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Urban Tree Drought Stress: A Practitioner-Focused Review of Detection and Monitoring Methods

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ABSTRACT

Urban trees are increasingly experiencing drought stress due to more frequent and severe drought periods. This stress leads to reduced growth, structural damage and even mortality, further exacerbating feedback effects within the urban hydrological cycle. Currently, tree health assessments by arborists rely primarily on visual inspections, which often detect stress symptoms too late for effective intervention. To address this issue, early drought stress detection methods are essential. This review examines existing methods for detecting drought stress in urban trees, evaluating their scalability, market availability and usability for practitioners. We conducted a two-part literature analysis: (1) a systematic review of stress detection methods applied to urban trees between 2010 and 2024, and (2) a snowball search assessing the potential and limitations of the individual methods found in the systematic review. The systematic review revealed that in urban areas, *Acer*, *Quercus* and *Tilia* are the most commonly investigated tree taxa. The most common methods are leaf gas exchange measurements, analysis of plant water potentials and chlorophyll fluorescence. Compared to studies in non-urban areas, soil moisture monitoring is less common in urban tree studies. The snowball search showed that urban tree drought stress monitoring is in its nascent stage. Of all identified methods, only soil moisture sensors and microtensiometers were deemed easy to use and commercially available, yet both lack scalability for city-wide application. Furthermore, there remains a significant gap between fine-scale, tree-based assessments and broad-scale monitoring approaches. Bridging this gap with integrated monitoring strategies will be crucial for improving early drought stress detection and urban tree management.

1 | Introduction

Urban trees intercept precipitation, offer shade, transpirational cooling, and are habitat for many species (Berland et al. 2017; Gillner et al. 2015; Pena et al. 2017). Therefore, they are an essential component of the city's (blue)–green infrastructure, but cities are harsh environments for trees (Czaja et al. 2020; Lüttge and Buckeridge 2023). Global projections for 2050 indicate that up to 40% of urban tree species are at risk in their current planting locations (Esperon-Rodriguez et al. 2022). These trees are significantly impacted by urban climate conditions (Franceschi et al. 2023) and the specific characteristics of their planting sites (Schütt, Becker, Reisdorff, and Eschenbach 2022). Urban tree planting sites are often characterised by compacted and poor soils, limited rooting space and restricted water availability (Schütt, Becker, Reisdorff, and Eschenbach 2022). Consequently, urban tree growth is heavily influenced by the quality of the soil and the permeability of the ground surface (Schütt, Becker, Reisdorff, and Eschenbach 2022). Dry and warm climatic conditions increase the probability of drought stress, which may further hinder urban tree growth (Dervishi et al. 2022; McDowell et al. 2022; Moser et al. 2017), and the ability of different tree species to cope with these unfavourable environmental conditions varies significantly (Franceschi et al. 2023).

Given that trees typically have long lifespans and are costly to nurse, plant and maintain, it is crucial for municipal green space agencies to manage their resources effectively and prioritise long-term tree health. A decline in overall tree health indicates that a tree has been subjected to *stress* for a significant duration. Here, stress is defined as a functional condition in which an organism experiences deviations from favourable conditions (Larcher 2000), ultimately affecting its development, growth, or metabolism (Lichtenthaler 1998). Stress for urban trees can be caused by pollution from traffic, demolition activities, the surrounding building structure and heat stress (Bierza and Bierza 2024; Bigelow et al. 2024; Haase and Hellwig 2022; North et al. 2017). Limited water availability, caused by reduced soil moisture and increased vapour pressure deficit during hot weather, is one of the major causes of stress in urban trees (Czaja et al. 2020; Haase and Hellwig 2022; Roloff 2021). Hereinafter, we refer to this type of stress as *drought stress*.

Drought stress manifests itself through various physiological and biochemical changes within trees. Figure 1 shows the spatiotemporal variability in plant stress responses along a reversibility scale and the methods that can be used to detect them. When plant tissues become dehydrated, they alter their phytohormones and amino acid production (e.g., the production of abscisic acid, proline; Brestic and Zivcak 2013; Buckley 2019). These physiological changes prompt the closure of the stomata, resulting in reduced transpiration and photosynthesis rates (Brestic and Zivcak 2013). This drought-induced decline in photosynthetic activity leads to an increased dissipation of light energy as heat and altered chlorophyll fluorescence (Kalaji et al. 2016; Murchie and Lawson 2013). Furthermore, water scarcity causes reductions in leaf water potential and leaf water content (Horike et al. 2023). Drought stress also affects stem dynamics, with trees responding by reducing stem growth (Franceschi et al. 2023; Moser et al. 2017). Mid-term stress reactions become visible through species-specific symptoms such as wilting, leaf rolling, or folding. Extended drought conditions may lead to leaf shedding or twigs dropping, ultimately resulting in dieback of larger branches and structural changes to the crown or, in the worst case, death of the whole tree (Roloff 2021).

There is a temporal gap between the onset of stress and its visible effects on tree health (Johnstone et al. 2013). Visual tree health monitoring by arborists is time- and resource-intensive. By the time these visible effects are detected, the tree health may have already deteriorated to such a degree that it renders recovery impossible. Stress must be identified early for municipalities to implement appropriate mitigation measures, such as watering (Bahe et al. 2021) or modifying the tree pit.

