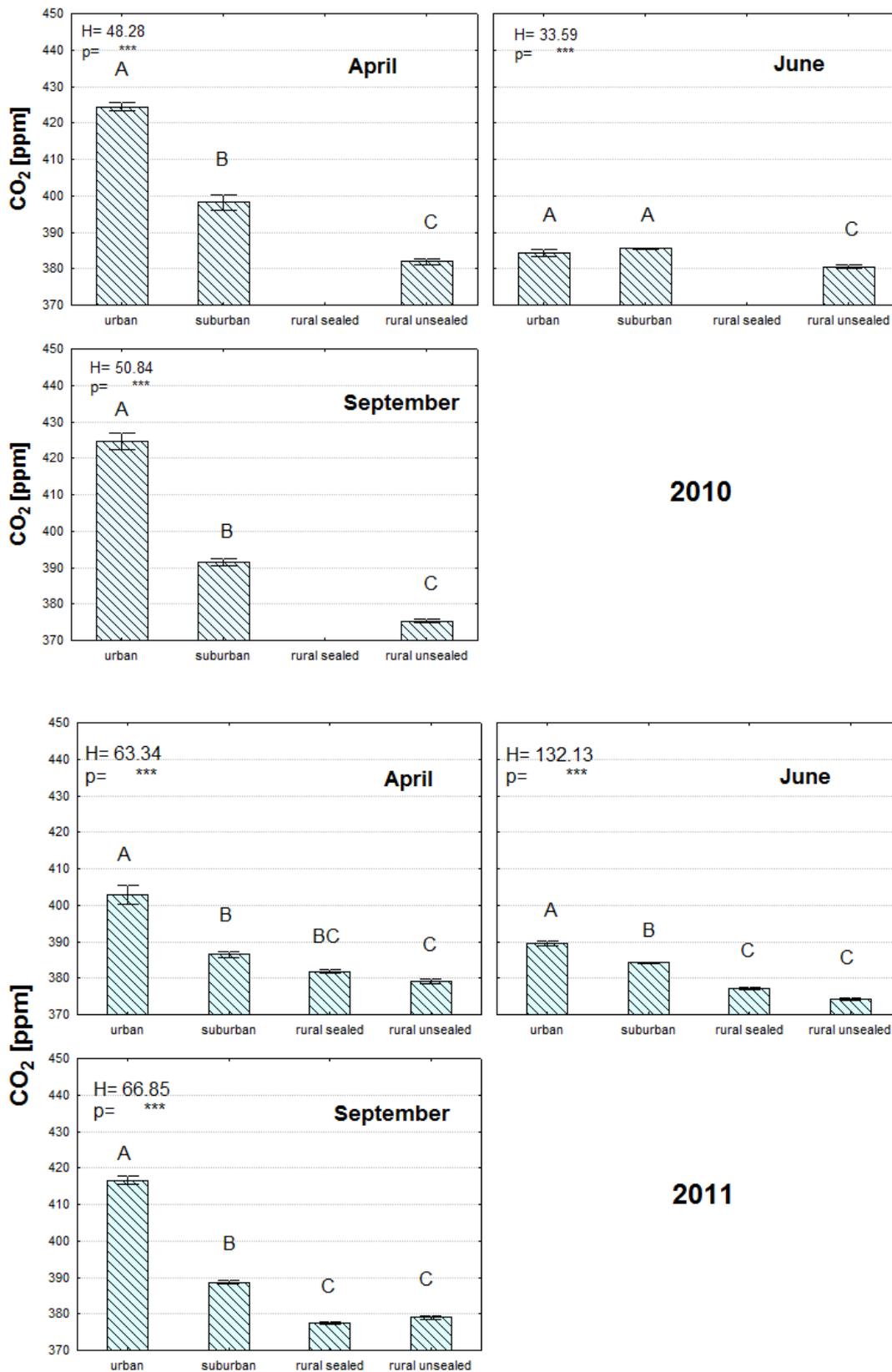


Fig. 4: CO₂ contents measured at study sites from urban to rural locations in April, June and September 2010 and 2011. Whiskers show mean standard error. Letters above bars indicate significances between the locations calculated by a post hoc Test after Kruskal-Wallis testing, *** = p < 0.001.

3.3 Soil

3.3.1 Soil profiles

Soils of all studied sites showed typical ‘urban soil’ characteristics. They have been and still are influenced by human activities and therefore, the World Reference Base (WRB) names this soil type ‘Anthrosol’. The soil taxonomy refers to the often not clearly definable young horizons and categorizes them into the class of ‘Entisols’. German soil sciences summarize anthropogenic influenced or anthropogenic modified soils as ‘Kolluvisols’. In the following, soil profiles of all eight study sites are described.

Urban sites



Fig. 5 a, b: *Tilia x vulgaris* was planted in a green lane disrupted by access pavements. The profile was dug in a distance from the tree stem of about 1.5 m. Excavation was done up to a depth of approximately 40 cm.



Tilia x vulgaris

As the genesis of soil originated from tree pits, refilled with a sandy substrate and rubber waste, the soil profile showed a typical A-C horizon sequence

jAh1-jAh2-M-Cv

of an ‘Anthrosol’ (‘Norm-Kolluvisol’) from fine sand containing small detritus and carbonate. Substrates beneath 4 dm surely still generated from human activity as borings with a “Pürckhauer” contained remains of settlement here. In the first 12 cm the Ah-horizon clearly contained lava granulates. The type of soil changed from silty sand to pure sand and in a depth of 37 cm the soil was defined as the highly weathered C-horizon with very low bulk density. Bulk density was also very low in the first 2 cm, but rose slightly from the A- to the M-horizon. Indeed, content of humus was high in the uppermost horizon, but moisture was low due to the coarse pore of sandy substrate and changed swiftly into a little fertile (dystric) substrate. Fine roots in the upper horizons occurred densely while they together with coarse

roots appeared in low density from 12 cm on in the M-horizon. Neither in borings with the “Edelman-borer” which were conducted for soil excavation nor in the soil profile itself, any edaphon was found.



Fig. 6 a, b: Soil profile for *Acer platanoides* was dug in a distance from the tree stem of about 1.5 m. Therefore, a pavement slab had to be lifted. Pürckhauer borings helped identifying soil characteristics.



Understorey species in the tree bases were rarely found. Occasionally *Hordeum murinum* and *Taraxacum* spec. were observed.

Acer platanoides

Soil excavation showed the A-C profile of a 'Calcaric-Regosol' ('*Sour-Pararendzina*') with the horizon-sequence:

jAh-jlCv-jelCv1-jelCv2.

Directly below the pavement, streets of ants appeared and holes of earthworms were recognized. Similar to the *Tilia*-site, tree pits were filled with a sandy substrate that evoked low soil moisture due to little water holding capacity. Clearly differing from the soil of the *Tilia*-site, however, was the natural basic material of gravel and carbonate holding pure sand that was mixed within tree pit construction. The loose substrate of the C-horizon already appeared after 3 cm. In a depth of approximately 8 cm building rubble like tile rests increased carbonate content. High sealing and little space forced strong roots of trees to switch to the surface. A dense net of fine roots below the paving slab was characteristic. Bulk density was moderate and decreased slowly in the dug up 35 cm. Content of humus was high in the Ah-horizon with low soil moisture. Within the next centimetres, water content swiftly further decreased. Fine roots in the upper horizons occurred densely in the first 8 cm. In deeper layers no roots were found.

Suburban sites



Fig. 7 a, b: At the suburban site, *Tilia x vulgaris* was planted into green strips and a soil profile was dug about 1 m away from tree stem.



Besides the grass, found understorey vegetation was *Poa annua*, *Taraxacum* spec. and *Plantago major*.

Tilia x vulgaris

A typical 'Anthrosol' with the horizon sequence

jAh-M-Cv

was found. As digging was easy and no conduits were in the direct surrounding of the profile construction, soil in a depth of more than 55 cm could be exposed and showed up the original natural soil (starting with another Ah-horizon). The sandy substrate in all depths of the uppermost anthropogenic soil showed only low moisture and soil bulk density. Humus contents were high in the first 12 cm, decreased to the loose substrate of the C-horizon that started in a depth of approximately 30 cm, and then increased again at a depth of about 55 cm, where the original Ah-horizon began.

Contrary to the urban sites, rooting of trees was strong: In the first 12 cm intensity of fine roots was moderate and also coarse roots appeared. In the C-horizon and the original Ah-horizon, no roots could be observed.



Fig. 8 a, b: *Acer platanoides* at the suburban site was planted into green strips. Soil sealing underneath the turf grass in form of lawn-grating slabs appeared and left open a free surface of about 30 %.



filled soil. Conspicuously often, the grass strip was contaminated with dog mess.

Acer platanoides

For the suburban *Acer*-site a ‘Regosol’ with the horizon sequence

jAh1-jAh2-jCv1-jCv2

was found. A-horizons up to a depth of 12 cm were of silty sand substrate. From this depth on the C-horizons followed. They were loose and allowed digging up a soil profile to a depth of about 36 cm. In the surface layer (0-2 cm), humus content of the Ah-horizon was very high and only little lower within the next centimetres. In the C-horizon that started from approximately 12 centimetres, content of humus was marginal. For the whole profile, moisture was low but increased to some degree in the lowermost depth. Rooting intensity was moderate to high in the Ah-horizon but very low to absent in depths from 12 cm on where the loose substrate of the C-horizon began. Carbonate could not be proved in any depth. As in the other profiles before, the studied soil was anthropogenic

Sealed rural sites



Fig. 9 a, b: Trees were planted into green strips that were frequently interrupted by paved building drives. Partly, tree bases were planted with spring flowers.



Carpinus betulus implemented the abundance of these seedlings. In the not horticulturally cultivated tree bases, edaphon was not found except for one beetle larva.

Tilia x vulgaris

Trees at the sealed rural sites rooted in a typical 'Anthrosol' with the dug up horizon sequence

jAh-M-IIcV.

Anthropogenic filled substrates were of silty sands up to a depth of approximately 35 cm. The uppermost layer, building the Ah-horizon in the first 10 cm only slightly differed from the following M-horizon. However, slags were characteristic here. Both horizons showed moderate humus contents and low bulk densities. Soil moisture was low for both horizons but higher in the Ah-horizon for those tree bases that were planted and watered by residents. However, density in rooting of *Tilia x vulgaris* was higher in the deeper M-horizon: While in the Ah-horizon only fine roots stretched out, the deeper M-horizon was moderately colonized by fine and coarse roots. Below the M-horizon a change in substrates was found: In a depth of about 35 cm a loose C-horizon from loamy sand was stripped. Different from all other studied sites, rubber waste was not found and negative tests on carbonate content underlined these observations.

Overall, green strip characteristics were heterogeneous. Partly tree bases were planted, watered and raked. Besides planted spring flowers, the understorey consisted of seedlings of *Quercus spec.* and *Crataegus spec.*, as well as grasses like *Poa annua* and *Hordeum murinum*. Closeness of the soil profile to a hedge of



Fig. 10 a, b: Green strips at the sealed rural sites for *Acer* were narrow. Supplementary to the filling of tree pits a humus substrate coated tree bases.



Rosa species were found. Besides *Crataegus* spec. seedlings of the studied trees grew in the strip.

Acer platanoides

The soil profile dug in the *Acer*-site showed the horizon sequence of a typical 'Anthrosol' that was overlaid by application of a mull. Therefore, the horizon sequence was defined as

jAh1-jAh2-M1-M2.

Loamy silts were the substrates within the first 30 cm of Ah-horizons. In spite of the loamy character and high humus contents, soil moisture was weak and aggregates of soil substrates were hardly built. Bulk density was very low. Fine roots were found in strong frequency in the first 15 cm. In the Ah2-horizon from 15-30 cm dense rooting was even stronger and accomplished by moderate abundance of coarse roots. A sharply restricted occurrence of coarse soil in the Ah2-horizon was peculiar. Building waste was only found in steel wires and carbonate content was tested negative. The M-horizon from 30-60 cm was of sandy silt and rooting densities decreased with increasing depth. In spite of high humus contents, also in the M-horizon soil moisture was weak and bulk density was very low. In a depth from 60 cm the substrate excavated changed to silty sand.

Understorey of roadside trees was planted and covered the grass strip completely. Most often

Rural unsealed sites



Fig. 11 a, b: *Tilia x vulgaris* was planted into a green strip that was disrupted by a dry drainage channel and private driveways.

*Tilia x vulgaris*

The profile exhibited an anthropogenic impacted ‘Cambisol’ with a change of layer and the horizon sequence

jAh1-M-IIcAh-IIBv.

The surface soil consisted of loamy sand substrates and the soil fabric was partly coherent despite low soil moisture. Humus content was high in the uppermost layer and still moderate in the M-horizon from 10-24 cm. The intensity of rooting, however, was only moderate and coarse roots were not observed in the anthropogenic soil. The high content in rubber waste that was supplied by a positive testing on carbonate was special to the clearly anthropogenic formed topsoil. Moreover, the high degree of soil sealing was noticed. The change of layer appeared in a depth of approximately 24 cm. The fossil Ah-horizon was of carbonate-free silty sand and was not rooted. This is also true for the following subtype-specifying Bv-horizon. The typical colour reflects release and oxidation of [Fe] due to chemical weathering.

Understorey was hardly found and grass strips showed only weak and patchy growth.



Fig. 12 a, b: Trees were planted into a wide green strip that was disrupted by a ditch drainage and private driveways. The profile was dug about 1 m from tree stem.



Acer platanoides

The soil profile exhibited the horizon sequence

jAh-jM1-jM2-jM3-jM-Go

of a 'Gleyic Anthrosol'. The Ah-horizon had a depth of about 10 cm and was very rich in humus. Soil moisture in contrast, was weak and according to that, the plasticity of soil samples, too. Bulk density was low and fine roots had developed moderately. The content of humus decreased within the following two M-horizons only little and soil moisture stayed at a low level. In spite of that the soil fabric changed from single grains to a little more sticky fabric. Bulk density was higher than in the uppermost horizon. From 10 cm on, first coarse roots were detected while appearance of fine roots decreased continuously. In a depth from 60 cm on, no roots were found anymore. First oxidative characteristics were found in the jM2-horizon in a depth of 15-29 cm: Few ochre coloured spots

signaling oxidation of iron compounds were found and in the M-Go-horizon they appeared in a moderate frequency implying influences of groundwater.

Edaphon was rarely found in form of earthworms and besides horticultural trimmed lawn only mosses on tree barks and at the tree bases were documented.

3.3.2 Correlation between specific soil characteristics and stem increment 2011-2012

In Table 3 ranking is listed for humus content (H) and sandiness (S) singularly and as a mean of both values. Soil quality ranking followed the scheme:

H: H4 > H3 > H2 > H1 > H0

S: loamy (l) > silty (u) > sandy (s)

→ Ls > Uls > Sl4 > Sl3 > Sl2 > Us > Su4 > Su3 > Su2 > Ss

Best soil quality was ranked as '1', lowest quality as '4'. Highest humus contents were marked 'H4', lowest 'H0'. In soil structure letters were written in upper cases when this type of soil was predominant, lower cases were used for lower proportions of a soil type. Numbers after letters (e.g., Sl2, Sl3) indicate contents of minor soil type, rising from 1 to 4. Humus content was validated higher regarding soil quality for tree growth than soil structure and therewith the sealed rural *Tilia*-soil was ranked '2' (H 2, S 3) while the suburban soil was ranked '3' (H 3, S 2).

Tab. 3: Soil quality ranked by humus content and sandiness for studied soils of *Acer platanoides*- and *Tilia x vulgaris* sites.

<i>Acer</i>	SOM (\triangleq humus content, H)	Soil texture (\triangleq sandiness, S)	Ranking
urban	H4, H1, H1, H1	Su2, Ss, Ss, Ss	4; 4 → 4
suburban	H4, H3, H1, H0	Su2, Su2, Ss, Su3	3; 3 → 3
sealed rural	H4, H4, H4, H4	Uls, Uls, Us, Su4	1;1 → 1
unsealed rural	H4, H3, H3, H3, H1	Sl2, Sl3, Sl4, Ls4	2; 2 → 2
<i>Tilia</i>	SOM (\triangleq humus content, H)	Soil texture (\triangleq sandiness, S)	Ranking
urban	H4, H3, H2, H1	Su2, Ss, Ss, Ss	4; 4 → 4
suburban	H4, H1/4, H1, H3	Su2, Sl2, Ss, Sl4	3; 2 → 3
sealed rural	H3, H3, H0	Su3, Su3, Su2	2; 3 → 2
unsealed rural	H4, H3, H3, H1	Sl2, Sl3, Su4, Su4	1; 1 → 1

In sites of both species ranking displayed an urban to rural gradient. Findings in general reflect the stem growth of studied trees. The higher the ranking for soil quality was (i.e. 1>2>3>4), the higher stem growth appeared to be. However, a correlation between soil quality and tree stem increment was only found in *Tilia* as graphics below suggest (Fig. 13). In a spearman's rank correlation the R was low in *Acer* (17%; $p=0.08$) while in *Tilia* more than 42% of stem increments were explained by soil ranking ($p < 0.001$).

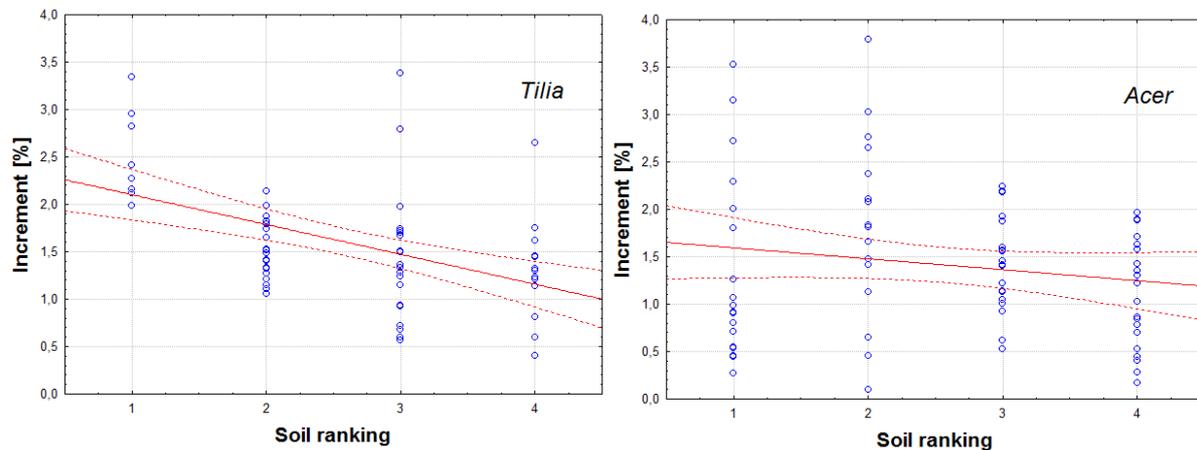


Fig. 13: Relation between stem increment and soil ranking for *Tilia x vulgaris* and *Acer platanoides*.