The increasing likelihood of droughts in urban areas underscores the need for reliable tools to detect tree drought

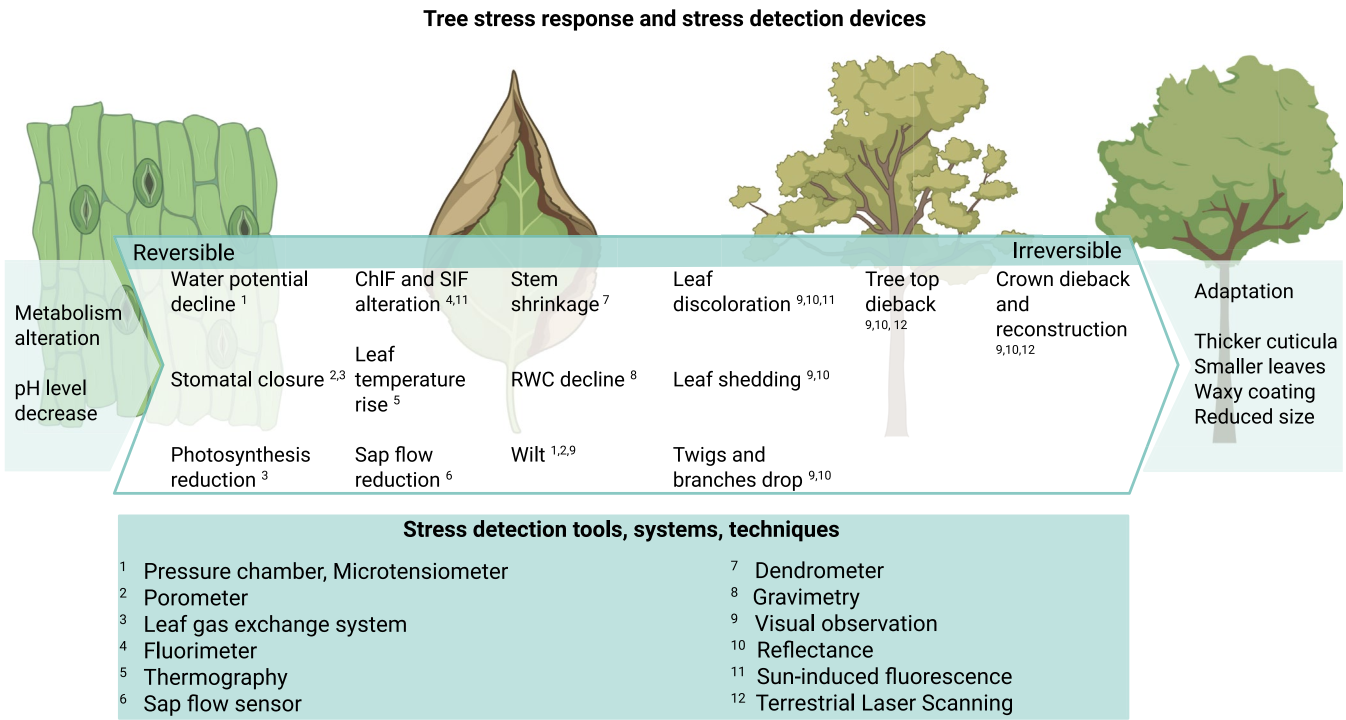

FIGURE 1 | Tree stress response and stress detection systems (ChlF: chlorophyll fluorescence; SIF: sun-induced chlorophyll fluorescence; RWC: relative water content). The aspects within the box indicate the scope of the tree stress responses and tools and techniques discussed in this review. Created in BioRender. Quambusch, M. (2025), https://BioRender.com/06shg5k.

stress early and at a broader scale (Jonard et al. 2020; Urban et al. 2017). Such stress detection is challenging because urban tree sites are highly heterogeneous and impacted by human activities (Bierza and Bierza 2024; Cârlan et al. 2020; Czaja et al. 2020). Humans select tree species based on the geographic location, (micro) climate and site conditions. Tree species differ in their stress reaction, ability to cope with drought stress and climate change (Cunha et al. 2025; Esperon-Rodriguez et al. 2022; Stratópoulos et al. 2019). For instance, some species tend to close their stomata quickly during drought periods (isohydric tree species), whereas others exhibit a broader range of water potential where they keep their stomata open (Henry et al. 2019; Klein 2014; Tardieu and Simonneau 1998). This variation in response poses a challenge to early drought stress detection. Also, the knowledge about the stress response varies based on the species and genera. This species-specific stress response and timing, coupled with the challenges of observation in urban areas, make a universal monitoring approach to early drought stress detection difficult. In this study, we review the literature on urban tree drought monitoring systems and determine the distribution of the genera studied.

Municipalities need effective tools, which are scalable, applicable and established. Therefore, our review examines what the trade-offs of commonly used methods for drought stress detection in urban trees with regard to the criteria of scalability, usability and availability are. We provide an overview of each method, their operating principle, use and limitations. We organized all reviewed methods under three monitoring categories: (i) tree-based analysis tools, (ii) airborne tools and (iii) soil monitoring tools. Finally, we evaluate the trade-off of each method. While undoubtedly important tools, modeling approaches are considered out of scope for this review.

2 | Data and Methods

2.1 | Literature Search

We conducted two different literature searches, one to grasp the general state of the art in stress detection monitoring in urban areas and another one that focuses on the strengths and challenges of the identified drought stress methods. For the first search, we used Web of Science, with the search strings 'urban AND tree AND drought' and 'urban AND tree AND water stress', and limiting the search to articles published between 01.01.2010 and 24.10.2024. All matching articles were accessed and their abstracts were screened. We excluded reviews and meta-analyses, non-English articles and articles that were topically out of scope, for example, articles on water logging and thermal comfort. Further, we excluded articles on methods that require extensive laboratory work, such as tree ring analysis, isotopic analysis and pigment analysis. These methods fell out of our scope because we are interested in methods that can be applied directly in the field; further elaboration can be found in the limitation section at the end of the discussion below.