3.3.3 Soil moisture

Month-specific differences in soil water content

Differences in soil water content between the examined months from 2011 to 2012 are shown in Figure 14. As the pattern between all sites appeared similar, monthly data were summed and locations were not taken into account. Overall, water content was low in late spring and high in mid and late winter for both species. Moreover, a decline of soil water content from the surface (0-10 cm) to a depth of 20-30 cm was found. Soil moisture decreased from approximately 14 to 7 % w/w from the topmost to the deepest soil layer in May / June 2011 and 2012 and from 21 to 13 % w/w in January and March.

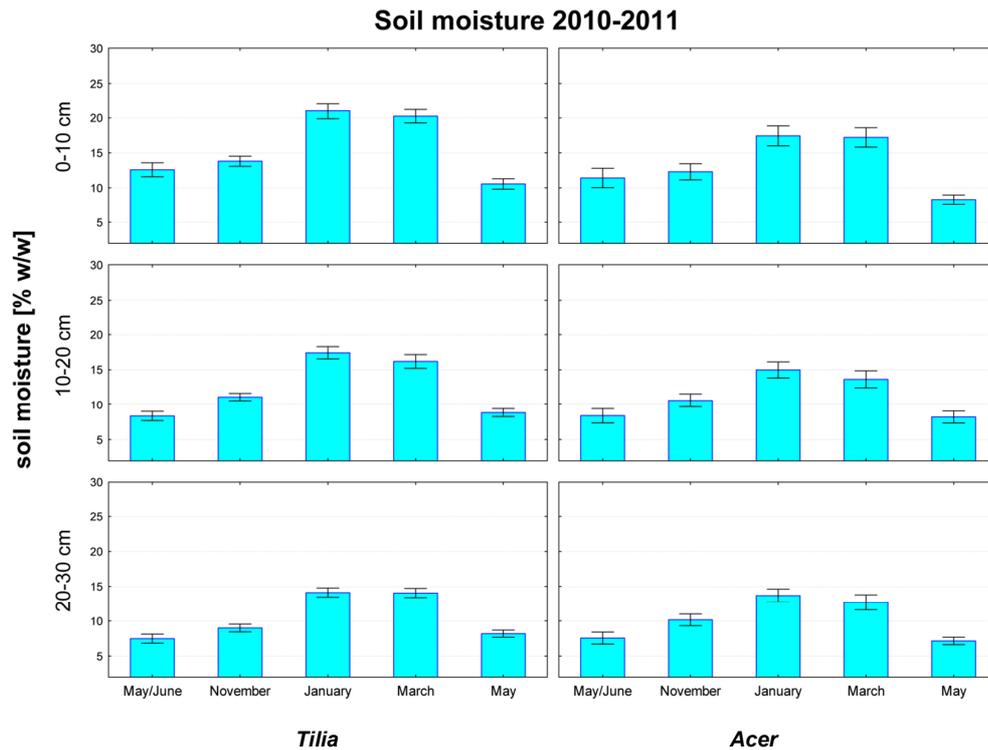


Fig. 14: Mean soil moisture from May 2011 to May 2012 in depths from surface to -30 cm, error bars show mean standard error.

Site-specific differences in soil water content

As the patterns of soil moisture were similar in all studied depths and months, data were summed for each site. Figure 15 clearly points out significantly higher soil moisture at the sealed rural sites. Moreover, data show differences between the *Tilia*- and the *Acer*-sites: While except for ‘rural sealed’, the *Tilia*-sites hardly differed from each other, soil moisture was much lower at the urban *Acer*-site compared to all other sites.

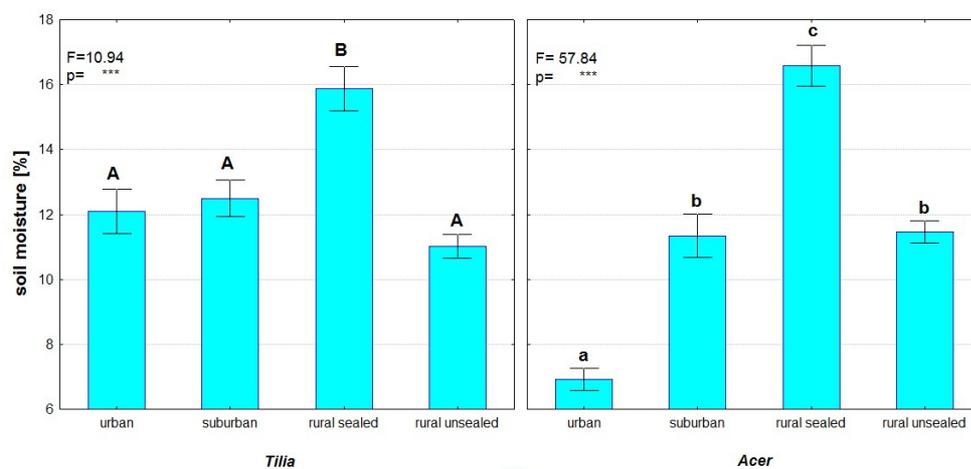


Fig. 15: Site-specific mean soil moistures from May 2011 - May 2012 in depths from surface to -30 cm, error bars show mean standard error, letters above bars indicate significant differences according to Tukey-HSD-Tests after one-way ANOVAs; F and p values refer to log-transformed data, $p^{***} < 0.001$.

3.3.4 Correlation between soil moisture and stem increment 2012

Neither in any depth nor month circumference growth of tree stems and soil moisture showed a correlation. This is true for *Tilia* as well as for *Acer*.

3.3.5 pH

The pH values were acidic at all studied sites. *Tilia*- as well as *Acer*-sites showed highest values of approximately 6-6.5 at the urban sites, while soil probes taken from the suburban sites were most acidic (5.1-5.7; Fig. 16). At the rural location, differences in pH were marginal in all soil depths for *Tilia*-sites. At the *Acer*-sites differences in soil pH got more prominent with increasing depths. Yet, differences were not significant.

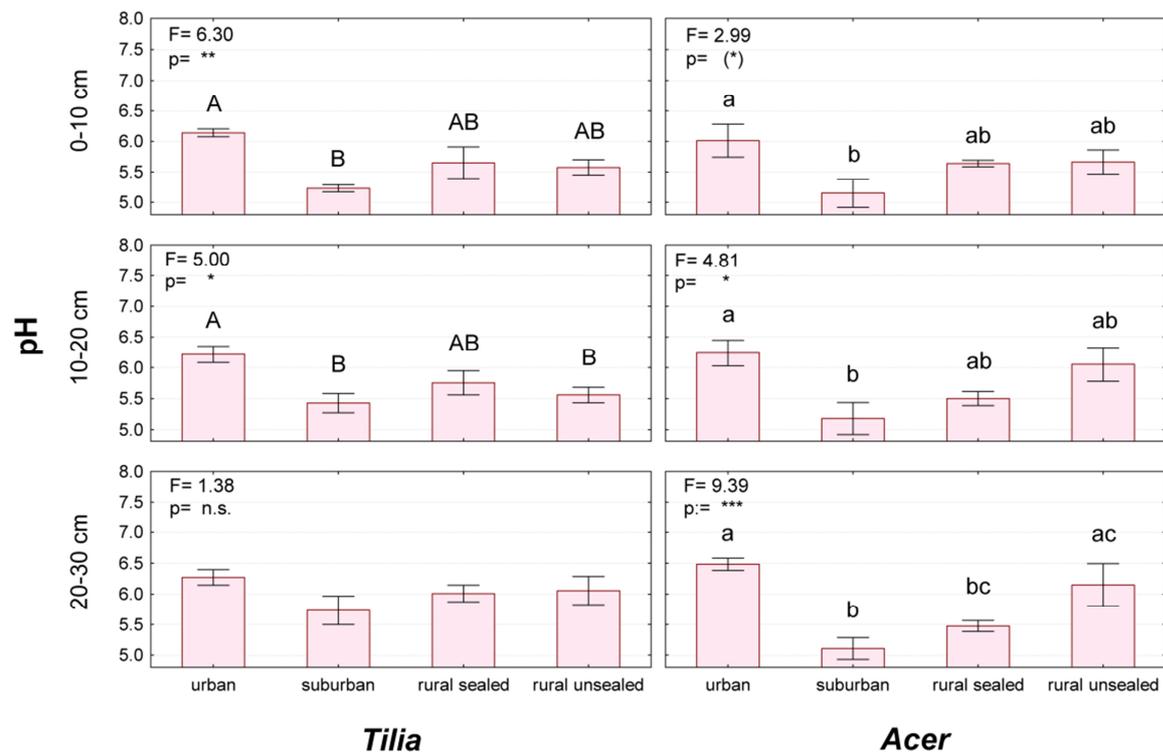


Fig. 16: Site specific mean pH values at studied sites of *Tilia x vulgaris* and *Acer platanoides* in three depths from surface to -30 cm, error bars show mean standard error. Letters above bars indicate significant differences according to Tukey-HSD-Tests after one-way ANOVAs, $p^{***} = <0.001$, $p^{**} = <0.01$, $p^* = 0.05$, $p^{(*)} =$ marginal significance >0.05 , n.s. = not significant.

3.3.6 Soil electrical conductivity

Soil conductivity from the topmost layer to a depth of 20-30 cm ranged between 51 and 188 $\mu\text{S}/\text{cm}$ for *Tilia* and between 90 and 204 $\mu\text{S}/\text{cm}$ for *Acer*-sites (Fig. 17). Highest values were measured at the sealed rural sites both for *Tilia* and *Acer*. However, significant differences hardly appeared between the sites of the species.

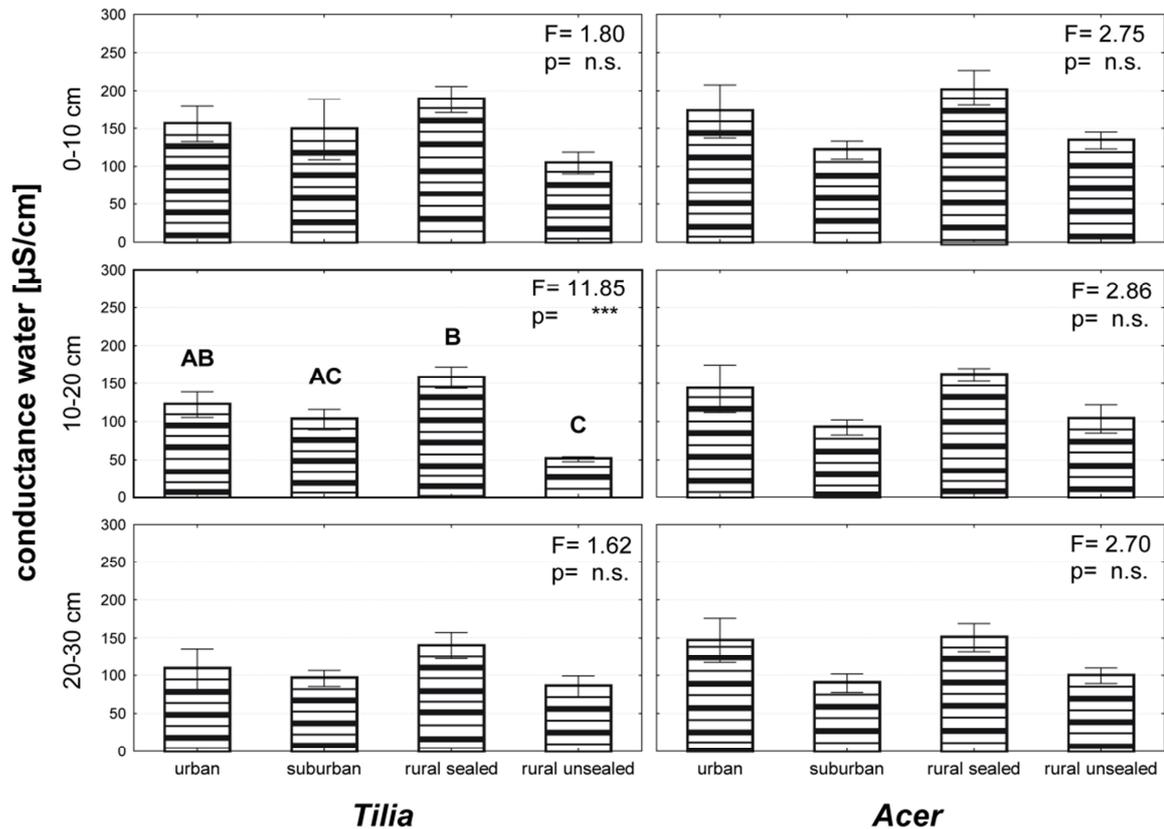


Fig. 17: Site specific mean electrical conductivity of the soils from sites of *Tilia x vulgaris* and *Acer platanoides* in three depths from surface to -30 cm, error bars show mean standard error. Letters above bars indicate significant differences according to Tukey-HSD-Tests after one-way ANOVAs, $p^{***} < 0.001$, n.s.= not significant.

3.3.7 Nutrient analyses

Carbon [C], Nitrogen [N], C/N

Contents of carbon and nitrogen clearly differed both between sites and species (Fig. 18). In *Tilia*-sites, significant differences in carbon and nitrogen content of the soils only appeared between sealed and unsealed sites. In *Acer* differences rarely occurred between the sealed and unsealed sites but within the sealed sites. Overall, significant differences occurred more than twice as often at *Acer*- than at *Tilia*-sites.

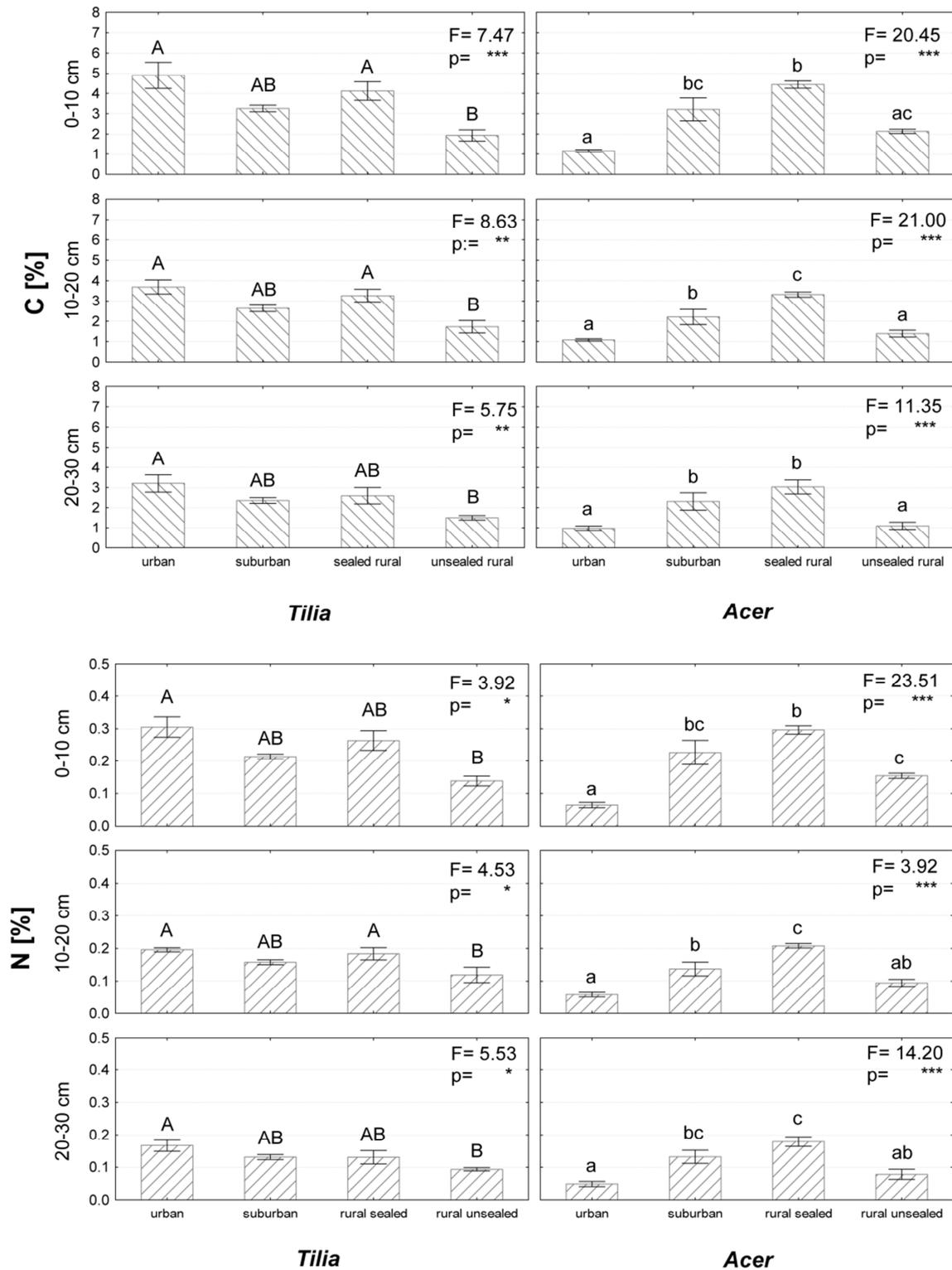


Fig. 18: Site-specific differences in mean carbon [C] and nitrogen [N] contents of soils taken from sites of *Tilia x vulgaris* and *Acer platanoides*, error bars show standard error, letters above bars show significances calculated by Tukey-HSD-Tests after one-way-ANOVAs, p***= <0.001, p**= <0.01, p* =0.05.

Tilia x vulgaris

Tilia-sites showed decreasing soil carbon contents from urban to rural in all depths. In the topmost soil layer, values ranged from 4.9 % w/w at the urban to 1.9 % w/w at the unsealed rural site. Carbon at the sealed rural site, however, was significantly higher than at the unsealed rural site. With increasing depth, site differences weakened and only differences between the urban and the unsealed rural site remained significant. Nitrogen showed an almost identical pattern of differences between the sites: Highest soil nitrogen contents were measured at the urban (0.3), lowest at the unsealed rural site (0.1). In general, the sealed rural site had higher soil nitrogen contents than the unsealed rural site. These differences were significant in a depth of 10-20 cm.

Acer platanoides

In *Acer*-sites, a gradient from low soil carbon contents at the urban site (1.2 % w/w in 0-10 cm) to high contents at the sealed rural site (4.4 % w/w in 0-10 cm) was proven. In all soil depths, C contents at the sealed rural site were more than three times higher at the urban site and fell from topmost to deepest layer. Soil carbon content at the unsealed rural site, however, was clearly lower than at the sealed rural site. Here, it differed significantly in both the upper and lower soil layer. As in *Tilia*, the pattern of soil nitrogen contents appeared almost equal at the *Acer*-sites. Soil N content was very low at the urban site and hardly fell from surface to the deepest layer (~0.05% w/w). At the sealed rural site, soil N contents were more than three times higher (0.3, 0.2 and 0.2 % w/w). Similar to *Tilia*-sites, the sealed site showed higher contents of nitrogen in the soil than the unsealed site at the rural location.

C/N ratios at studied sites ranged between 14 and 21. A trend for decreasing ratios from urban to rural sites was found (Fig. 19).

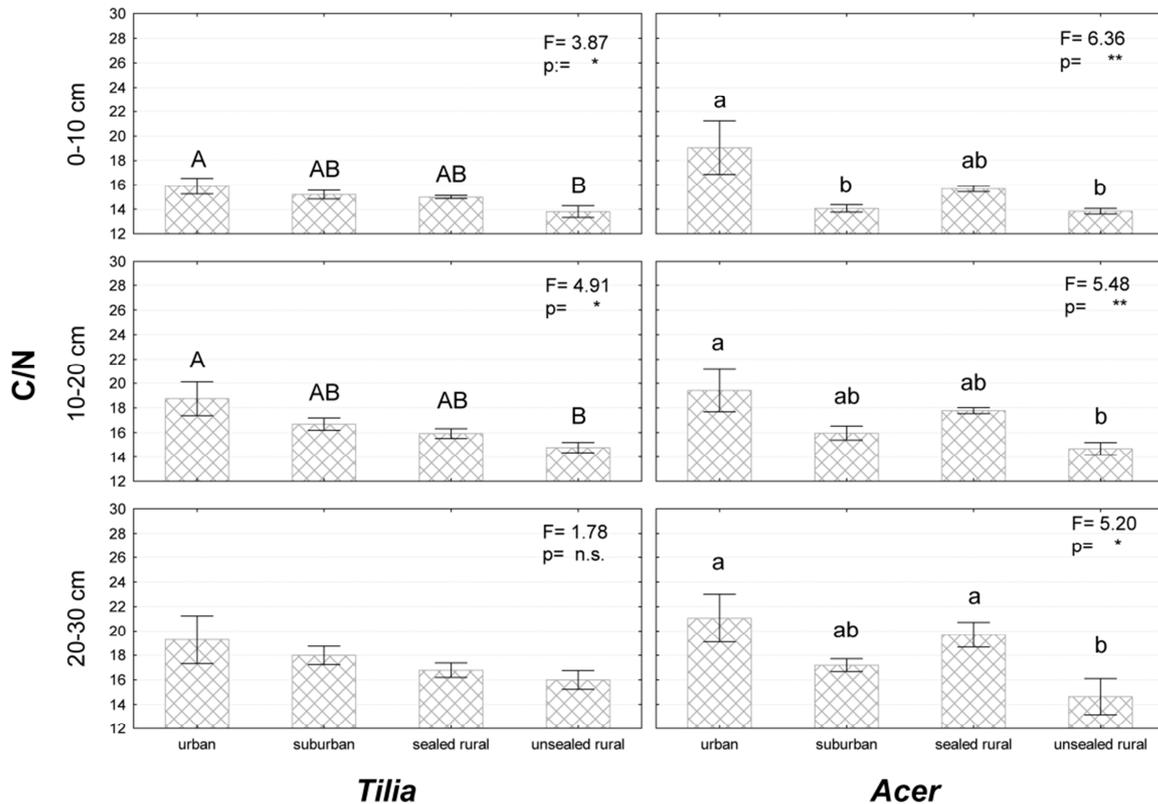


Fig. 19: Site specific mean C/N ratios of the soil taken from different depths at sites of *Tilia x vulgaris* and *Acer platanoides*. Error bars show standard error. Letters above bars indicate significant differences according to Tukey-HSD-Tests after one-way ANOVAs, $p^{**} = <0.01$, $p^* = 0.05$, n.s.= not significant.

Tilia x vulgaris

For *Tilia*-sites, the C/N ratio of the soils decreased continuously from urban to rural sites and it rose with increasing depth (Fig. 19). Significant differences between the sites were found in the soil layers of 0-10 and 10-20 cm. C/N ratios stayed under 20 in all depths and at all sites.

Acer platanoides

Likewise, C/N ratios of the soils decreased from the urban to the rural *Acer*-sites and rose with increasing depth (Fig. 19). A continuous decline was not found, however, as the high C/N ratio at the sealed rural site interrupts the pattern: C/N ratios were higher than at the suburban and unsealed rural site and lower than ratios for the urban site. C/N ratios of soils from the urban sites were significantly higher than those from the unsealed rural site in all soil depths.

Phosphor [P]

Contents of soil phosphor varied in a range from 54.6 mg/kg at the unsealed rural *Tilia*-site to 173.6 mg/kg at the urban *Acer*-site (Fig. 20). Significant differences in P content within one species appeared only in greater soil depths.

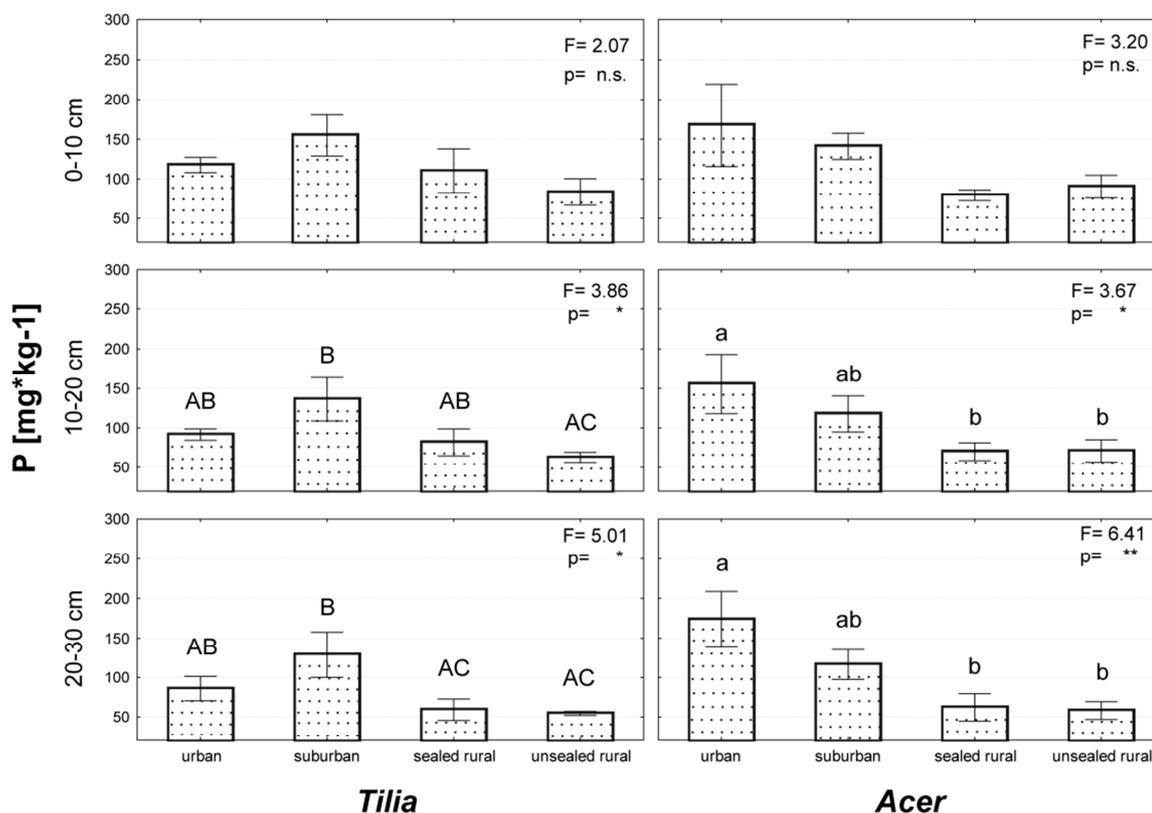


Fig. 20: Site specific mean P contents of soils from sites of *Tilia x vulgaris* and *Acer platanoides*, error bars show mean standard error. Letters above bars indicate significant differences according to Tukey-HSD-Tests after one-way ANOVAs, $p^{**} = <0.01$, $p^* = 0.05$, n.s. = not significant.

Tilia x vulgaris

Site-specific differences in soluble soil P contents were low for the urban and rural sites in all depths. Values ranged between 117.6 mg/kg (urban, 0-10 cm) and 54.6 mg/kg (rural unsealed, 20-30 cm). Samples of the suburban site showed distinctively higher soil P contents in all depths (154.8 mg/kg, 136.4 mg/kg, 128.9 mg/kg). In the soil layers of 10-20 and 20-30 cm soil P contents of the suburban site were significantly higher than those from the other sites.

Acer platanoides

Soil P contents were highest at the urban site and lowest at the rural location in all depths. Nevertheless, P contents from urban and rural sites only differed significantly in the deepest layer. Here soil P content was almost three times higher at the urban than at the rural sites (173.6 vs. 62.3, and 58.3).

Potassium [K]

Soil potassium contents ranged from 242 to 118 mg/kg for *Tilia*-sites and from 188 to 93 mg/kg for *Acer*-sites (Fig. 21). In general, soil K concentration at the sealed sites neither differed for *Tilia* nor for *Acer*. Contents fell from the topmost to the deepest soil layer for both species. Except for the unsealed *Tilia*-site, K concentrations in the deepest layer were similar and differed by only ~60 mg/kg in both species.

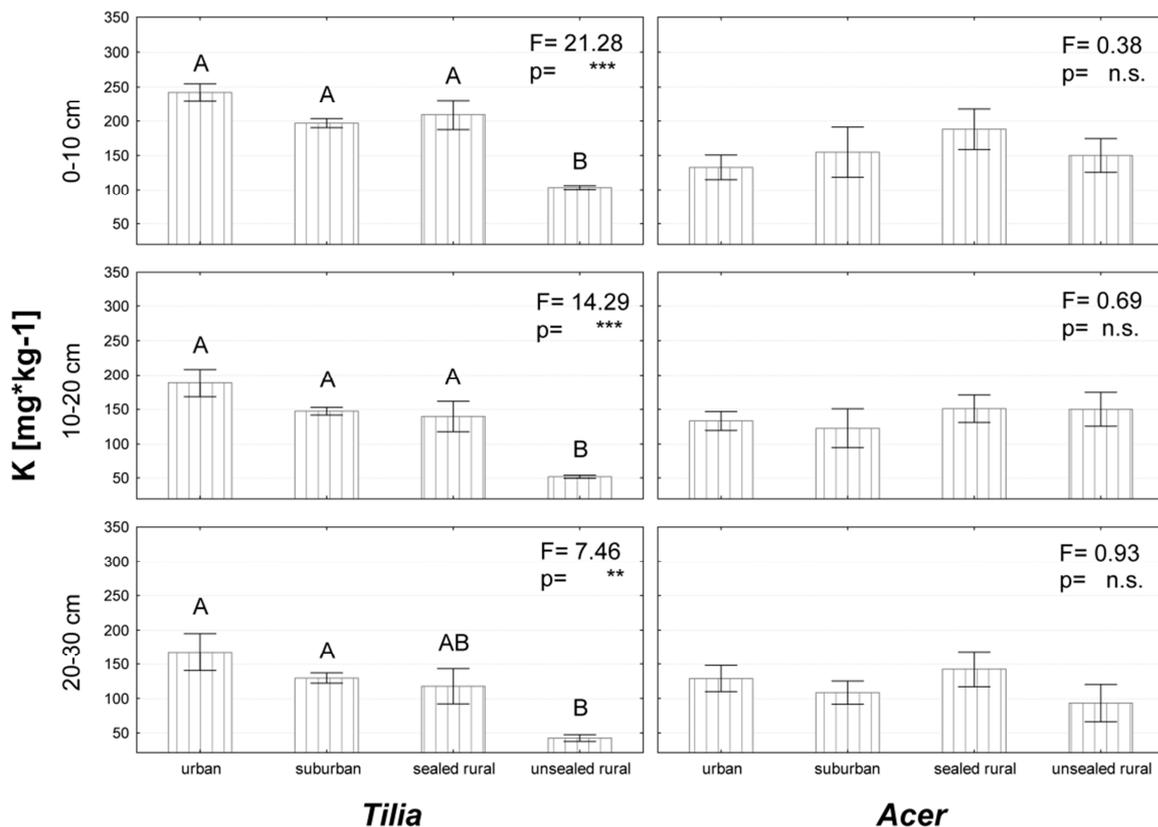


Fig. 21: Site specific mean soil K content at sites of *Tilia x vulgaris* and *Acer platanoides*. Error bars show standard error. Letters above bars indicate significant differences according to Tukey-HSD-Tests after one-way ANOVAs, $p^{***} < 0.001$, $p^{**} < 0.01$, n.s. = not significant.

Tilia x vulgaris

For the sealed rural sites, mean soil K content of *Tilia* was 216 mg/kg in the topmost layer. The unsealed rural sites had a significantly lower content of potassium (103 mg/kg) than all sealed sites. This pattern continued in all soil layers to K contents of 168 to 118 mg/kg for the sealed sites and 43 mg/kg for the unsealed rural site.

Acer platanoides

Soil K contents of all *Acer*-sites did not differ significantly from each other in any depth and a clear pattern for potassium concentrations was not found. Soil K contents slightly decreased with increasing soil depth.

3.4 Stem circumference increment

Stem increment of *Tilia x vulgaris* and *Acer platanoides* differed between the years. In all years, *Tilia* showed highest growth, whereas increments of *Acer* were lowest. Nevertheless, similar patterns appeared in stem growth at the sites in 2010, 2011 and 2012. Low growth of *Tilia* and *Acer* at the sealed urban sites was evident and a trend for higher stem growth from urban to rural appeared for both species in all studied years. Strongest stem increment was measured in June 2010 and 2011. This might also be true for 2012, but data cannot prove this as monthly data acquisition was not conducted from April to July in 2012. Ending of growth was earliest at the urban site in all years. In the following, graphics are shown for stem circumference increment of the examined trees for the years 2010, 2011 and 2012 (Fig. 22-25). Months that show beginning and ending of growth as well as the months of strongest increment are visualized. In the following text, remarkable differences between the sites and conspicuous characteristics are named for each year and species subsequently. As neither normal distribution nor homogeneity of variances for monthly increment of stem circumferences could be reached, non-parametric pair wise comparisons were conducted.

3.4.1 Comparison of monthly growth

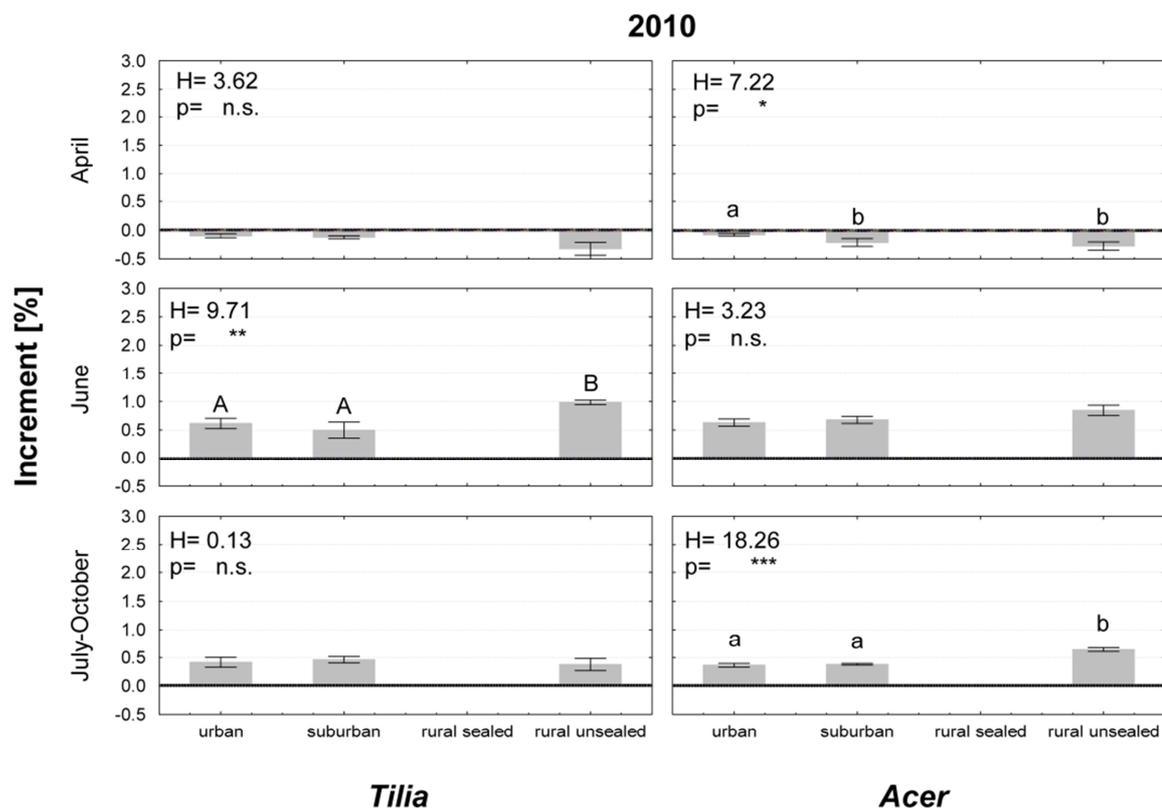


Fig. 22: Monthly stem circumference changes for *Tilia x vulgaris* and *Acer platanoides* 2012, error bars show \pm standard error. Letters above bars show significant differences according to Mann-Whitney U-tests for pairwise comparisons after Kruskal-Wallis tests, $p^{***} = <0.001$, $p^{**} = <0.01$, $p^* = 0.05$, n.s.= not significant.

Tilia x vulgaris 2010

Negative stem growth was measured at all sites in April (Fig. 22). Despite higher circumference decrease from urban to rural, significant differences between the sites were not found in spring. In the month of highest growth (June) significant differences between the sites were obvious: At the rural location stem increment was 0.99% and thus roughly twice as high as at the suburban (0.49%) and still much higher than that of the urban site (0.61%). Cumulated growth data for the months July to October were similar in this time period for all locations and showed no significant differences. Cessation of stem circumference growth for the urban and suburban site was considered for August and October, respectively.

Acer platanoides 2010

Negative stem growth in April showed a pattern similar to *Tilia*: While stem circumference decrease was low at the urban site (-0.08%), shrinkage of tree stems at the suburban and unsealed rural site showed pronounced negative growth (-0.21 and -0.28%). Growth in June was highest at all sites and did not differ significantly from each other. In July, however, differences in growth between the sealed sites and the unsealed rural site were significant (not shown): Growth at the sealed sites had decreased rapidly, while increment at the unsealed rural site was still more than twice as high (0.24 and 0.25% versus 0.51%). Increment rates for August to October showed significantly higher growth at the unsealed site than at the urban and suburban site. Ending of growth was documented in August for trees at the urban and suburban site.