The remaining articles were screened for the following information: (i) the country of research, (ii) the species studied, (iii) the study site (urban vs. non-urban) and (iv) the methods used. The measured parameters were categorised into method groups—for example, stomatal conductance, transpiration and net photosynthesis were grouped as leaf gas exchange; maximum quantum yield of photosystem (PS) II, quantum yield of PSII, and JIP-test were grouped as chlorophyll fluorescence. Further information can be found in the supplement (Table S1A). Overall, we categorised the method groups into the following monitoring categories: tree-based analysis tools, airborne tools and soil monitoring tools.

Once the method groups commonly used in urban areas were identified, a 'snow-ball' literature search was conducted to assess the state-of-the-art and potential of each of these methods. For this literature search, we used three sources: Nature, Web of Science and Scopus. We entered the search strings 'urban AND tree', 'city AND tree' or 'tree' and combined them with the following method-specific search words: 'plant water potential', 'leaf gas exchange', 'sap flow', 'relative water content', 'stem water content', 'stem diameter variation', 'trunk diameter variation', 'terrestrial laser scanning', 'chlorophyll fluorescence', 'SIF', 'sun-induced chlorophyll fluorescence', 'thermography', 'reflectance', 'remote sensing' or 'stress', 'monitoring', 'detection', 'drought', and 'water'. Urban studies were prioritized whenever possible. Additional studies from forest and horticulture systems were included if urban studies were lacking.

2.2 | Comparative Assessment

To assess the trade-off of each stress detection method, we categorised the methods as shown in Table 1, with our parameters being (i) scalability, (ii) availability on the market and (iii) usability for practitioners. Scalability refers to the method's ability to be effectively applied across large areas or in diverse environments. Market availability indicates how accessible or commercially available the method is, while usability for practitioners evaluates how user-friendly and practical the method is for those in the field. In this review, practitioners are defined as municipalities and companies that provide data analysis software to municipal governments. The tree inspectors and municipalities need city-wide data analysis tools that are available in the field, easy to interpret, applicable and established. We evaluate each method based on the conducted literature review and the personal experience of the authors. The comparison presented is therefore inherently qualitative.

3 | Results

The systematic search with the search strings 'urban AND tree AND drought' resulted in 827 hits and 'urban AND tree AND water stress' resulted in 516 hits; combined, this led to 1388 potentially relevant manuscripts. After removing 266 duplicates, 1122 papers were left for further inspection, and 834 papers were not in the scope of the review. Tree response to drought stress was the subject of 288 papers, and out of those, 112 were conducted in urban areas. We analysed the place of research, the observed tree species and applied methods of the 112 urban tree studies. The applied methods of the 112 urban tree studies are compared to the 288 papers on studies in both urban and non-urban sites.

3.1 | Systematic Literature Search on Tree Response to Drought Stress in Urban Areas

Most of the urban tree studies were conducted in the United States, followed by studies conducted in Germany and China (Figure 2). This has a direct effect on the tree taxa most commonly reported on. Indeed, most literature on urban trees considers *Acer*, *Quercus* and *Tilia* (Figure 3), which are common in the northern Hemisphere. In contrast, studies in non-urban areas mostly report on typical forest tree genera *Pinus* and *Picea*, followed by *Eucalyptus* and *Fraxinus* (not shown here).

The methods used to detect stress differ slightly between non-urban tree studies and urban tree studies (Figure 4). The most commonly reported tree-based stress detection methods in urban areas are measurements of leaf gas exchange, plant water potential and chlorophyll fluorescence (ChlF). Regarding soil water monitoring-based methods, soil moisture is more often monitored than the soil matric potential. In comparison to overall studies, urban areas apply fewer soil moisture sensors. A possible explanation might be the highly compacted urban soil and high occurrence of sealed surfaces around the trees that make the proper installation difficult (see also Section 3.2). Overall, in urban studies, reflectance and thermography are commonly applied as stress detection methods, while we found no urban study that has applied airborne sun-induced chlorophyll fluorescence (SIF).

The urban environment presents a set of conditions that influence the physiological response of a tree and can be studied