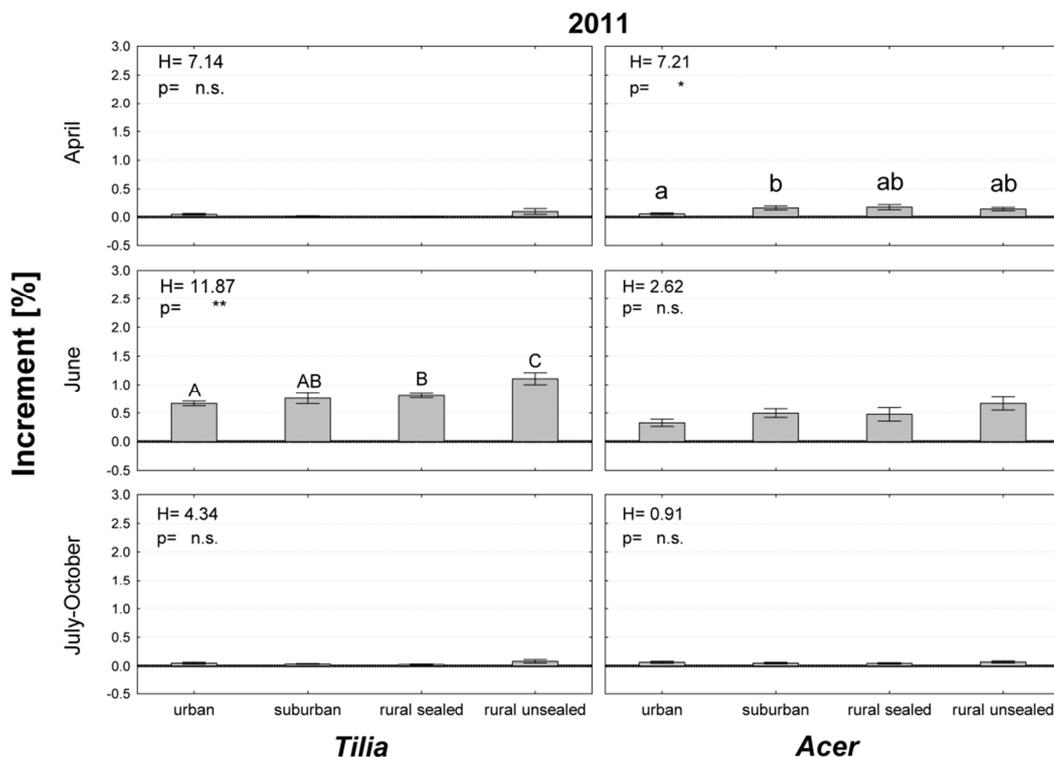


Fig. 23: Monthly stem circumference changes for *Tilia x vulgaris* and *Acer platanoides* 2011, error bars show \pm standard error. Letters above bars show significant differences according to Mann-Whitney U-tests for pairwise comparisons after Kruskal-Wallis tests, $p^{**} = <0.01$, $p^* = 0.05$, n.s. = not significant.

Tilia x vulgaris 2011

Slightly positive growth was measured in April and increment of stems was already strong in May at all sites (

Fig. 23). Higher growth from urban to rural was significant in most cases along the sealed temperature-gradient (i.e. urban, suburban, rural sealed) from May to August (not shown). Similar to 2010, increments of stems decreased at the urban site in July and ceased in August. Growth at the suburban and both rural sites reached cessation in September. A renewed growth of 3 of 8 trees at the urban site caused a high mean value in stem increment rates in September and led to a high variance here. Hence, nonparametric testing between the urban and all other sites showed no significant differences in growth. The end of stem growth, however, appeared for most of the urban trees in October (not shown).

Acer platanoides 2011

Increment of stem circumference for *Acer* was low throughout 2011 at all sites. This is particularly true for trees at the urban site: Strongest mean increment was less than 0.33% in June (

Fig. 23). Moreover, the time span of vegetative growth was short at the urban site: Increment had not started in April yet and cessation of *Acer platanoides* stem growth was already reached in July. Growth at the other sites was higher and longer. However, significant differences in stem circumference growth rarely appeared: Differences in growth neither occurred between the temperature-gradient sites nor between the sites with different soil sealing. Cessation of stem increment was documented in August for the suburban and rural sealed sites and in September for the unsealed rural site. An enhancement of stem circumference growth was measured in October at all sites. Indeed, this was highest at the unsealed rural site, but still below 0.1%.

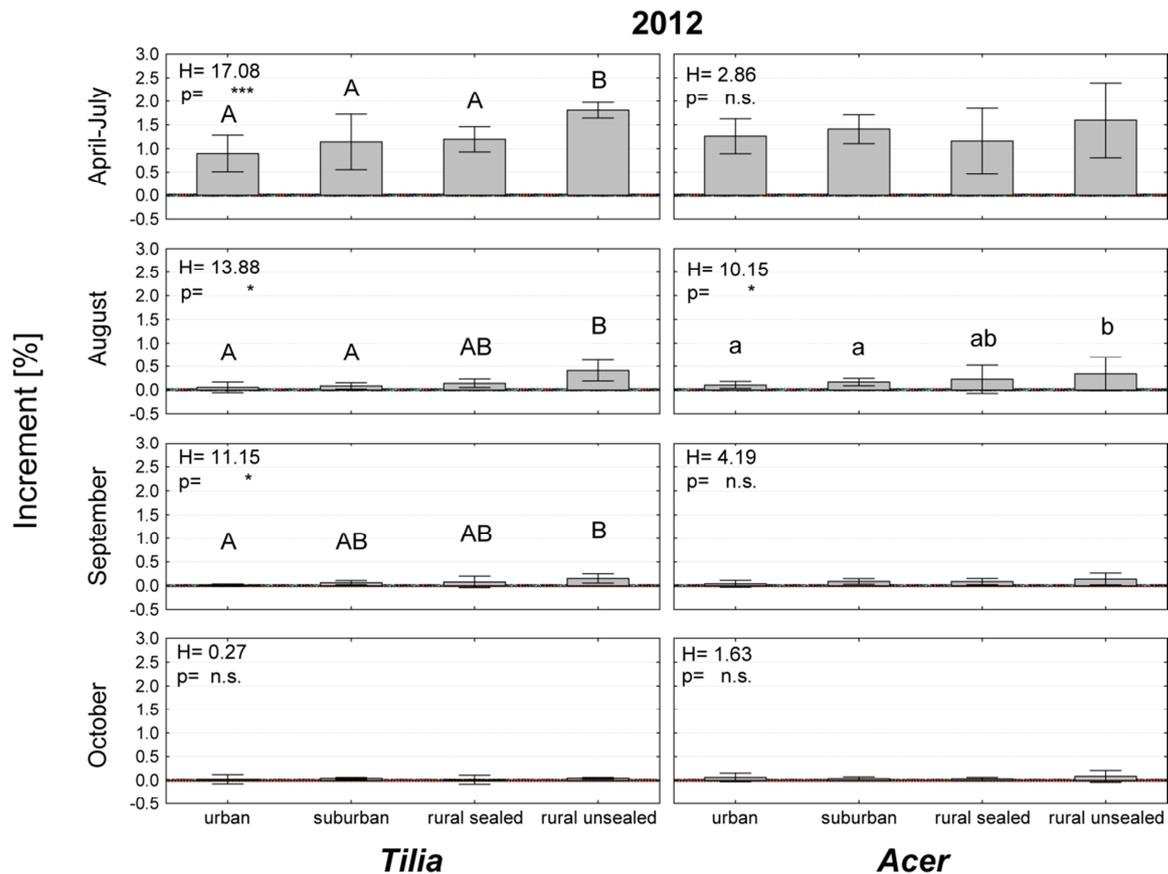


Fig. 24: Monthly stem circumference changes for *Tilia x vulgaris* and *Acer platanoides* 2010, error bars show \pm standard error. Letters above bars show significant differences according to Mann-Whitney U-tests for pairwise comparisons after Kruskal-Wallis tests, $p^{***} = <0.001$, $p^* = 0.05$, n.s. = not significant.

Tilia x vulgaris 2012

In 2012, increment of stem circumferences was similar along the sealed temperature-gradient sites. Only a slightly higher (though significantly) stem growth from urban to rural was calculated (Fig. 24). Differences in stem growth mostly appeared between sealed sites and unsealed site. In August, averaged growth was almost three times as high at the rural unsealed site compared to the adjacent sealed rural site (0.41 and 0.14%). Overall, the difference in length of growth is remarkable: Urban trees ceased growth in August, suburban trees in September, and trees of both rural sites in October.

Acer platanoides 2012

Differences in growth of stem circumferences along the sealed temperature-gradient sites did not appear to be significant. In the time span “April-July”, *Acer platanoides* at the sealed rural site showed lower increment than trees at the urban and suburban site (Fig. 24). Significant differences in growth appeared between sites of different soil sealing but not between the sites with comparable soil sealing. With increasing distance between the sites, strength of significances increased simultaneously. For the sealed sites, cessation of

stem circumference growth was reached in September, showing marginally higher increment rates from urban to rural. Positive stem growth at the unsealed rural site was found as late as in October.

3.4.2 Comparison of annual growth

Site-specific comparison

Figure 25 shows the site-specific pattern of increasing stem growth from the urban to the rural sites per year. In Figure 26 the stem growth of every study year is shown.

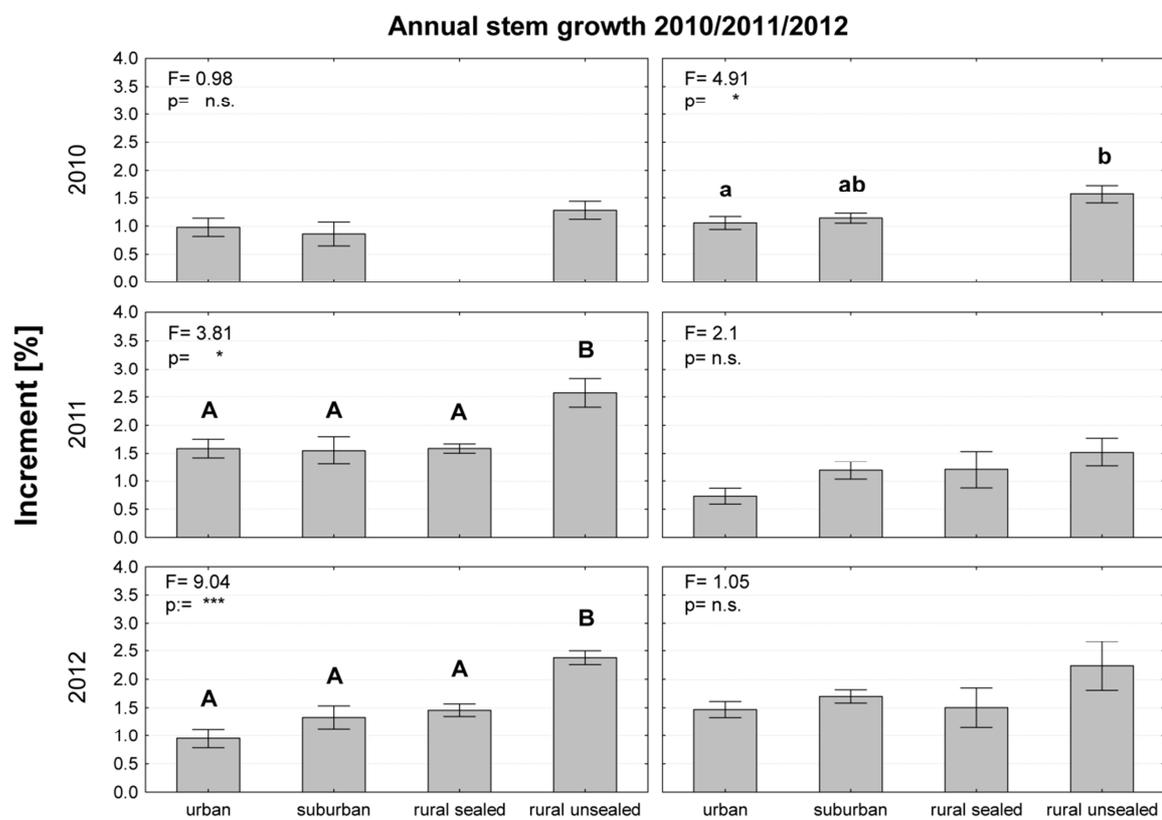


Fig. 25: Site-specific comparison of mean annual growth for the years 2010, 2011, and 2012, error bars show \pm standard error. Letters above bars show significant differences between sites calculated by Tukey HSD tests after one-way ANOVAs, F and p values refer to original data for *Tilia* and to logarithmized data for *Acer*, $p^{***} = <0.001$, $p^* = 0.05$, n.s. = not significant.

Tilia x vulgaris 2010-2012

In 2011 as well as in 2012, differences in yearly stem increments of *Tilia* were significant only between the sealed and unsealed sites. Tree stem circumferences in 2011 increased by 1.59% at the urban site, whereas increment rates for *Tilia* were less than two third of this in 2010 and 2012 (0.98 and 0.95%). The mean increasing rate for the unsealed rural site of *Tilia x vulgaris* in 2011 and 2012 was approximately twice as high (2.57 and 2.38%) as in 2010 (1.28%).

Acer platanoides 2010-2012

Contemplating the rural sites in Figure 25 for the years 2011 and 2012, higher stem growth at the unsealed than at the sealed rural site is obvious. Due to high variances in stem growth within the sites, significant differences were not revealed, however. Comparing growth of the sites between the years, differences were conspicuous (Fig. 25): In 2011, circumference increment of stems at the urban site was low. At the unsealed site, stem growth in 2010 and 2011 was nearly the same, but clearly lower than in 2012 (1.57 and 1.52% versus 2.24%).

Site-unspecific comparison

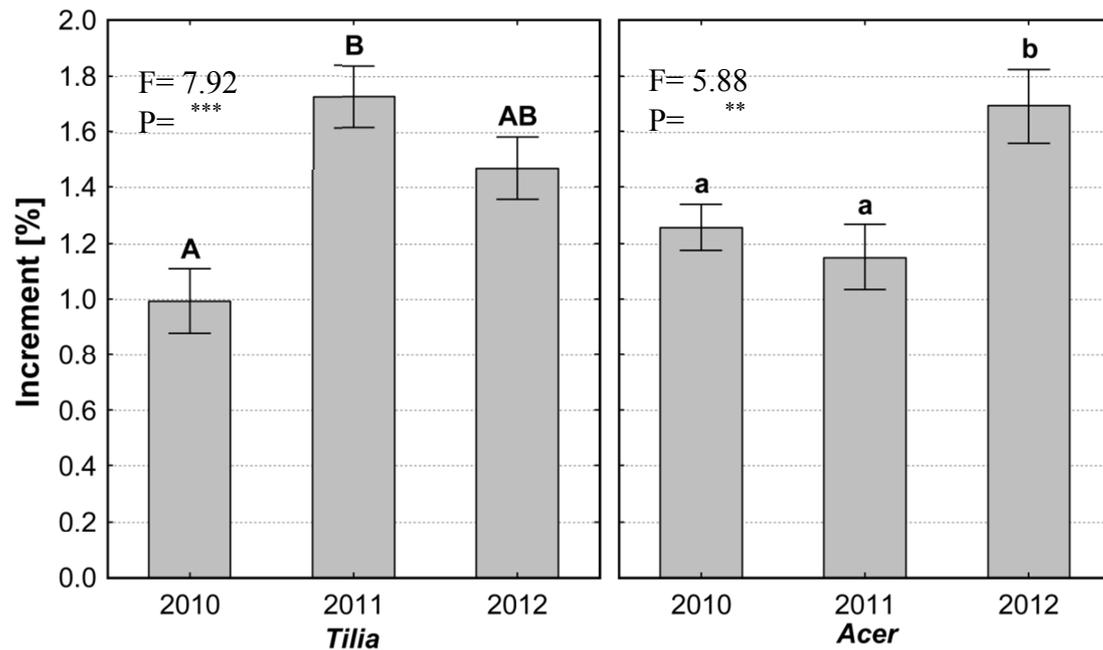


Fig. 26: Comparison of annual stem growth from 2010 to 2012. Data of sites 'rural sealed' were excluded for both species to provide comparable data sets. Letters above bars show significant differences between sites calculated by Tukey HSD tests after one-way ANOVAs, error bars show \pm standard error, $p^{***} = <0.001$, $p^{**} = <0.01$.

In site-unspecific comparison of stem increment, differences in annual growth become evident for both species (**Fehler! Verweisquelle konnte nicht gefunden werden.**): Lowest growth of *Tilia* in 2010 compared to strongest stem increment in 2011 was significant according to ANOVA. By contrast, growth of *Acer* in 2011 was weakest. Strongest increments were measured in 2012 and differed significantly from 2010 and 2011.

3.5 Crown plumbing

3.5.1 Site-specific differences in crown volume

Crown volumes in 2012 differed both between the sites and the species (Fig. 27). However, differences between the sealed sites of *Tilia x vulgaris* were at least partly evoked by human activities: Pruning of trees in late summer 2011 reduced the tree crown volume of rural trees at the sealed site severely, whereas crowns of urban and suburban *Tilia* trees were not trimmed. Therefore, tree crown volume was lowest at the sealed rural site and differed significantly from the suburban site ($p < 0.01$). At the unsealed rural site, thinning of *Tilia* tree crowns was moderate and reduced crown volumes were not significantly smaller compared to the other sites.

In contrast, *Acer platanoides* was not pruned back at any study site. Crown volumes of *Acer* at the suburban site were significantly lower than at the other sealed sites. Trees at the unsealed rural site had most extensive crowns. In spite of obvious differences, crown volumes of *Acer platanoides* from sealed sites and the unsealed site did not differ significantly.