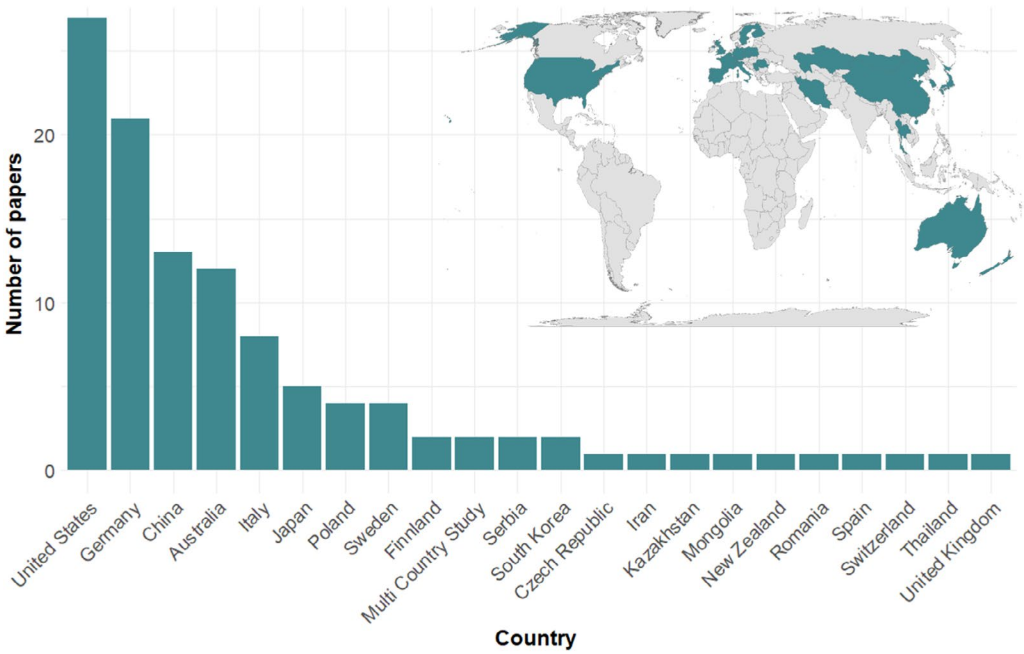

FIGURE 2 | Countries where urban drought stress studies were conducted. Results are based on 112 evaluated studies.

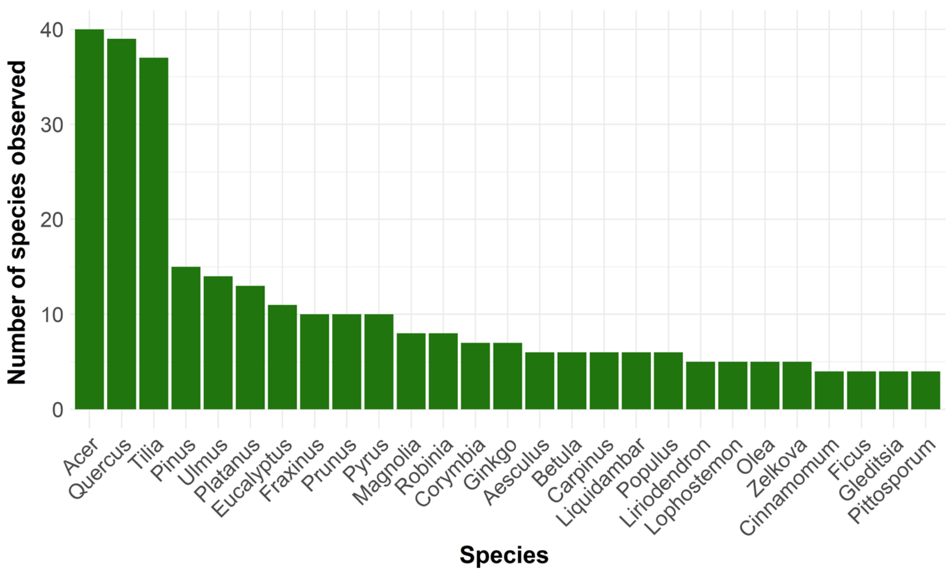

FIGURE 3 | *Genera* of trees observed in urban drought stress studies (112 evaluated studies). Only genera that occur more than four times are shown. Each study may be represented in multiple columns if multiple species or cultivars were observed.

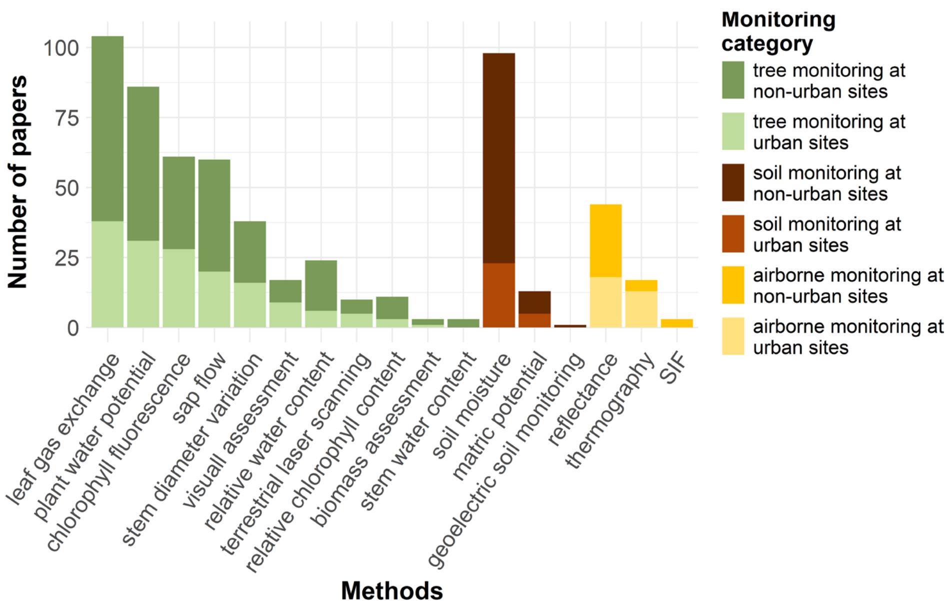

FIGURE 4 | Overview of tree drought stress detection methods found in the systematic search (SIF: sun-induced chlorophyll fluorescence). Each study may be represented in multiple columns when multiple detection methods are observed concurrently.

through rigorous scientific methods, for example, (Anys and Weiler 2025; Schneider et al. 2022). When conducting research on tree-stress detection in urban areas, researchers must take extra precautions to secure equipment against theft and vandalism, address legal and privacy concerns when using optical sensors, accommodate higher communication demands, and obtain permission from a larger number of stakeholders (Dyson et al. 2019). Soil is frequently off limits due to pipes, cables and other subsurface infrastructure (Bobylev 2016). The methods analysed above were tested for research purposes. In the following sections, we describe the state-of-the-art discussion of stress detection methods, keeping in mind their scalability, usability and availability in an urban context.