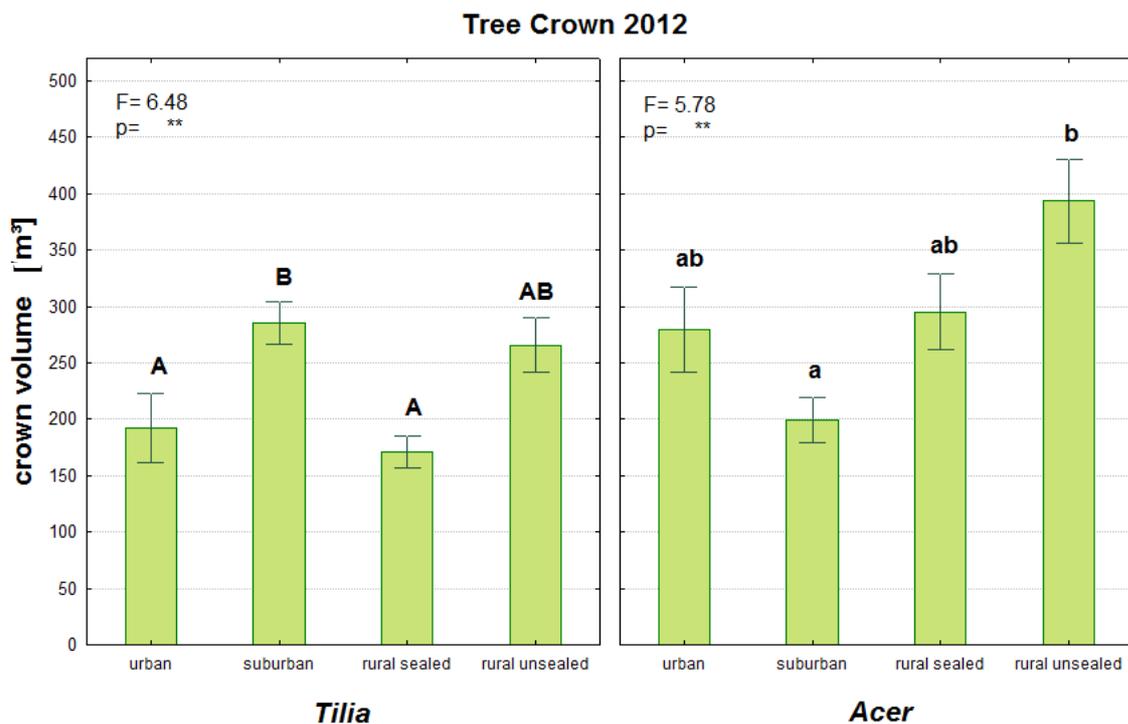


Fig. 27: Site-specific mean crown volumes of *Tilia x vulgaris* and *Acer platanoides* 2012, letters above bars show significant differences between sites calculated by a post hoc test (Tukey HSD) after one-way ANOVA, error bars show \pm standard error, F and p values refer to original data for *Tilia* and to log-transformed data for *Acer*, $p^{**} = <0.01$.

3.5.2 Correlation between crown volume and stem increment 2012

Tilia x vulgaris

For the urban site, a slight positive relation between crown volume and stem growth was proven (Fig. 28, left): The overall fit for the regression model explained approximately 56 % of the variation of data ($p > 0.08$). On the contrary, data for the suburban site did not show a correlation. Crown volume and stem increment of trees at the sealed rural site were also slightly related to each other, with a $r^2 = 0,59$ (not shown).

Acer platanoides

Correlation between volume of tree crowns and increment of stem circumferences was poor: ($p > 0.95$, $r^2 < 0.001$) at the urban site (not shown). For the unsealed rural site, data assume a negative correlation between crown volume and stem growth. However, as high and low stem growth was measured for trees of variable crown sizes at all sites, p-values were well above the significance level of ≤ 0.05 (Fig. 28, right).

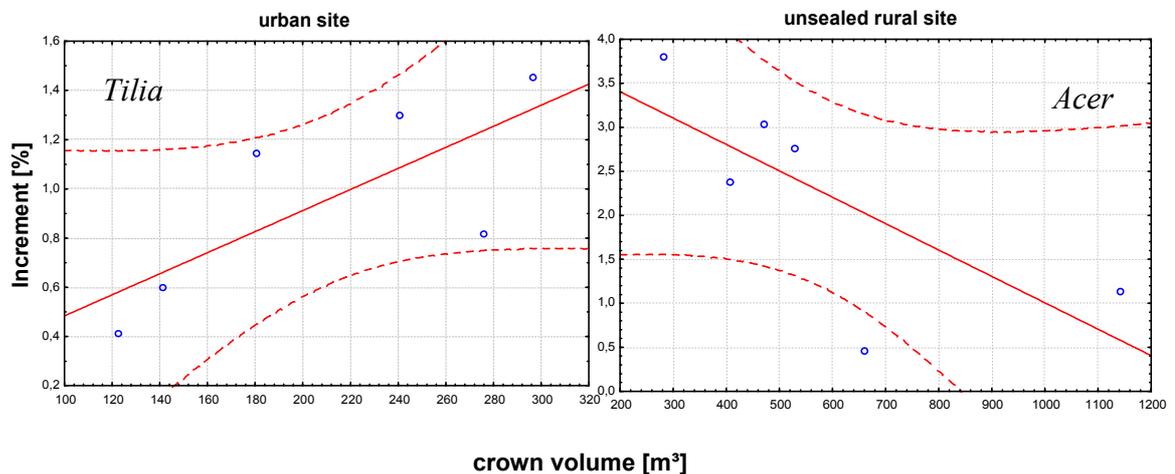


Fig. 28: Relationship between crown volume and stem circumference increment for *Tilia x vulgaris* and *Acer platanoides*. The figure shows positive (*Tilia*) or negative (*Acer*) correlation for the urban site and the unsealed rural site.

3.6 Bud development of *Tilia x vulgaris* and *Acer platanoides*

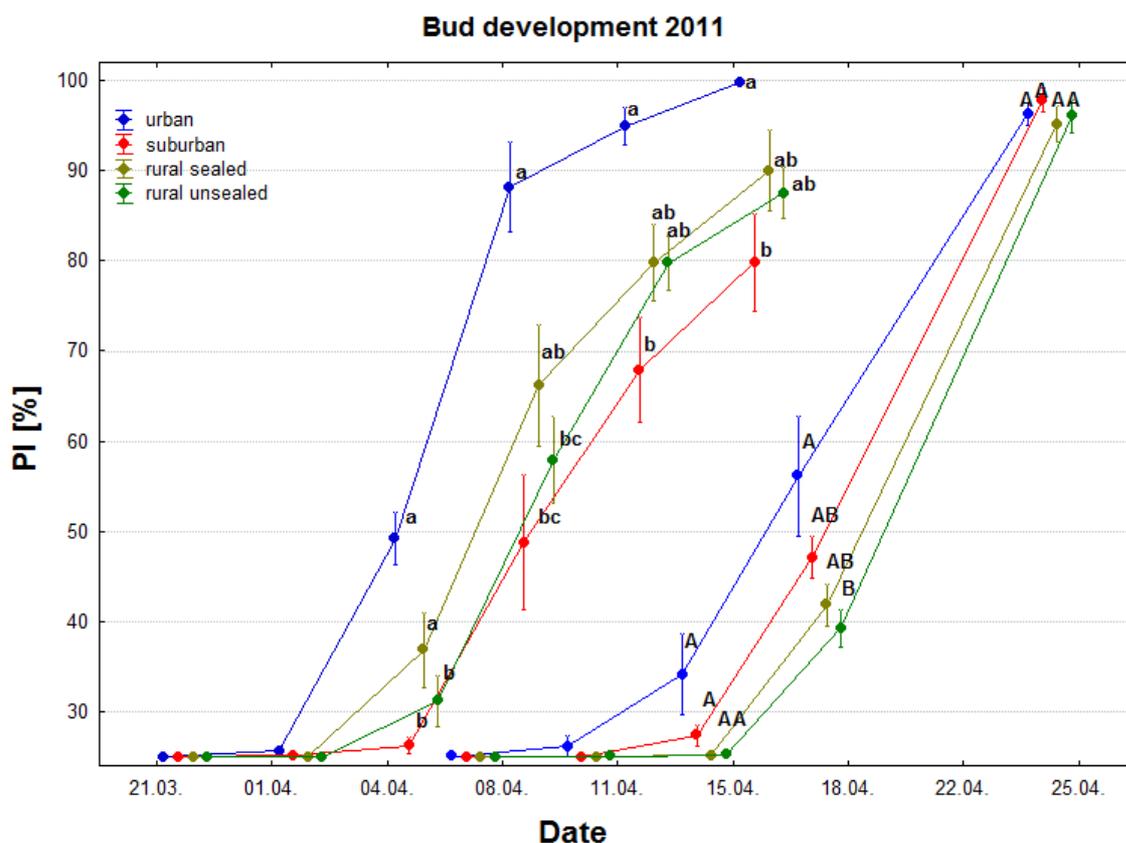


Fig. 29: Bud development 2011 for *Tilia x vulgaris* (right) and *Acer platanoides* (left) from March 21st to April 25th. PI: Mean phenological index calculated by mean percentage stage of bud burst per tree. Lower cases indicate significant differences in PI between *Acer*-sites, upper cases between *Tilia*-sites. Whiskers show standard errors.

Tab. 4: Results of an ANOVA on the phenological index of *Acer platanoides* at different locations. P-values are given as: *** < 0.001, ** < 0.01, * < 0.05.

Date	F	P
04.04.	12.23	***
08.04.	7.03	**
11.04.	6.54	**
15.04.	4.56	*

Acer platanoides

In the observed time span, bud development of *Acer platanoides* at the urban site was always further advanced than at the other sites (Fig. 29). Already on April 1st, few buds in stage P3 were detected at the urban site, while buds at all other sites still were in stage P2. On April 4th, bud burst had started at all sites. At that time, urban trees had reached a PI of nearly 50%, whereas bud development at the suburban site was still low (26.2%). PI's of trees at the rural sites was between early urban and late suburban development. Development of flower buds had almost ceased at the urban site on April 11th while it was still in progress at the suburban and both rural sites. The latter showed similar bud stages with slightly higher PIs at the unsealed rural site. Up to the last observation date on April 15th this pattern persisted: Urban trees showed significantly higher PI's than suburban trees, rural trees hardly differed in flower bud development (Tab. 4).

Buds of urban *Acer* trees not only developed earliest but also fastest. At the urban site, slowing down of bud development appeared only after nearly full development of flower buds (88.2%) was reached on April 8th. Likewise, buds developed fastest from April 4th to April 8th at the sealed rural site but showed a remarkably lower PI on April 8th: Slower development of tree buds already appeared at a PI of 66.2 %. For trees at the unsealed rural site, slowing down of bud development occurred later, on April 11th, when *Acer* trees had reached a PI of approximately 79.2 %. At the suburban site, bud development was fastest between April 4th and April 11th. Overall, development was slower and clearly later than at the other sites.

Tilia x vulgaris

Burst of *Tilia* tree leaf buds occurred later than for *Acer* trees: First budding was visible on April 11th on some urban trees, while *Tilia x vulgaris* at all other sites did not show leaf buds dehisced yet. PI was highest at the urban site for the whole time span (Fig. 29). Different than for *Acer* trees, PIs of suburban *Tilia* closely followed bud development of urban trees and did not significantly differ from urban tree PIs at any time. Buds of rural *Tilia x vulgaris* developed latest and just as for *Acer* trees, PI's were nearly identical at both rural sites with little higher PIs for trees at the sealed compared to the unsealed site. Overall, significantly different PIs between the sites appeared rarely throughout the observation time (Tab. 4).

As the Figure 29 shows, curves for the PIs of the suburban and rural sites were close to each other. The only statistical difference for bud development appeared on April 18th when the PI of urban trees had already reached well above 50 % while it was still below 40% at the sealed rural site. At this point in time, bud development diverged farthest from each other. Subsequently, bud development slowed down moderately for urban trees and accelerated at the rural sites. For suburban trees bud development hardly changed its rate. On April 25th bud development was fully completed at all sites.

4 DISCUSSION

4.1 Reliability and weaknesses of applied methods

Measurements of climatic conditions were conducted directly at the sites of studied trees, i.e. within the borders of the city of Hamburg. The location assumed as 'rural' is located in a residential area that may be better defined as 'peri-urban'. However, in spite of this, documented atmospheric temperatures have already revealed distinct differences between the inner city and these peri-urban locations showing a temperature difference from 'urban' to 'rural' of about 0.9 K.

Temperature

Differences in air temperature were estimated per month based on mean daily temperature values (DWD). Thus, the temperature-gradient assumed for the period 1971-2000 had been based upon estimated temperatures that did not consider within-day differences. The value of the actual temperature-gradient is a mean 24h value, therefore. From 2010-2012, microclimatic deviations from these approximated values could be directly measured for the studied sites and at close intervals that allowed for daily temperature-curves.

CO₂

In order to verify a gradient in atmospheric CO₂ contents, measurements were conducted with a mobile IRGA. Despite trying to measure under similar conditions on each study day, the atmospheric CO₂ documented might have been affected by several circumstances:

- a. Measurements at chosen sites were not always taken at the same survey mark. It is likely that microclimatic differences within sites had occurred and were not taken into account.
- b. The height and position of the ambient air probe head of the IRGA was not fixed for measurements.
- c. The temporal component of decreasing CO₂ over the course of the day was considered by calculating a correction factor. Yet, these diurnal CO₂ measurements were only taken at one site per location. That means, individual microclimatic characteristics at measured sites were not considered in the calculation of the correction factor.

Soil analyses

Analyses of urban soils are elaborate and costly. For reliable statements on correlation between soil and tree vitality factors like stem growth, soil samples need to be taken along the entire vertical and horizontal root dimensions of trees. With respect to conduits, samples were only calculated for depths up to 30 cm. Because of the laborious sampling process, soil data had to be approximated by relatively few samples. Additionally, a sampling design including soil samples from various distances to the tree stem may have shown important variation in nutrient and water content.

Stem growth

Measuring incremental growth of tree stems by D1 measure cords turned out to be a simple and relatively inexpensive method to obtain reliable data without damaging the tree. Nevertheless, cords and their position should have been controlled more often as they were fixed with only a spiral spring to allow for stem growth against marginal resistance. Because of loss or misalignment of cords (strong stem growth or human interference), there are missing data points. Reconstructing data would have been possible if new tapes could have been fixed exactly at the same stem height. Therefore, the exact position of measure cords should have been marked at initial attachment (e.g., by a water resistant pen or a pin).

Excluded trees

The postponed identification of species in summer 2010 showed five *Tilia* trees at the unsealed rural site to be of another species. Data of these were not included in further studies. Furthermore, two trees at the urban *Tilia* site with a lower degree of tree base sealing and obviously less often or less severe pruning were excluded from later calculations. Thus, only data from 73 trees instead of 80 were used for analysis.

Crown plumbing

The number of trees studied with respect to crown volume was small; only eight trees per site were measured for height and width. In order to calculate the degree of correlation between crown volume and stem growth, only trees of the same site could be taken into account. However, small sample sizes did not allow for a conclusive statement on this correlation.

4.2 Roadside trees along urban to rural gradients

In a review paper, Dobbertin (2005) discussed the usefulness of growth measurements as indicators for the vitality of trees and the stress to which they are exposed. He emphasized that stress-inducing factors can affect vitality of trees immediately or over longer time periods. In urban areas, stresses resulting from root damage, specific atmospheric climate and soil characteristics occur for most roadside trees and affect them over longer time periods (e.g., Balder 1998, Pauleit et al. 2002, Sæbø et al. 2003, Cekstere and Osvalde 2010). Additionally, other stresses like defoliation of tree crowns due to insect calamities, drought or pruning of crowns lead to immediate reactions in growth of trees. Moreover, use of de-icing salt in roadsides leads to an absorption of Na^+ and Cl^- ions that destroy cellular tissues and results in leaf burn (Cekstere et al. 2008).

This thesis comprises observation data of tree vitality and environmental factors from the vegetation periods of three consecutive years. Therefore, long-term influences of the examined factors on tree vitality or growth can be made only with caution.

4.2.1 Temperature and CO_2

Generally, high atmospheric temperature and CO_2 were found to increase plant growth (e.g., FACE experiments, reviewed by (Ainsworth and Long 2005). Plants, and trees in particular, have an optimal range for atmospheric temperature in which photosynthesis is maximised. Rising temperatures of up to 3°C by 2100 (Rechid et al. 2014), therefore, probably will not harm the production of carbohydrates but potentially increase biomass production by accelerating photosynthesis. Thus, when considering CO_2 and temperature as the sole factors responsible for distinguishing tree growth in the city alone, highest tree growth of roadside habitats would be expected at the warmest sites with highest atmospheric CO_2 concentration at the urban core. However, a positive correlation between ambient temperature or CO_2 , and stem growth could not be found in this study. At the urban sites, highest ambient temperatures and CO_2 were measured, while growth was lower compared to suburban and rural sites.

Onset of stem growth indeed appeared earliest at the urban and, thus, the warmest sites in 2011. However, longer growing seasons for *Tilia* and *Acer* were not found. Although ambient urban autumn temperatures were well above 5°C for a longer time than at the suburban or rural sites, the end of the growing period appeared earliest at the central city sites for both species. Linking low growth of studied urban trees and short growing seasons to higher temperatures might be a logical step. A possible explanation for this might be that rates of photorespiration increase more than photosynthesis at high temperatures (Gozlinski and Gej 1984). RuBisCo, the enzyme that binds CO_2 in C_3 plants, also constantly binds O_2 and produces CO_2 . Production of carbohydrates is obstructed and thus cell growth is reduced. Zhang et al. (2005) found a depression in net photosynthesis in *Parashorea chinensis* (an emergent tree species in Southeast Asian rainforests) at high atmospheric temperatures. They suggested that a high proportion of electrons was allocated from the electron chain of photosystem II to photorespiration to protect the tree's photosynthetic apparatus. This may have accounted for the low levels of midday photosynthesis. In addition to photorespiration, cellular respiration both at day

and at night reduces the net carbohydrate production of plants. Moreover, respiration at night is enhanced at higher temperatures and reduces net carbohydrate production. In *Lolium perenne*, Nijs et al. (1989) showed that higher darkrespiration under low irradiance but higher temperatures counterbalances the increased carbon gain of increased atmospheric CO₂. If losses in carbohydrates through respiration are greater than yields through photosynthesis, increasing temperatures can lead to a net decrease in biomass production. This seems to be the case for *Tilia* and *Acer* trees in roadside habitats in the present study:

Monthly measurements of ambient CO₂ in this thesis showed lowest concentrations at the rural location and in the summertime. Although carbohydrate production was not measured directly in this study, stem growth in summer can serve as an indicator for carbohydrate production. In addition to the negative effects of higher atmospheric temperature, also the results of IRGA measurements suggested high CO₂ values to be negatively correlated to stem growth. With respect to the annual patterns in CO₂ content, these findings support the propositions of Berry and Colls (1990a, 1990b) that a higher sum of a photosynthetically active area in summer compared to that in spring and autumn reduces CO₂ content. In other words, CO₂ is particularly high in the colder months as a result of the warming. Pataki et al. (2007) emphasized the higher natural CO₂ consumption in summer in greener rural areas than in urban sites and also mentioned high CO₂ content in winter due to anthropogenic gas combustion. Measurements taken over the years 2010 and 2011 are in line with these observations. CO₂ content was lower with the increasing presence of greening from urban to rural sites and from sealed rural to unsealed rural sites.