3.2 | Drought-Induced Tree Stress Detection in Urban Areas: Methods and Their Trade-Offs

Based on the systematic search, we identified three overarching categories of methods: tree-based detection methods, airborne detection methods and soil water monitoring methods. The tree-based monitoring section is divided into three groups, focusing on (i) the water cycle (water potential, leaf gas exchange, relative leaf water content (RWC), sap flow, stem water content), (ii) morphological changes and biomass assessments (stem diameter variation and terrestrial laser scanning [TLS]) and (iii) fluorescence tools (handheld active and passive chlorophyll fluorescence tools). The airborne stress detection section is divided into reflectance, thermography and sun-induced chlorophyll fluorescence via remote sensing. The soil water monitoring section is divided into two parts: soil moisture measurements with sensors (including volumetric water content and matric potential measurements) and geoelectric soil moisture monitoring. In the last section, all methods and their trade-offs are assessed.

3.2.1 | Tree-Based Stress Monitoring

3.2.1.1 | Plant Water Potential. Water potential represents the energy required to move water between compartments in a closed system. Plant water potential (Ψ) is expressed as the difference in free energy between water in the plant's cells and pure water at sea level under atmospheric conditions, with the latter set to zero (see, for example, Porporato and Yin (2022)). Water flows from the soil into the root and within the plant from the root to the leaf along the gradient of the water potential. As the soil dries out, for example, during a prolonged drought, the soil water potential drops, forcing the water potential in the plant (root, stem and leaf) to drop even more to ensure root water uptake (Scharwies and Dinneny 2019).

Plant water potential provides highly valuable information about plant water status and the response to drought (Rodriguez-Dominguez et al. 2022). In general, plant water potential is expected to drop as the plant experiences drought stress and can thus be used to assess the degree of physiological drought stress (Pérez-Harguindeguy et al. 2016). Higher tree canopy temperatures were also associated with a decline in water potentials (Dale and Frank 2022).

The water potential can be measured with (i) the pressure chamber (also called the Scholander bomb), (ii) the psychrometer and (iii) the microtensiometer. The pressure chamber is a widely used method to measure the leaf water potential (Cregg et al. 2023; Dale and Frank 2022; Matyssek and Herppich 2019) because it is transportable and cheap. Its drawback is that it depends on fast and precise handling of individual leaves or branches (Matyssek and Herppich 2019; Rodriguez-Dominguez et al. 2022). In addition, there is a lack of standardised protocol to measure leaf water potential with the pressure chamber

(Rodriguez-Dominguez et al. 2022). Psychrometers allow the measurement of stems and leaves (Li et al. 2020; Matyssek and Herppich 2019). However, the leaf surface has to be prepared and a fixed and elaborate measurement setup is required (Matyssek and Herppich 2019), which is challenging in urban settings. Also, stem and leaf psychrometers are expensive (Konings et al. 2021). Microtensiometers continuously measure stem water potential (Blanco and Kalcsits 2021). The method is microinvasive as it requires the installation of a sensor membrane of several mm diameter at the trunk or a branch. Blanco and Kalcsits (2021) compared the microtensiometer and pressure chamber values and concluded that despite small differences, the scale of the water stress was similar and hence both methods are a feasible tool to measure plant water stress (Blanco and Kalcsits 2021).

All these methods are limited in the number of samples that can be observed. Of the three, the psychrometer appears least feasible for an urban stress assessment and monitoring. Measuring the water potential with the pressure chamber is an established method in urban areas (Figure 4), and it can detect stress early. However, its destructive nature and the labour-intensive handling of the pressure chamber make the upscaling to stands or whole urban forests impossible. The observation with microtensiometers allows continuous monitoring of selected trees, but it is invasive. The microtensiometer has the easiest usability once it is installed.

3.2.1.2 | Leaf Gas Exchange. The opening and closing of the stomata regulate the gas exchange of the leaves, which causes the leaf water potential to drop to very negative values and thus lifts the water from the roots to the leaves. Henry et al. (2019) describe this as a constant trade-off between water use and response to (drought) stress (Henry et al. 2019). One of the first responses to water stress is the closure of the stomata in order to minimise transpiration loss and to prevent overly negative plant water potentials that could damage the xylem (Konarska et al. 2016). Stomata closure is reflected in a reduced stomatal conductance (Urban et al. 2017). The stomatal conductance is often measured alongside the net photosynthesis (A), photosynthetic potential (A_{max}), transpiration (E) and the intrinsic water use efficiency (iWUE; Ahongshangbam et al. 2023; Salamon-Albert et al. 2022; Vastag et al. 2020). The photosynthesis is affected by the amount of chlorophyll in the leaves. Therefore, the measurement of the leaf gas exchange is often combined with measurements of the relative chlorophyll content (Rahman et al. 2023; Wang et al. 2023). A reduced stomatal conductance and water use efficiency were observed during increased vapour pressure deficit (Gillner et al. 2017). The leaf gas exchange can be measured using portable exchange measurement systems (Matyssek and Herppich 2019). Chaerle and van der Straeten (2000) differentiate between diffuse porometer and gas exchange systems. Both of these methods provide leaf scale point measurements, are labour-intensive and lack spatial heterogeneity (Chaerle and van der Straeten 2000). The process is hard to automate because every leaf has to be individually inserted into a device. Small-leaved species are particularly challenging, as their leaves can be too small to be measured (Ellsäßer et al. 2020). During the measurements, the leaf must be attached to the tree. To conduct these measurements on tall, pruned trees, a high ladder or an aerial platform is needed, further slowing down the data collection and decreasing its scalability.