If only temperature and CO₂ are considered as the explanatory factors for tree growth in this study, lower growth of stems could be predicted for higher respiration (for urban trees, especially night-time darkrespiration). This might have minimised net carbohydrate production of *Tilia* and *Acer* more strongly at the urban than at the rural location. Regarding atmospheric CO₂ content, Ziska et al. (2003) showed clearly higher growth of *Ambrosia artemisiifolia* at the urban compared with suburban and rural locations in Maryland (USA). Although the difference of atmospheric CO₂ content between the study sites was small, the authors suggested a link between ambient CO₂ and growth of weeds. In contrast, I did not find any significantly positive effect of CO₂ content on the growth of trees in this research study. This can be explained by a number of reasons: the small differences in CO₂ concentration (appr. 25 ppm, compared to several 100s ppm differences in CO₂ content of designed experiments) along the studied gradient, the highest CO₂ concentration during winter when trees were not ready to use it, and the particularly lower contents in summer, and the possibly overruling effect of other factors.

Overall, I infer that the influences of ambient temperature and CO₂ on stem growth of *Tilia x vulgaris* and *Acer platanoides* were only marginal for the short time span of observation covered in this study and other stress factors had stronger impacts on tree growth. For example, I found higher growth of rural trees of both species at the unsealed compared to the sealed sites, although differences in ambient temperature and CO₂ were negligible.

4.2.2 Soil characteristics and soil sealing

The quality of a site for plants regarding vitality and growth is known to be controlled by soil characteristics rather than by climatic factors (Collie and Schumacher 1953). The studied soils were developed from natural substrates deposited during the last ice ages but they have been severely disturbed by anthropogenic influences like refilling of excavated boreholes, and tree- and building-pits. Microclimatic site differences and diverse management practices have resulted in a mosaic of soils in cities, characterised by site-dependent chemical and physical properties.

One of the most important physical factors in urban soils for rooting and aboveground growth of trees is bulk density (e.g., Balder 1998, Hiller and Meuser 1998, Pauleit 2003, Scharenbroch and Catania 2012). In the present study, bulk density was not measured directly and characterisations of soil compaction were collected by subjective observations. Soil moisture, however, may give indirect information about the substrate quality of the examined soils for growth, such as capacity for water and nutrient storage, resistance to rooting growth and possibility for spreading. In the following paragraphs, the importance of soil moisture, aeration, nutrients, pH, and electrical conductivity (\cong salinity) for the growth pattern of roadside trees are discussed.

Soil moisture

Variation in soil moisture is closely linked to climate. Periods of high ambient temperatures with longer duration decrease soil moisture, while precipitation and low temperatures increase or stabilise soil moisture. Schoenholtz et al. (2000) reported in his review a close positive correlation between soil moisture and tree growth. Bauweraerts et al. (2014) concluded drought to be a severe stress factor for the growth of trees. In a study on the effects of heat waves on seedling growth of *Quercus rubra* and *Pinus taeda*, the authors found that heat waves produced more stress than uniformly applied heat of the same amount. Levels of CO₂ and soil water were considered to be potentially interacting factors and elevated CO₂ partially mitigated the negative effects of heat waves. However, results of their studies also showed drought to be a more severe stress factor than heat waves.

Tilia x vulgaris is known for its limited drought resistance. In a climate-species-matrix (KLAM), Roloff et al. (2008a, 2008b) categorised this species as part of group 3.1, which is characterised by low drought resistance but high frost hardiness. The GALK-Arbeitskreis Stadtbäume (2006) (Municipal Gardens and Parks Heads Conference) estimated the resistance of *Tilia x vulgaris* to urban climate, including the deficiencies in water storage of sealed soils and soils with high compaction, as problematic for the same reason. *Acer platanoides*, with higher drought resistance and frost hardiness, was categorised as part of group 2.1 in the KLAM. However, sensitivity to drought as a consequence of higher bulk density in urban soils was rarely found in a literature review by Roloff et al. (2008a, 2008b). Perhaps because of the higher drought resistance and frost hardiness, the GALK-Arbeitskreis Stadtbäume (2006) found only a slight limitation for the suitability of *Acer platanoides* in plantings along urban roadsides.

In urban regions, trees often have to make use of their plasticity in rooting structure as groundwater is difficult to reach (Balder 1998). They develop a dense network of shallow roots in order to provide an sufficient supply with near-surface water and nutrients (e.g., Bijoor et al. 2011, Bauerle and Centinari 2014).

Results of this study do not corroborate the prediction of higher stem growth with higher soil moisture at the rural location. Soil moisture at the sealed sites was higher than at the unsealed ones but stem growth was lower here. Most likely, this is due to the overlay of a well-humified layer of organic matter (i.e. 'mull'; Ad-Hoc-Arbeitsgruppe Boden 2005) at the *Acer* site and an overall high organic content of the soil at the *Tilia* site. Substrates offered high capacity for water storage and additional watering of tree bases by residents at the sealed *Tilia* site kept soil moisture high. Roots of urban linden and *Acer platanoides* surely have lost their natural propensity to spread into deeper horizons due to lack of space and damage through road- and building-work or the installation of conduits. Therefore, trees have been forced to use soil water found in the first 30 cm more intensively. Lack of space and the resulting density of shallow roots were conspicuous at the sealed urban *Acer* site and the strongly compacted suburban *Tilia* site. In spite of their high flexibility and ability to adapt to given soil conditions, roots still suffer from low water supply, especially those of *Tilia x vulgaris*, as they have to compete for water and nutrient sources with the herbaceous plants and shrubs planted at their bases. Moreover, findings may support the assumption that soil moisture is not a good measure of plant-available water. In addition to soil water, soil aeration can also limit above- and below-ground growth of urban roadside trees (e.g., Balder 1998, Kutschera and Lichtenegger 2013).

Soil aeration

Roots in highly sealed urban soils often suffer from low porosities implying low aeration. Rahman et al. (2013) suggested a deficit in oxygen results from paving, which inhibits cell respiration and, thus, healthy rooting and adequate nutrient uptake. Most likely, this led to reduced growth of *Pyrus calleryana* along roadsides in Manchester, UK. Overall, sealing seems to be a major factor that influenced stem growth of the studied roadside trees. Water and nutrient supply for the tree is provided by fine roots and by symbiotic ecto- (*Tilia*) or endo- (*Acer*) mycorrhiza. Lack of water and oxygen as a consequence of soil compaction and sealing often leads to dieback of fine roots and of mycorrhiza. Alzetta et al. (2012) reported lower health of root tips and colonization by ectomycorrhiza in roadside linden trees compared with urban park trees in Padova, Italy. Here, low root and mycorrhiza performance was related to high soil compaction. Besides bulk density and low porosity, the lowering of the groundwater table can also negatively affect roots and, thus, the vitality of urban trees. The soil profile excavated at the unsealed rural *Acer* site showed ochre coloured spots in the deeper horizons, which indicate varying groundwater table. In urban soils, changing groundwater tables are characteristic and represent a major challenge for tree roots (Blume et al. 2014). The unsealed rural *Acer* site, however, was the only site where these changes were visible. Here, soil under the grass-strip did not seem to be compacted and allowed tree roots to expand widely in the substrate of medium bulk density.

The growth of *Acer platanoides* here was the highest for all *Acer* sites; however, the negative effects of low aeration on growth of tree stems may have been negligible overall.

Unfavourable conditions for plants and urban roadside trees in particular may not only occur as a result of physical deficits, like reduced water-holding capacity and infiltration or high bulk density and consequent low aeration (e.g., Jim 1998, Streckenbach 2012) but also as a result of the chemical conditions. However, chemical soil quality (e.g., content of macro- and micronutrients, and heavy metals) from urban to rural areas of a city does not change in a predictable way because of the high spatial variability and patchiness of urban soils. Diverse chemical parameters characterise urban soils. Cekstere and Osvalde (2013) found soil chemical properties and pH as well as de-icing salt to affect the growth of urban linden trees in the city of Riga, Lettland, and Scharenbroch et al. (2005) showed that adding bio-char and bio-solids to increase nutrient supply of urban trees worked better than adding NK fertilizers. Scharenbroch and Catania (2012) developed an index comprising the minimum data set (MDS) of parameters that might be used to classify the suitability of urban soils for tree growth (Urban site quality index, USQI). They studied physical, chemical and biological components of urban soils in a residential area of Chicago (IL), USA, and found soil texture, soil pH and soil organic matter (SOM) to be the key factors affecting vitality and growth of urban trees. In studies at hand, the soil texture and bulk density as well as SOM were estimated directly in the field, based upon the description of soil profiles (Ad-Hoc-Arbeitsgruppe Boden 2005). Only pH and the available fraction of nitrogen (N), phosphorus (P), and potassium (K), as well as electrical conductivity, were analysed in the laboratory.

Nutrients, pH and salinity

Soils both function as sources and sinks for elements and pollutants (De Kimpe and Morel 2000, Sauerwein 2011). Urban soils are characterised by elevated pH and salinity, increased content of environmental contaminants, reduced organic matter content, and altered microbial populations (e.g., Stach 1969, Eckstein et al. 1974, Pfeiffer 1988, Craul 1999, Pouyat et al. 2007). Although litter decomposition is enhanced within cities (Dorendorf et al. 2015), nutrient content of urban soils are mostly very low because leaf litter, tree branches and further tree debris are often taken out of the natural cycle (e.g., Timilsina et al. 2014). Low N content, for example, can be a typical characteristic of urban soils because N is accumulated in organic top soil layers, which are rarely found in urban areas (e.g., De Kimpe and Morel 2000, Sieghardt et al. 2005). Although nitrogen deposited by NO_x-emissions may be high in cities, N is often low in urban soils due to physical deficiencies and quick percolation of plant-available nitrogen. However, it has to be kept in mind that urban soils are extremely heterogeneous and nitrogen in soils close to streets or in sidewalks may be high due to gas exhaust from cars and excrement of pets (e.g., Balder 1998, Sieghardt et al. 2005).

In agriculture, the ratio of C and N is used to classify soils and C/N ratios function as an indicator for soil quality concerning biomass production (e.g., Craul 1992, Finck 2007). In the present study, highest growth was found at locations with low C/N ratios where content of N was relatively high compared to C. At the urban *Acer* site, absolute values

of C and N were low. To explain these values, we can assume that the low input of leaf litter (constant removal of SOM) and the very high degree of sealing promoted reduced overall decomposition level of organic matter. At the urban *Tilia* site, however, C and N were the highest values measured at any site even though growth of urban linden trees was the lowest. As calculations for the C/N ratio show, concentrations of C and N are not the only determinants of soil quality with respect to tree growth. In fact, a wide range of C/N ratios was calculated for both urban *Tilia* and *Acer* sites. In contrast, the rural sites for both species showed a narrow range of C/N ratios for sealed as well as for unsealed sites. Like in soil moisture, this is most likely due to the substrates under *Tilia* and *Acer* at the sealed rural sites. Due to grass verges here, both sites are able to accumulate more water and leaf litter. Furthermore, horticultural amelioration of tree bases by residents has been carried out for trees at the sealed rural *Tilia* site until the present. Concerning the unsealed rural sites, the *Tilia* site showed a good balance between C and N although their absolute values were low, most likely due to the very sandy substrate of the tree pits here. The same is true for the unsealed rural *Acer* site, although the sandiness of the grass verge was lower.

Phosphorus is also vital for plants and plays a key role in energy supply and growth (e.g., Gurevitch et al. 2002, Finck 2007). The plant-available fraction of P in soils is often low, however. For soils examined in this study, a gradient of higher to lower plant-available P was found from urban to rural locations for the *Acer* sites. The P content of the *Tilia* sites were inconsistent but showed a similar trend of decreasing content from urban to rural locations and from surface to deeper soil layers. Elgharably and Ito (2014) demonstrated that the availability of P is negatively related to soil salinity. Moreover, they found microbial activity and, therefore, N and P availability in coarser soils to be higher than in dense fine clay soils. These findings predict for higher P availability with low salinity and coarse soil texture. The present results, however, are not in agreement with this prediction of higher P availability in less saline or coarser soils. However, for high P release, the abundance of apatites is mandatory. Urban soils often show higher P concentrations due to high content of rubber waste and resulting apatite. The results of this present study are in line with this observation. At the suburban *Tilia* site, soluble P content was highest and so was the content of rubber waste when estimated directly from the soil profile at sites. Growth of trees was not highest here, however, and weakest growth was found at the urban location for the *Acer* sites, where P was the highest.

Another essential macronutrient for plant growth is potassium. In its plant-available state, K originates from potassium feldspar, common and hydrous mica or is washed into soils through precipitation (Finck 2007, Schachtschabel et al. 2010). Scharenbroch and Catania (2012) showed positive effects of NK fertilizer on urban tree growth. However, positive effects of bio-char and bio-solids on tree growth were much greater. In the study for this thesis, plant-available K did not show especially high or low concentrations at any site except for the unsealed rural *Tilia* site, where concentrations of free K^+ ions was low. However, growth of tree stems was highest here, and a positive correlation between plant-available potassium and stem growth is not supported by the present results.

Incorporating the content of all studied soil elements, soil pH is decisive in converting them into plant-available forms. Moderately acidic pH values in soils foster, for example,

the release of phosphates out of apatite (e.g., Gurevitch et al. 2002, Finck 2007, Schachtschabel et al. 2010). Kazlauskaitė-Jadzevičė et al. (2014) as well as Doichinova et al. (2014) also showed that the solubility and availability of heavy metals is increased in urban soils by low pH values. In natural soils, acidity increases over time. Urban soils are neutral to alkaline in most cases, as rubber waste containing Ca^{2+} can be often found in roadside tree or other built-up substrates. However, all examined soil samples in this study were moderately acidic and thus within the optimal range for N, P, and K release from mineral forms and availability for plants (Schroeder 1992, Finck 2007). Obviously, the different plant-available nutrient contents found in the soils were not the results of unfavourable (alkaline) pH values.

In the 1970s and 1980s, high Na^+ and Cl^- ions in the soil played a major role in damages recorded for roadside trees in Hamburg (Eckstein et al. 1977, Petersen and Eckstein 1988, Pfeiffer 1988). However, as a consequence of more restrictive legislations, the use of de-icing salts has been reduced in Hamburg during the last decades (Eckstein 2000, Däumling 2012). In the soils of the roadside trees investigated in this thesis, conductivity in soil samples was low and did not differ significantly between the sites. Overall, conductivity at the *Tilia* and *Acer* sites did not show an impact on the growth of studied trees. It could be speculated, however, whether the somewhat higher growth of trees at the unsealed rural compared to the sealed rural sites might hint at the use, and negative effect, of de-icing salt at the sealed rural site, where the highest conductivity values were found. However, the detrimental effects of high salinity on roadside trees would be visible earlier in leaf parameters like leaf margin necrosis than in reduced stem, branch or twig growth (e.g. Brahe 1974, Eckstein 2000).

Analyses of soil parameters in this study did not indicate that any single soil nutrient limited growth of *Tilia x vulgaris* or *Acer platanoides* trees at the studied sites in Hamburg. When studied soils were ranked from 1 to 4 according to the parameters of humus content ($\hat{=}$ SOM) and sandiness ($\hat{=}$ soil texture) (see Tab. 3) for both species, a positive relation between soil quality and stem growth was found. Although the unsealed rural *Tilia* site represented the sandiest site with the lowest nutrient concentrations, growth of tree stems was highest here. In the unsealed rural *Acer* site, nutrient content was only slightly higher but growth of tree stems was highest here, too. Trees of sites with higher plant-available nutrient content did not show the highest growth. This supports the assumption that nutrient content alone is not the salient characteristic to define urban soils. Interpreting the results on stem growth and nutrient concentration, it is most probable that they are not directly linked with each other.

As differences in soil pH were marginal in the studied soils and were in the favourable range for nutrient availability at all sites, I infer that the physical soil parameter of bulk density, and thus soil sealing, is a more important parameter affecting growth of urban roadside trees in Hamburg. For example, I found higher growth of trees at the unsealed rural sites with lower nutrient content in both species than at the sealed rural sites with higher nutrient content. It is likely that the observed detrimental effects on tree growth resulted from reduced soil aeration, evoked by high bulk densities, and low absolute soil water content and availability for trees.

4.2.3 Crown volume

In early life stages, crown volume and stem diameter have been shown to be positively correlated in several broadleaved trees (Hemery et al. 2005). A correlation between crown volume and stem growth was also found in young trees of *Cunninghamia lanceolata* (Mei and Sun 2013). In this study on urban trees, however, there was only a weak positive correlation between tree crown and stem growth in *Tilia x vulgaris* and it was even negative in *Acer platanoides*. In general, urban roadside trees have to cope with a reduced photosynthetically active area due to pruning or even topping of tree crowns. Moreover, they have to face the stresses resulting from the often enormous wounds acting as entry points for pathogens. These might be the possible reasons for results that deviate from those of Hemery et al. (2005) and Mei and Sun (2013).

In spite of severe pruning of *Tilia x vulgaris* at the sealed rural site in 2011, stem growth was not reduced in 2012 compared with stem growth of trees at this site in 2011. In 2012, annual growth of pruned trees at the rural location was even slightly higher than at the urban and suburban site, where no pruning had been carried out. This shows that pruning had no detrimental effect on wood development of trees in 2012, and it also indicates that stem growth might be independent from the photosynthetically active area, at least within the study period. Yet, comparing stem growth of the European linden at the severely pruned sealed rural site with that at the only slightly pruned unsealed rural site shows differences in stem growth. Strongly pruned linden trees revealed lower growth than those that were only cut for maintenance. Thus, it seems that the quality and quantity of pruning is important for stem growth. In more detail, the quality and quantity of pruning of tree crowns at the rural location probably determined whether tree growth was stimulated or inhibited. Several studies on trees have indicated that the divergent reactions of trees to pruning may depend on the quality and quantity of pruning. For example, stem growth of Norway spruce (*Picea abies* (L.) Karst) was shown to be stimulated by moderate pruning (Pokorný et al. 2012). Monterey pine (*Pinus radiata* (D. Don) was shown to have reduced stem growth but significant stimulation of epicormic growth due to pruning (Lange et al. 1987). Roloff (2013) also emphasized the more pronounced epicormic growth of heavily pruned *Tilia* in cities.

In this thesis, the relation between crown volume and stem growth in 2012 was slightly positive for *Tilia x vulgaris* as trees with larger crowns had higher growth. This same relation was found along the urban-to-rural temperature-gradient as well as in comparison of linden trees within the urban location. Epicormic growth was not studied in detail at any location. Using visual comparisons, epicormic growth at stem bases of all rural linden trees seemed comparably high, although pruning differed in quantity and quality. Thus, pruning did not seem to have affected the allocation of above-ground biomass to epicormic shoots or stem growth. For *Acer platanoides* at the unsealed rural site, a negative relation between crown volume and stem growth was found when estimated crown volumes measured in late winter before stem growth had started were related to annual stem growth from 2012.

When comparing crown volumes to stem growth of *Acer platanoides* between locations, however, a positive relation becomes evident: tree crowns at the urban sites were small and stem growth was low, whereas crowns and stem growth of trees at the rural location were higher.

Conclusive statements on the correlation between crown volume and stem growth are difficult to make as the very limited number of studied trees reduces the explanatory power of the statistical analyses. The apparently negative putative correlation between crown volume and stem growth in *Acer* at the unsealed rural site might be due to the low number of comparable studied trees. For *Tilia*, this might be true as well. Moreover, the reactions of urban trees to crown-pruning probably not only depends on the severity of the pruning but also on species characteristics (Roloff 2013).

4.2.4 Summary on stem increment influencing factors

The growth of urban roadside trees in Hamburg were mostly likely influenced by all the studied parameters: atmospheric temperature and CO₂ content, soil pH and salinity, soil moisture and nutrient content (C and N content, C/N ratio, phosphorus and potassium) as well as crown volume. Clear answers on the amount of variability in stem growth accounted for by each factor cannot be given, as these factors interact with each other and influence growth of tree stems at different levels (e.g., Balder 1998, Pauleit 2003, Alzetta et al. 2012). With respect to global warming, the results do not indicate that growth of roadside trees mainly depends on climatic factors like atmospheric temperature and CO₂. Trees of both species showed higher growth at the colder rural location with lower atmospheric CO₂ concentrations than at the warmer urban sites with higher CO₂ concentrations. The correlation between atmospheric temperature and CO₂ and stem growth appeared to be negative, implying wood biomass production to be more pronounced for *Tilia* and *Acer* at lower temperatures and lower CO₂ levels. Indeed, *Tilia x vulgaris* and *Acer platanoides* will most likely shift northwards with global warming, but they may also be able to tolerate the temperature increase of 2-3 K that is projected by the year 2100 (IPCC 2007, Rechid et al. 2014). However, the total sum of negative influences, especially the effects of chemical and physical soil parameters in heavily urbanised parts of cities (e.g., Alzetta et al. 2012) seem to override the potentially positive influences of higher atmospheric temperatures and CO₂ concentrations on the growth of the studied trees. The effect of soil conditions on urban roadside trees may be illustrated in the comparison between trees at the sealed and unsealed rural sites within one species. The growth of trees seems to be more strongly impacted by C/N, P, K, pH, salinity, sealing, bulk density, plant available water and aeration of roots than atmospheric temperature or CO₂ concentration.

Not only in view of climate change but also with regard to the global shift in rural to urban areas, studies on different varieties or cultivars of native trees should be carried out in cities to forecast their future vitality and growth in heavily urbanised areas (e.g., Pauleit 2003, Xu et al. 2006). Pauleit et al. (2002) studied urban forestry practises in several European cities and assessed the variety in species as too low. Sjöman et al. (2012) reviewed urban tree databases from ten major Nordic cities and found very low diversity, especially in roadside trees. The requirements for trees suitable for planting in

European cities are currently the subject of several research studies. In order to find the optimal urban roadside tree resistant to limitations in vitality or growth due to the urban climate, several subspecies of *Acer platanoides* are being tested along urban roadsides on behalf of the GALK in diverse cities in Germany, for example. Sæbø et al. (2003) reviews findings for the choice of urban trees in the Northern countries and stresses the incremental planting of alien species that are adapted to warmer climates here. They advised for intensive studies on clones of suitable species and spreading their use over different parts of one city to ensure the highest possible protection against insect calamities and diseases. Based on findings regarding urban trees, a climate species matrix developed by Roloff et al. (2008a, 2008b) or the GALK-list for roadside trees, 2006, can work as a tool for urban landscape planners in choosing tree species resilient to their specific urban climate.

4.2.5 Bud development

On a global scale, data on onset and cessation of growth indicate a lengthening of the growing season by about 10-20 days during the last few decades. This extension of the growing season is associated with recent global warming (e.g., Beaubien and Freeland 2000, Linkosalo et al. 2006, Vitasse and Basler 2012). To forecast further shifts in phenological development of plants in times of climate change, an impressive number of studies have addressed the change in timing and length of the growing period (Chuine 2000, Ahas et al. 2002, Chmielewski et al. 2004, Luo et al. 2006, Dantec et al. 2014). In general, all studies have found progressively earlier spring activities and relate it to climatic warming.

In view of tree budding, the sum of days above 5° C for some period of time in winter and early spring (thermal time) is decisive for the phenological development of a plant (Gurevitch et al. 2002). In trees, thermal times required for budburst depend on previous chilling times (Kozłowski et al. 1991). Fu et al. (2012) indicated that the combination of chilling time in winter and warming in spring are important for budburst. Already by the 1980's, Murray et al. (1989) had studied the phenological responses of European trees in relation to climate warming and found species with low chilling requirements (number of days $\leq 5^\circ$ C) and thermal times (like the early-spring flowering plant *Crataegus monogyna*) to flush distinctively earlier under warmer conditions.

Along the urban-to-rural gradient in this study, significant differences in bud development were found both for *Tilia x vulgaris* and *Acer platanoides*. Urban sites with significantly higher daily atmospheric temperatures had earlier bud development of flowers (*Acer*) and leaves (*Tilia*). Differences in phenology between the suburban and the rural locations, however, were generally small and not significant. This might be due to only small differences in atmospheric temperature between the suburban and the rural sites.

Roetzer et al. (2000) also found a trend for plants to flower earlier in urbanized areas than in the corresponding rural areas but also reported an earlier and stronger forcing of pre-spring flower buds as opposed to full-spring flowering trees, irrespective of location (i.e.

urban or rural). In addition, Ahas et al. (2002) found phenological events occurring in pre-spring to be more sensitive to warming than full-spring phenophases, too.

However, Zacharias (1972) showed that the beginning of flowering of *Tilia euchlora* varies also within the urban area, reflecting the microclimatic variability within the urban core. A similar microclimatic variation within the urbanized area might have also affected trees in Hamburg. Nonetheless, results in this study on bud development strongly verified the positive correlation between atmospheric temperature and phenological events both in *Acer platanoides* and *Tilia x vulgaris*.

In the present study, recorded chilling times with temperatures $\leq 5^{\circ}$ C in autumn and winter 2010/2011 lasted for a total of more than 2000 hours (based on 30 min interval recordings) or 79 continuous days at the urban location. Thus, the chilling demands for *Acer* and *Tilia* were most likely easily fulfilled (Kozłowski et al. 1991, Wesółowski and Rowiński 2006, Caffarra and Donnelly 2011) at this urban location in Hamburg and even more at the cooler suburban and rural locations. In summary, the results on the phenological development of roadside trees presented in this thesis might have resulted from three causes: differences in air temperature between early spring and full spring, air temperature differences between the urban and rural locations, and differences in species requirements (Wesółowski and Rowiński 2006) for bud development between *Acer* and *Tilia*.

With respect to soil conditions, different degrees of soil sealing most likely did not influence the timing of bud burst in the studied trees. Their development was almost identical between the sealed and unsealed rural sites for both species. Although swelling of buds appeared slightly earlier at the sealed than at the unsealed sites, differences were not significant for *Acer* or *Tilia*. However, an effect of soil conditions on the phenological development of urban trees was recently reported by Öztürk et al. (2015), who found the leaf development to be positively related to soil temperature.

5 KEY FINDINGS

Regarding the most influential factors on stem growth and vitality of the urban roadside trees *Tilia x vulgaris* and *Acer platanoides*, results of the present study indicate the following:

1a. The atmospheric climatic factors air temperature and CO₂ were not the decisive factors influencing stem growth of urban roadside trees in Hamburg. High atmospheric temperatures at night, however, might affect the net photosynthesis rate by draining carbohydrates produced during the day to fuel respiration at night.

1b. The relative influence of each studied factor on tree growth was difficult to estimate by results generated by single-factor studies and was confounded by interactions with additional factors that most probably masked the influences of rising atmospheric day-temperatures and CO₂ concentrations.

2. Findings indicate the fundamental influence of tree pit characteristics on urban roadside trees even though studied features of urban soils could not explain this phenomenon:

- Nutrients in studied soils were not limiting for tree growth.
- Soil pH was optimal for nutrient uptake.
- Soil conductance was much lower than found in studies conducted in the 1980s on roadside soils in Hamburg, displaying the effects of decreased use of de-icing salt.

In terms of soil physics, however, it can be assumed that the sealing of tree bases seemed to be negatively correlated to stem growth of trees.

3. An unusual finding of this thesis is the shift in vegetation cycles at the warmer urban climate: Trees of both species started stem growth and budding earliest at the urban location but also ceased growth earliest so that their growing seasons were not lengthened.

4. In terms of phenology, these results on budding of the studied trees underline a positive correlation between temperature and beginning of tree phenophases. Earlier onset at the warmest urban sites argues for a dependency of bud development of *Acer platanoides* and *Tilia x vulgaris* from temperature.

6 OUTLOOK

The results of this thesis raise the question of whether native trees in north European cities might be even able to profit from the warmer atmospheric temperatures predicted with climate change by enhanced growth. However, earlier budding trees are exposed to higher risks of frost damage by sudden cold snaps which might decrease their overall vitality in the future. Given the various urban factors that affect tree growth negatively, the focus of urban forestry should be on the overall health and resistance of urban roadside trees, and special attention should be paid to the design of tree pits. Significant increases in tree pit size have been advocated by researchers in this field for years (e.g. Pauleit 2003). Moreover, the quality of soil that is used to fill tree pits and the microclimate of the planting site need to be studied in more detail as the soil not only provides a safe and firm substrate for rooting, but is also the source for nutrients, oxygen and water. In the late 1990s, Jim (1998) suggested setting aside natural soils collected from natural areas, or areas similar to natural conditions, and filling tree pits from these reserves when planting roadside trees in cities. However, the specific conditions along roads in cities ask for optimized artificial substrates which satisfy the needs for tree growth and at the same time are able to withstand stressors like soil compaction. The standard soil substrates used in roadside tree plantings in cities in Germany today seem to fulfill many of these requirements but are characterized by a too high soil pH for optimal tree growth.

Water-use efficiency and thus adaptation to drought stress differs among tree species. Gillner et al. (2015) found *Acer platanoides* to have extremely low water use efficiency and drought resistance and thus suggested to choose shady stands for *Acer* species. Within the next years, I assume drought stress to be the urgent problem for trees in European cities and especially those planted along roadsides. In the future, it should be investigated how drought and the interplay with other urban stressors affect vitality and growth of roadside trees and how negative impacts of these stressors can be minimized. Further, comparative studies on tree species should unravel which species and/or cultivars are able to withstand future urban climates. In order to allow for best possible growth conditions for roadside trees in cities also with comparatively small tree pits, the quality of artificial soil substrates need to be studied more intensively. Not only tree species should be tested but also different soil substrates and their capacity to enhance tree vitality.

7 REFERENCES

- Ad-Hoc-Arbeitsgruppe Boden. 2005. *Bodenkundliche Kartieranleitung*. Fifth edition. Bundesanstalt für Geowissenschaften und Rohstoffe und Niedersächsisches Landesamt für Bodenforschung, Hannover.
- Ahas, R., A. Aasa, A. Menzel, V. G. Fedotova, and H. Scheifinger. 2002. Changes in European spring phenology. *International Journal of Climatology* 22:1727–1738.
- Ainsworth, E. A., and S. P. Long. 2005. What have we learned from 15 years of free-air CO₂ enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO₂.
- Alzetta, C., L. Scattolin, C. Scopel, and S. M. Accordi. 2012. The ectomycorrhizal community in urban linden trees and its relationship with soil properties. *Trees - Structure and Function* 26:751–767.
- Balder, H. 1998. *Die Wurzeln der Stadtbäume-Ein Handbuch zum vorbeugenden und nachsorgenden Wurzelschutz*. First edition. Ulmer, Stuttgart.
- Bauerle, T. L., and M. Centinari. 2014. Assessment of root system development among four ornamental tree species through time via X-ray Computed Tomography. *HortScience* 49:44–50.
- Bauweraerts, I., M. Ameye, T. M. Wertin, M. A. McGuire, R. O. Teskey, and K. Steppe. 2014. Water availability is the decisive factor for the growth of two tree species in the occurrence of consecutive heat waves. *Agricultural and Forest Meteorology* 189-190:19–29.
- Beaubien, E. G., and H. J. Freeland. 2000. Spring phenology trends in Alberta, Canada: links to ocean temperature. *International Journal of Biometeorology* 44:53–59.
- Berland, A. 2012. Long-term urbanization effects on tree canopy cover along an urban-rural gradient. *Urban Ecosystems* 15:721–738.
- Berry, R. D., and J. J. Colls. 1990a. Atmospheric carbon dioxide and sulphur dioxide on an urban/rural transect - I. Continuous measurements at the transect ends. *Atmospheric Environment* 24A:2681–2688.
- Berry, R. D., and J. J. Colls. 1990b. Atmospheric carbon dioxide and sulphur dioxide on an urban/rural transect—II. Measurements along the transect. *Atmospheric Environment. Part A. General Topics* 24:2689–2694.
- Bijoor, N. S., H. R. McCarthy, D. Zhang, and D. E. Pataki. 2011. Water sources of urban trees in the Los Angeles metropolitan area. *Urban Ecosystems* 15:195–214.
- Blume, H.-P., P. Felix-Henningnissen, H.-G. Frede, G. Guggenberger, R. Horn, and K. Stahr. 2014. *Handbuch der Bodenkunde*. First edition. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

- Bowers, J. E., and M. A. Dimmitt. 1994. Flowering Phenology of Six Woody Plants in the Northern Sonoran Desert. *Bulletin of the Torrey Botanical Club* 121:215.
- Brahe, P. 1974. Klimatische Auswirkungen von Gehölzen auf umbauten Stadtplätzen. *Stadt und Grün/ Das Gartenamt* 2:61–70.
- Bruns, E., F.-M. Chmielewski, and A. J. H. VanVliet. 2003. The Global Phenological Monitoring Concept Towards International Standardization of Phenological Networks. Pages 93–104 in M. D. Schwartz, editor. *Phenology: An Integrative Environmental Science*. Wageningen.
- Burghardt, W. 1994. Soils in urban and industrial environments. *Zeitschrift für Pflanzenernährung und Bodenkunde* 157:205–214.
- Caffarra, A., and A. Donnelly. 2011. The ecological significance of phenology in four different tree species: effects of light and temperature on bud burst. *International journal of biometeorology* 55:711–21.
- Cakmak, I. 2000. Tansley Review No. 111. *New Phytologist* 146:185–205.
- Carreiro, M. M., and C. E. Tripler. 2005. Forest remnants along urban-rural gradients: Examining their potential for global change research.
- Cekstere, G., N. Gerts, and A. Osvaldea. 2008. Toxic impact of the de-icing material to street greenery in Riga, Latvia. *Urban Forestry & Urban Greening*.
- Cekstere, G., and A. Osvalde. 2010. Macronutrient Status in the different-aged lime trees (16:16–22.
- Cekstere, G., and A. Osvalde. 2013. A study of chemical characteristics of soil in relation to street trees status in Riga (Latvia). *Urban Forestry and Urban Greening* 12:69–78.
- Chmielewski, F. M., and T. Rotzer. 2001. Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology* 108:101–112.
- Chmielewski, F., a Müller, and W. Küchler. 2004. Mögliche Auswirkungen klimatischer Veränderungen auf die Vegetationsentwicklung in Sachsen. *Hu Berlin*:108.
- Chuine, I. 2000. A unified model for budburst of trees. *Journal of theoretical biology* 207:337–347.
- Collie, T. S., and F. X. Schumacher. 1953. Relation of soil characteristics to site index of loblolly and short - leaf pines in the lower Piedmont region of North Carolina | Clc. <http://library.wur.nl/WebQuery/clc/461066>.
- Craul, P. J. 1992. *Urban Soil in landscape design*. John Wiley & Sons, Hoboken, New York.
- Craul, P. J. 1999. *Urban Soils: Applications and Practices*. John Wiley & Sons, Hoboken, New York.

- Dantec, C. F., Y. Vitasse, M. Bonhomme, J.-M. Louvet, A. Kremer, and S. Delzon. 2014. Chilling and heat requirements for leaf unfolding in European beech and sessile oak populations at the southern limit of their distribution range. *International journal of biometeorology* 58:1853–64.
- Dobbertin, M. 2005. Tree growth as indicator of tree vitality and of tree reaction to environmental stress: A review.
- Dobbertin, M., and A. Giuggiola. 2006. Baumwachstum und erhöhte Temperaturen. *Forum für Wissen*:35–45.
- Doichinova, V., M. Zhiyanski, A. Hursthouse, and J. Bech. 2014. Study on the mobility and bioavailability of PTEs in soils from Urban Forest Parks in Sofia, Bulgaria. *Journal of Geochemical Exploration* 147:222–228.
- Donnelly, A., M. B. Jones, and J. Sweeney. 2004. A review of indicators of climate change for use in Ireland. *International journal of biometeorology* 49:1–12.
- Doobe, G. 2004. Bäume in unserer Stadt. Hamburg.
- Dorendorf, J., A. Wilken, A. Eschenbach, and K. Jensen. 2015. Urban-induced changes in tree leaf litter accelerate decomposition. *Ecological Processes* 4:1–16.
- Dow, G. J., J. A. Berry, and D. C. Bergmann. 2014. The physiological importance of developmental mechanisms that enforce proper stomatal spacing in *Arabidopsis thaliana*. *New Phytologist* 201:1205–1217.
- Eckstein, D. 2000. Dentreökologischer Wirkungsnachweis von Auftausalz und Bodensanierung an Straßenbäumen. *Jahrbuch der Baumpflege*:134 – 141.
- Eckstein, D., E. Frisse, and W. Liese. 1974. Holzanatomische Untersuchungen an umweltgeschädigten Straßenbäumen der Hamburger Innenstadt. *Forest Pathology* 4:232–244.
- Eckstein, D., E. Frisse, and F. Quiehl. 1977. Holzanatomische Untersuchungen zum Nachweis anthropogener Einflüsse auf die Umweltbedingungen einer Rotbuche. *Angewandte Botanik*.
- Elgharably, A., and O. Ito. 2014. Available N and P, Microbial Activity, and Biomass in Saline Sandy and Clayey Soils Amended with Residues of Wheat and Alfalfa. *Communications in Soil Science and Plant Analysis* 45:2868–2877.
- Fellenberg, G. 1984. Urban ecology. *Die Naturwissenschaften* 71:393–403.
- Finck, A. 2007. Pflanzenernährung und Düngung. Sixth edition. Gebrüder Borntraeger, Stuttgart.
- Fitter, A. H., and R. S. R. Fitter. 2002. Rapid changes in flowering time in British plants. *Science (New York, N.Y.)* 296:1689–1691.