The leaf gas exchange is a well-studied method (Figure 4), which can be used to detect stress early, but the use of handheld devices is labour-intensive, making the upscaling process impossible. The devices are used for research purposes, and interpretation of the results is complex, which makes the devices difficult to use for practitioners.

3.2.1.3 | Relative Leaf Water Content. As shown for the common urban trees *Tilia cordata* and *Quercus robur*, RWC is declining during drought stress (Selig and Bohne 2017), making it a good indicator of tree drought stress. The RWC is measured by relating the leaf weights at leaf collection (fresh weight), after rehydration (saturated weight) and after drying (dry weight; Ahongshangbam et al. 2023; Selig and Bohne 2017). The specifics of rehydration (time and method) influence the result and make the assessment error-prone (Arndt et al. 2015). The method is also too labour-intensive for a widely applied stress monitoring of urban trees.

A promising development in this area is the use of electromagnetic radiation in the microwave spectrum at different frequencies to detect water mass per leaf area, relative water content and leaf water potential (Browne et al. 2020; Gente and Koch 2015; Konings et al. 2021). Konings et al. (2019) state that such microwave sensing should be preferred over optical spectral imaging and thermal infrared imaging for observing the vegetation water content because it allows observations independently of the clouds and the daytime (Konings et al. 2019). However, a major challenge here is the separation of vegetation water content and soil moisture because their microwave signals are captured together. Field observation and ground-based calibration might be required to account for a vertical segregation of the signals (Konings et al. 2021). Terahertz frequencies allow observations of a higher resolution compared to microwave frequency observations (Browne et al. 2020). Such observations allow a non-invasive measuring of leaves and canopy. However, more research is needed to solve the above-stated difficulties in the interpretation of the data. To date, no ready-to-use device is on the market (Browne et al. 2020).

All introduced water content measuring methods can currently not be applied on a large scale for urban stress monitoring. The gravimetric method has been tested in urban areas (Figure 4), but is too labour-intensive and therefore not scalable in urban areas. The method lacks scalability and usability, and there is no ready-to-use device. Microwave sensing and terahertz observation protocols for urban areas are potentially scalable, but the data processing workflows need to be established (Konings et al. 2019).

3.2.1.4 | Sap Flow. Sap flow is the process by which water and dissolved nutrients move through a tree's vascular system, along the gradient of water potential, usually from the roots to the leaves. Therefore, sap flow measurements provide a direct method to quantify the amount of water moving through a tree, which is closely linked to transpiration and water availability in the soil. The sap flow is also influenced by the wind speed, vapour pressure deficit and air temperatures (Rahman et al. 2017). There are two major classes of sensors to assess sap flow: the heat-pulse (HP) method (Green et al. 2003) and the thermal dissipation probe (TDP) method (Granier 1987). Both methods involve inserting needles into the tree's sapwood, and the radial pattern of the sapwood has to be determined. The HP method produces accurate, instantaneous sap velocity measurements using brief heat pulses and has relatively low power requirements, but it demands meticulous installation, calibration and consideration of wounding effects and wood variability. In contrast, the TDP method is simpler to implement and continuously measures sap flux density, although it consumes more energy due to its constant heat supply and can be susceptible to signal drift induced by natural temperature gradients. As a continued development from TDP, the transient thermal dissipation (TTD) probe aims to overcome high energy usage challenges by employing a more efficient heating cycle (Do and Rocheteau 2002a, 2002b).

Although sap flow sensors are among the most common methods for estimating individual tree water use, they require careful calibration to obtain accurate absolute values. In addition, the inserted needle can cause a wound, leading to a wounding effect (Burgess et al. 2001). Uncertainty in the radial pattern, such as incorrect estimation of the conductive sapwood, can lead to errors during the scaling step (Zhang et al. 2015). Misalignment of the inserted needles in the HP method can result in erroneous sap flux density estimates (Ren et al. 2017).

Sap flow has been studied repeatedly in urban areas (Figure 4), often combined with soil moisture sensors. However, the upscaling is difficult, as the sensor is invasive, the correct position of the needles in the tree is hard to estimate, but crucial for a precise measurement. Currently, the handling and availability make it a suitable tool for research purposes.

3.2.1.5 | Stem Water Content.

The volumetric water content of trunk or stems (VWC_{stem}) provides valuable information on the status of the hydraulic system of plants, but its specific response to drought depends on the species (Song et al. 2023). The water stored in trees buffers their transpirative demand as the first proportion of transpiration on any given day is sustained by VWC_{stem} (Goldstein et al. 1998; Matheny et al. 2015; Schäfer et al. 2000; Yan et al. 2020). Under drought conditions, when the hydraulic connectivity between roots and the soil water is disrupted, VWC_{stem} can be crucial for plant survival because this is the only water source available during these times for stress (Körner 2019). In a drought and rewetting experiment at Biosphere 2, for example, Kühnhammer et al. (2023) and Werner et al. (2021) observed particularly striking differences in the temporal dynamics and plasticity of VWC_{stem} of the observed trees. Some of the trees kept their VWC_{stem} constant despite the drought; for others, the VWC_{stem} decreased rapidly (Kühnhammer et al. 2023; Werner et al. 2021).

VWC_{stem} can be measured (i) with dendrometers, (ii) with time-domain reflectometry (TDR) and recently with (iii) HP-velocity sensors. The dendrometer measures stem diameter fluctuations, which are indirectly related to VWC_{stem} changes. It is traditionally the preferred method to infer changes in VWC_{stem}. Dendrometers allow for non-destructive and continuous measurements, but disentangling growth and VWC_{stem} changes can be challenging (see, e.g., Cermák et al. 2007; Turcotte et al. 2011). Dendrometers can also be used to measure the stem diameter variation during growth; hence, they are debated in detail in the stem diameter variation chapter. TDR is the only other commonly used method for continuous measurements. It measures the dielectric properties of a given matrix—soil or wood—and derives VWC_{stem} from them (Kühnhammer et al. 2023; Matheny et al. 2015; Wullschleger et al. 1996). Heat-pulse-velocity sensors also allow for continuous measurements of VWC_{stem} using TDR principles. The advantage of these sensors is that they measure both sap flow (see above) and VWC_{stem}.

We have not found a study that uses systematic monitoring of VWC_{stem} in urban areas to measure drought stress. This might be because drought stress detection based solely on VWC_{stem} is difficult due to the aforementioned inter-species variability of its dynamics. The difficult interpretation reduces user-friendliness. Theoretically, applying the discussed methods at street scale is possible once the sensor measurement setup is established, but it is currently only applied in scientific contexts.

3.2.1.6 | Stem Diameter Variation.

Drought stress and poor soil conditions in urban areas lead to reduced stem growth (Moser et al. 2017; Schütt, Becker, Reisdorff, and Eschenbach 2022). Besides the above-mentioned fluctuations in stem water content, stem diameter changes can be caused by radial growth, thermal expansion and contraction as well as internal tension caused by the expansion and contraction of the xylem (Daudet et al. 2005).

Stem diameter variations, also called trunk diameter fluctuations, are monitored using dendrometers (Conesa et al. 2023). There are several indicators that can be derived from stem diameter variations, ranging from different daily trunk diameter changes to growth rates for different time periods (Blaya-Ros et al. 2024; Conesa et al. 2023). The maximum and minimum daily trunk diameter reflects the availability of water and evaporative demand (Ortuño et al. 2010). The use of maximum daily trunk shrinkage (MDS) was reported to be a good water stress indicator for almonds and lemon trees, as it followed the same patterns as stem water potential (Goldhamer and Fereres 2001; Ortuño et al. 2006). Another indicator is the tree water deficit (TWD). It can be derived by comparing the trunk under fully hydrated to water limited conditions. The TWD can serve as an indirect measure of the midday water potential and allows for a prediction of the canopy water status (Dietrich et al. 2018), which makes it a valuable indicator for drought stress.

The measurement of the stem diameter variations indices have the potential to be fully automated once installed and offer precise information (Ortuño et al. 2010). Yet, the sensors require maintenance and severe weather like heavy rainfall can pose a threat to them (Ortuño et al. 2010). Sensors should be installed on several trees, since there is natural viability between individuals. If trees are growing fast, the signal of the growth rate is hard to discern from diameter fluctuations (Ortuño et al. 2010). In a comparison by Conesa et al. (2023) the stem diameter variation measurements were less preferable compared to microtensiometers (Conesa et al. 2023).

In conclusion, dendrometer have been studied in cities (Figure 4) and can be used to continuously monitor water stress in trees. Their application in water management has been tested outside of urban areas. They require a stable measurement set up, but can be installed non-invasively, which makes them easier to install and more scalable than sap flow sensors. Their scalability for stress monitoring is still limited to a few trees or stands, though.

3.2.1.7 | TLS. The use of TLS has increased rapidly over the last years. It allows for a digital 3D representation of trees and has been used to quantify pruning (Liu et al. 2024), crown regeneration after V-trimming below power lines (Lecigne et al. 2018), and general changes in crown shape (Olivier et al. 2017). Hence, major impacts of stress that lead to changes in crown shape can be detected and quantified using TLS, as has been shown for forest trees (Jacobs et al. 2021). It has also been observed that trees with reduced vitality exhibit different branching patterns than vital trees, and these differences can be detected with TLS (Heidenreich et al. 2024). While TLS allows for the objective quantification of changes in crown and branching patterns, it is an elaborate procedure that is not suitable for measuring many trees, not to mention the tens or hundreds of thousands of trees that make up the urban forest. Mobile laser scanning may be a way forward, but in order to measure trees from all sides, a system mounted to a pedestrian would be needed (D'hont et al. 2024). Airborne laser scanning, while easily covering large areas, does not produce enough detail below the crown and along the trunk of trees (D'hont et al. 2024).

In conclusion, TLS can only detect stress that manifests itself over the course of months or even years and is not suitable for detecting early symptoms of stress. At present, only a few trees can be assessed, but in the future, city-wide assessments could probably be achieved for accessible trees through mobile laser scanning.

3.2.1.8 | Active Chlorophyll Fluorescence Measurements. Light energy is transformed in three ways in the leaf: (i) photochemical, (ii) as heat and (iii) as fluorescence (Murchie and Lawson 2013; Strasser et al. 2000). Between 0.6% and 5% of the energy is re-emitted as chlorophyll florescence (ChlF; Moustaka and Moustakas 2023). When the stomata close during drought stress condition, the amount of light, which is, used photochemically declines resulting in altered dissipation of energy as heat and chlorophyll fluorescence. An advantage of chlorophyll fluorescence is the fact that it can detect plant stress before visual signs appear (Chaerle and van der Straeten 2000).