- Fu, Y. H., M. Campioli, G. Deckmyn, and I. A. Janssens. 2012. The impact of winter and spring temperatures on temperate tree budburst dates: results from an experimental climate manipulation. *PloS one* 7:e47324.
- GALK-Arbeitskreis Stadtbäume. 2006. Straßenbaumliste 2006.
- George, K., L. H. Ziska, J. A. Bunce, and B. Quebedeaux. 2007. Elevated atmospheric CO₂ concentration and temperature across an urban–rural transect.
- Gillner, S., J. Vogt, A. Tharang, S. Dettmann, and A. Roloff. 2015. Role of street trees in mitigating effects of heat and drought at highly sealed urban sites. *Landscape and Urban Planning* 143:33–42.
- Gozlinski, H., and B. Gej. 1984. Gas exchange and accumulation of mineral components in assimilatory organs of trees growing in urban conditions. *Polish Ecological Studies*.
- Gregg, J. W., C. G. Jones, and T. E. Dawson. 2003. Urbanization effects on tree growth in the vicinity of New York City. *Nature* 424:183–187.
- Gurevitch, J., S. M. Scheiner, and G. A. Fox. 2002. *The Ecology of Plants*. Sinauer Associates, Inc., Sunderland.
- Häkkinen, R., and P. Hari. 1988. The efficiency of time and temperature driven regulation principles in plants at the beginning of the active period. *Suomen metsätieteellinen seura*.
- Häkkinen, R., T. Linkosalo, and P. Hari. 1998. Effects of dormancy and environmental factors on timing of bud burst in *Betula pendula*. *Tree physiology* 18:707–712.
- Hänninen, H., and K. Tanino. 2011. Tree seasonality in a warming climate.
- Hasenauer, H., R. R. Nemani, K. Schadauer, and S. W. Running. 1999. Forest growth response to changing climate between 1961 and 1990 in Austria. *Forest Ecology and Management* 122:209–219.
- Heide, O. M. 1974. Growth and Dormancy in Norway Spruce Ecotypes (*Picea abies*) I. Interaction of Photoperiod and Temperature. *Physiologia Plantarum* 30:1–12.
- Heide, O. M. 2003. High autumn temperature delays spring bud burst in boreal trees, counterbalancing the effect of climatic warming. *Tree physiology* 23:931–936.
- Heide, O. M., and A. K. Prestrud. 2005. Low temperature, but not photoperiod, controls growth cessation and dormancy induction and release in apple and pear. *Tree Physiology* 25:109–114.
- Heide, O. M. 2008. Interaction of photoperiod and temperature in the control of growth and dormancy of *Prunus* species. *Scientia Horticulturae* 115:309–314.

- Heide, O. M. 2011. Temperature rather than photoperiod controls growth cessation and dormancy in *Sorbus* species. *Journal of Experimental Botany* 62:5397–5404.
- Hemery, G. E., P. S. Savill, and S. N. Pryor. 2005. Applications of the crown diameter–stem diameter relationship for different species of broadleaved trees. *Forest Ecology and Management* 215:285–294.
- Hiller, D. A., and H. Meuser. 1998. *Urbane Böden*. Page 161. Springer, Berlin.
- Iakovoglou, V., J. Thompson, L. Burras, and R. Kipper. 2001. Factors related to tree growth across urban-rural gradients in the Midwest, USA. *Urban Ecosystems* 5:71–85.
- Idso, C. D., S. B. Idso, and R. C. Balling. 2001. An intensive two-week study of an urban CO₂ dome in Phoenix, Arizona, USA. *Atmospheric Environment* 35:995–1000.
- IPCC. 2007. *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, New York.
- Jensen, kai. 2011. Klimabedingte Änderungen in terrestrischen und semi-terrestrischen Ökosystemen. Page pp 143–176 *Klimabericht für die Metropolregion Hamburg*. Springer Berlin Heidelberg.
- Jim, C. 1998. Physical and chemical properties of a Hong Kong roadside soil in relation to urban tree growth. *Urban Ecosystems* 2:171–181.
- JUNTTILA, O. 1982. The Cessation of Apical Growth in Latitudinal Ecotypes and Ecotype Crosses of *Salix pentandra* L. *Journal of Experimental Botany* 33:1021–1029.
- Kazlauskaitė-Jadzevičė, A., J. Volungevičius, V. Gregorauskienė, and S. Marcinkonis. 2014. The role of pH in heavy metal contamination of urban soil. *Journal of Environmental Engineering and Landscape Management* 22:311–318.
- De Kimpe, C. R., and J.-L. Morel. 2000. URBAN SOIL MANAGEMENT: A GROWING CONCERN. *Soil Science* 165:31–40.
- Kose, N., and H. T. Guner. 2012. The effect of temperature and precipitation on the intra-annual radial growth of *Fagus orientalis* Lipsky in Artvin, Turkey. *TURKISH JOURNAL OF AGRICULTURE AND FORESTRY* 36:501–509.
- Kozłowski, T. T., P. J. Kramer, and S. G. Pallardy. 1991. *The Physiological Ecology of Woody Plants*. Kozłowski, T. T., P. J. Kramer and S. G. Pallardy. *Physiological Ecology: The Physiological Ecology of Woody Plants*. Xix+657p. Academic Press, Inc.: San Diego, California, USA; London, England, Uk. Illus. Maps.
- Kutschera, L., and E. Lichtenegger. 2013. *Wurzelatlas mitteleuropäischer Waldbäume und Sträucher*. Second edition. Stocker, Graz.

- Lange, P. W., C. De Ronde, and B. V. Bredenkamp. 1987. The Effects of Different Intensities of Pruning on the Growth of *Pinus radiata* in South Africa. *South African Forestry Journal* 143:30–36.
- Lindman, H. R. 1974. *Analysis of variance in complex experimental designs*. W. H. Freeman, Oxford.
- Linkosalo, T., R. Hakkinen, and H. Hanninen. 2006. Models of the spring phenology of boreal and temperate trees: is there something missing? *Tree Physiology* 26:1165–1172.
- Long, J. N., and F. W. Smith. 1990. Determinants of Stemwood Production in *Pinus contorta* var. *Latifolia* Forests: The Influence of Site Quality and Stand Structure. *The Journal of Applied Ecology* 27:847.
- Lovett, G. M., M. M. Traynow, R. V. Pouyat, M. M. Carreiro, W.-X. Zhu, and J. W. Baxter. 2000. Atmospheric deposition to oak forests along an urban-rural gradient. *Environmental science & technology* 34:4294–4300.
- Luo, Z., O. J. Sun, Q. Ge, W. Xu, and J. Zheng. 2006. Phenological responses of plants to climate change in an urban environment. *Ecological Research* 22:507–514.
- Martin, C., and J. C. Stutz. 2013. *Tree Health in Phoenix, Arizona, U.S.*
- Mei, G.-Y., and Y.-J. Sun. 2013. Relationship between Crown Diameter and Diameter at Breast Height of *Cunninghamia lanceolata* Scenery and Recreation Forest. *Bulletin of Botanical Research*.
- Meyer, F. H. 1993. *Bäume in der Stadt*. Ulmer Eugen Verlag, Ulm.
- Miehlich, G. 2010. Die Böden Hamburgs. Pages 18–27 *Der Hamburger Pflanzenatlas*. First edition. Dölling und Galitz Verlag, München, Hamburg.
- Murray, M. B., M. G. R. Cannell, and R. I. Smith. 1989. Date of budburst of fifteen tree species in Britain following climate warming. *Journal of Applied Ecology* 26:693–700.
- Neil, K., and J. Wu. 2006. Effects of urbanization on plant flowering phenology: A review. *Urban Ecosystems* 9:243–257.
- Niemelä, J. 2011. *Urban ecology*. Oxford University Press, Oxford, New York.
- Nijs, I., I. Impens, and T. Behaeghe. 1989. Leaf and canopy responses of *Lolium perenne* to long-term elevated atmospheric carbon-dioxide concentration. *Planta* 177:312–20.
- Oke, T. R. 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society* 108:1–24.

- Öztürk, M., İ. Bolat, and A. Ergün. 2015. Influence of air–soil temperature on leaf expansion and LAI of *Carpinus betulus* trees in a temperate urban forest patch. *Agricultural and Forest Meteorology* 200:185–191.
- Pataki, D. E., T. Xu, Y. Q. Luo, and J. R. Ehleringer. 2007. Inferring biogenic and anthropogenic carbon dioxide sources across an urban to rural gradient. *Oecologia* 152:307–322.
- Pauleit, S. 2003. Urban street tree plantings: identifying the key requirements.
- Pauleit, S., N. Jones, G. Garcia-Martin, J. L. Garcia-Valdecantos, L. M. Rivière, L. Vidal-Beaudet, M. Bodson, and T. B. Randrup. 2002. Tree establishment practice in towns and cities – Results from a European survey. *Urban Forestry & Urban Greening* 1:83–96.
- Petersen, A., and D. Eckstein. 1988. Holzbiologische Untersuchungen ueber die Belastung und Erholungsfähigkeit von Stadtbaeumen in Hamburg. 17. Oekologie-Forum der Umweltbehoerde. Hamburg (Germany, F.R.). 15 Nov 1985.
- Pfeiffer, E.-M. 1988. Auswirkungen von Bodensanierung auf streusalzgeschaedigte Baeume im Hamburger Stadgebiet. 17. Oekologie-Forum der Umweltbehoerde. Hamburg (Germany, F.R.). 15 Nov 1985.
- Pokorny, R., I. Tomaskova, and R. Slipkova. 2012. The Effect of Air Elevated [CO₂] on Crown Architecture and Aboveground Biomass in Norway Spruce (*Picea Abies* (L.) Karst). *BALTIC FORESTRY* 18:2–11.
- Pouyat, R., P. Groffman, I. Yesilonis, and L. Hernandez. 2002. Soil carbon pools and fluxes in urban ecosystems. *Environmental Pollution* 116.
- Pouyat, R. V., I. D. Yesilonis, J. Russell-Anelli, and N. K. Neerchal. 2007. Soil Chemical and Physical Properties That Differentiate Urban Land-Use and Cover Types.
- Rahman, M. A., P. Stringer, and A. R. Ennos. 2013. Effect of Pit Design and Soil Composition on Performance of *Pyrus calleryana* Street Trees in the Establishment Period. *Arboriculture & Urban Forestry*.
- Rathcke, B., and E. P. Lacey. 1985. Phenological Patterns of Terrestrial Plants.
- Rechid, D., J. Petersen, R. Schoetter, and D. Jacob. 2014. Klimaprojektionen für die Metropolregion Hamburg. Hamburg.
- Roetzer, T., M. Wittenzeller, H. Haeckel, and J. Nekovar. 2000. Phenology in central Europe--differences and trends of spring phenophases in urban and rural areas. *International journal of biometeorology* 44:60–66.
- Roloff, A. 1989. Tree vigour and branching pattern. *J.For.Sc* 5:206–216.

- Roloff, A. 2013. Stadt- und Straßenbäume der Zukunft – welche Arten sind geeignet? Pages 173–187 Aktuelle Fragen der Stadtbaumplanung, -pflege und -verwendung. A. ROLOFF, D. THIEL, H. WEIß, Dresden.
- Roloff, A., S. Bonn, and S. Gillner. 2008a. Baumartenwahl und Gehölzverwendung im urbanen Raum unter Aspekten des Klimawandels. Dresden.
- Roloff, A., S. Bonn, and S. Gillner. 2008b. Klimawandel und Baumartenwahl in der Stadt-Entscheidungsfindung mit der Klima-Arten-Matrix (KLAM). *Stadt und Grün* 57:53–60.
- Sæbø, A., T. Benedikz, and T. B. Randrup. 2003. Selection of trees for urban forestry in the Nordic countries. *Urban Forestry & Urban Greening* 2:101–114.
- Sage, R. F., and D. S. Kubien. 2007. The temperature response of C(3) and C(4) photosynthesis. *Plant, cell & environment* 30:1086–1106.
- Sauerwein, M. 2011. Urban Soils-Characterization, Pollution, and Relevance in Urban Ecosystems. *URBAN ECOLOGY: PATTERNS, PROCESSES, AND APPLICATIONS*:45–58.
- Schachtschabel, P., H.-P. Blume, G. W. Brümmer, F. Scheffer, R. Horn, E. Kandeler, I. Kögel-Knabner, R. Kretschmar, K. Stahr, B.-M. Wilke, G. Welp, and S. Thiele-Bruhn. 2010. *Lehrbuch der Bodenkunde*. Scheffer/Schachtschabel. 16th edition. Spektrum Akademischer Verlag, Heidelberg.
- Scharenbroch, B. C., and M. Catania. 2012. Soil quality attributes as indicators of Urban Tree performance. Pages 214–228 *Arboriculture and Urban Forestry*.
- Scharenbroch, B. C., J. E. Lloyd, and J. L. Johnson-Maynard. 2005. Distinguishing urban soils with physical, chemical, and biological properties. *Pedobiologia* 49:283–296.
- Schoenholtz, S. H., H. Van Miegroet, and J. A. Burger. 2000. A review of chemical and physical properties as indicators of forest soil quality: Challenges and opportunities.
- Schroeder, D. 1992. *Bodenkunde in Stichworten*. Fifth edition. Gebrüder Borntraeger, Berlin, Stuttgart.
- Sieghardt, M., E. Mursch-Radlgruber, E. Paoletti, E. Couenberg, A. Dimitrakopoulos, A. Rego, Francisco Hatzistathis, and T. B. Randrup. 2005. The Abiotic Urban Environment: Impact of Urban Growing Conditions on Urban Vegetation. Pages 281–323. Springer, Berlin.
- Sjöman, H., J. Östberg, and O. Bühler. 2012. Diversity and distribution of the urban tree population in ten major Nordic cities. *Urban Forestry and Urban Greening* 11:31–39.
- Stach, W. 1969. Untersuchung über die Auswirkung der Winterstreuung und anderer Ernährungsphysiologischer Faktoren auf die Straßenbäume der Hamburger Innenstadt. Universität Hamburg.

- Streckenbach, M. 2012. Urbane Böden- eine Lebensgrundlage für Gehölze? http://www.streckenbach.org/dbt_04_2012.html.
- Sukopp, H., and R. Wittig. 1998. Stadtökologie. Second edition. Gustav Fischer, Stuttgart.
- Timilsina, N., C. L. Staudhammer, F. J. Escobedo, and A. Lawrence. 2014. Tree biomass, wood waste yield, and carbon storage changes in an urban forest. *Landscape and Urban Planning* 127:18–27.
- Vitasse, Y., and D. Basler. 2012. What role for photoperiod in the bud burst phenology of European beech. *European Journal of Forest Research* 132:1–8.
- Watkins, R., J. Palmer, M. Kolokotroni, and P. Littlefair. 2002. The balance of the annual heating and cooling demand within the London urban heat island.
- Weltecke, K., and T. Gaertig. 2012. Influence of soil aeration on rooting and growth of the Beuys-trees in Kassel, Germany. *Urban Forestry and Urban Greening* 11:329–338.
- Wesołowski, T., and P. Rowiński. 2006. Timing of bud burst and tree-leaf development in a multispecies temperate forest. *Forest Ecology and Management* 237:387–393.
- Xu, W., X. He, W. Chen, J. Hu, and H. Wen. 2006. [Responses of Shenyang urban tree phenology to climate warming]. *Ying yong sheng tai xue bao = The journal of applied ecology / Zhongguo sheng tai xue xue hui, Zhongguo ke xue yuan Shenyang ying yong sheng tai yan jiu suo zhu ban* 17:1777–81.
- Zacharias, F. 1972. Bluephaseneintritt an Strassenbaeumen (insbesondere Tilia x euchlora Koch) und Temperaturverteilung in Westberlin | Clc. <http://library.wur.nl/WebQuery/clc/247995>.
- Zhang, C., and Y. Lin. 2012. Panel estimation for urbanization, energy consumption and CO2 emissions: A regional analysis in China.
- Zhang, J. L., L. Z. Meng, and K. F. Cao. 2005. Sustained diurnal photosynthetic depression in uppermost-canopy leaves of four dipterocarp species in the rainy and dry seasons: does photorespiration play a role in photoprotection? <http://treephys.oxfordjournals.org/content/29/2/217.full.pdf>.
- Ziska, L. H., J. A. Bunce, and E. W. Goins. 2004. Characterization of an urban-rural CO2/temperature gradient and associated changes in initial plant productivity during secondary succession. *Oecologia* 139:454–458.
- Ziska, L. H., D. E. Gebhard, D. A. Frenz, S. Faulkner, B. D. Singer, and J. G. Straka. 2003. Cities as harbingers of climate change: Common ragweed, urbanization, and public health. *Journal of Allergy and Clinical Immunology* 111:290–295.

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Melli hat mir im Stadtdschungel sehr geholfen, die besten Strecken zu finden und Bodenproben zu nehmen.

Nikola ist nicht nur meine Bürokollegin, sondern hat auch 2010 schon die kleinen Holzhäuschen mit Lotte Korell gebaut, in denen ich die Temperaturlogger untergebracht habe, die Simon dann an den Baumstämmen angebracht hat. Außerdem hat Nikola mich zu diversen Veranstaltungen begleitet.

Tätigkeiten im Gewächshaus und davor haben stattgefunden und liefen reibungslos, weil Marion Klötzl alles sehr gut organisiert und geordnet hat.

Für den letztlich nicht auswertbaren Keimversuch habe ich mich auf die geschulte Hilfe im Beizen von Samen von Jutta Krüger verlassen können.

Die Endphase meiner Arbeit war sehr lang und Christian Butzeck hat zunächst als Leidensgenosse und dann als promovierter Ökologe begleitet und unterstützt, was mir bei der Formatierung sehr schwergefallen ist.

Steffi hat mich noch schnell in Mendeley eingeführt und Eli hat's umgesetzt.

Was Du, Vicky, für mich getan hast und tust, kann ich kaum in Worte fassen. Nie hätte ich gedacht, dass das AC-Praktikum damals der Beginn einer so wunderbaren Freundschaft werden könnte und Du mich so stark machst! Zusammen mit Franzi haben wir drei dann doch über fachlichen Fragen gegrübelt, aber auch im Privaten -Pflegestufe- habt ihr beide mir unermüdlich dabei geholfen, überhaupt meine eigentliche Arbeit machen zu können.

Franzi, ohne Dich hätte ich diesen ungewöhnlichen Rollstuhl auch nicht!

Zum Schluss danke ich auch meinen Eltern dafür, dass Ihr diese Zeit mit mir und einigen Tiefschlägen überstanden habt und mir den Hund liebevoll abnehmt, wenn es nicht geht.

Ich hatte unglaublich viele Hände, die mir gereicht wurden und damit meine ich nicht nur die Armbeugen, in die ich mich einhaken durfte. Danke Euch allen!