There are several ChlF parameters, which can be assessed (Swoczyna et al. 2022). The maximum quantum yield of photosystem II (F_v/F_m) is a common parameter to predict plant stress. The interpretation of the F_v/F_m ratio is straightforward in their analysis, as it only drops in response to stress (Banks 2018). Apart from F_v/F_m, the quantum yield of photosystem II (φ PSII) and the performance indices (potential) of energy for energy conservation from the photons absorbed by PSII (PI_{tot} and PI_{abs}) can also be used for stress detection (Strasser et al. 2010). In fact, while F_v/F_m, PI_{tot} as well as φ PSII decrease with decreasing relative water content, PI_{tot} and φ PSII show the stronger reaction (Kalaji et al. 2017).

In urban areas, different stressors occur simultaneously, and it is not clearly understood which ChlF parameter can be used to distinguish different stressors (Gorbe and Calatayud 2012; Kalaji et al. 2018). There are different handheld and stationary ChlF systems. Several portable devices exist, operating with continuous excitation chlorophyll fluorescence systems and the PAM (pulse-amplitude modulated) system, and PAM systems can also be coupled well with, for example, leaf gas exchange tools (Banks 2018; Moustaka and Moustakas 2023; Swoczyna et al. 2022). To conduct ChlF measurements, a dark adaptation of around 20–25 min is required (Kalaji et al. 2017). In the field, leaf clips are attached to the tree leaves for that purpose. The third system is ChlF imaging systems, which require more setup, and limited standard handling protocols are available (Lawson and Vialet-Chabrand 2018).

ChlF measurements can detect stress very early and are non-invasive. ChlF has been applied in several urban tree studies (Figure 4). Nevertheless, ChlF measurements are point measurements, lacking spatial and temporal resolution while also being labour-intensive. The devices are easy in their handling, but the data interpretation is complex. The tool is therefore more suitable for experimental set-ups with few trees.

3.2.1.9 | SIF With Handheld Devices. In comparison to active chlorophyll fluorescence (ChlF), where artificial light is applied, passive chlorophyll fluorescence measures the chlorophyll fluorescence induced by sunlight (known as SIF). This has the advantage that the dark adaptation period, necessary in active ChlF measurements, can be omitted (Jonard et al. 2020). SIF can be used to gain information on the physiological state of trees (Hernández-Clemente et al. 2017). Baraldi et al. (2019) studied light acclimatised and dark-adapted leaves of *Liquidambar styraciflua* and observed that the combination of drought and salt stress showed a significant effect on dark-adapted leaf F_v/F_m. The light acclimated leaves exhibited a significant decline of the non-photochemical quenching (NPQ) during drought stress (Baraldi et al. 2019). In locations of different levels of urbanisation (traffic square, riverbed, park), significant difference in the chlorophyll fluorescence yield were found (van Wittenberghe et al. 2014).

In conclusion, handheld SIF devices have similar challenges as active ChlF measurements, as they lack spatial and temporal resolution and are labour intensive. SIF sensors do not require dark adaptation; however, they can potentially be used in airborne or satellite-based measurements (see Section 3.2.2).

3.2.2 | Airborne Stress Monitoring

3.2.2.1 | Thermography. Stomatal closure causes transpiration to cease, resulting in a rise in leaf temperature as evaporative cooling at the leaf surface stops. Thus, the state of the stomata can be indirectly investigated by measuring leaf or canopy temperature. Observation of stomata closure via surface temperature, using infrared thermography, is a promising tool for stress detection, due to its ability to detect physiological changes days before visual symptoms appear (Gerhards et al. 2019; Urban et al. 2017). The detection process can be automated (Chaerle and van der Straeten 2000) by installing thermal cameras above the tree canopy or carried out with drones, airplanes, or satellites to survey larger areas (Smigaj et al. 2024). To infer plant stress from temperature readings, different stress indicators can be used. Suitable indices are the Crop Water-Stress Index (CWSI), the Temperature–Vegetation Dryness Index (TVDI) and the Temperature Vegetation Index (TVX; Urban et al. 2017). Gupta et al. (2024) concluded that due to reoccurring inspection processes, the species-dependent temperature behaviour and the expertise required to interpret the results, city-wide health monitoring is hard to implement (Gupta et al. 2024). Ellsäßer et al. (2020) suggested that assessing stomatal conductance from thermal imaging can be difficult and hyperspectral data might be more useful (Ellsäßer et al. 2020). The measurements have to be done in clear sky conditions (Urban et al. 2017), and the thermal camera requires a calibration to convert the measured infrared radiation to surface temperature (Gerhards et al. 2019). Further, current EU drone regulations established by the European Aviation Safety Agency (EASA) strictly regulate the use of drones. Specially, the use of drones in urban areas requires careful adherence to regulations to address safety concerns and privacy issues (Alamouri et al. 2023).

In summary, thermography could be used for stress measurement with reasonable accuracy over large areas. First thermography studies of urban trees are available (Figure 4). The individual tree stress analysis is complicated, however, because airborne or satellite-based thermal images lack spatial and temporal resolution. Images collected with drones could bridge that gap, but current rules make their use in cities difficult.

3.2.2.2 | Reflectance. Detecting water stress in urban trees using optical remote sensing relies on analysing changes in tree reflectance, particularly in the visible (VIS), near-infrared (NIR) and shortwave-infrared (SWIR) spectral regions. Altered spectral properties in trees stem from physiological changes in both leaf structure and leaf pigment concentration (Chaerle and van der Straeten 2000). Specifically, stressed trees may exhibit increased reflectance in the visible range due to chlorophyll degradation, reduced NIR reflectance due to cell structure changes, and higher SWIR reflectance, as water content in leaves decreases under drought conditions (Ceccato et al. 2001).

Vegetation indices (VIs) are mathematical combinations of reflectance values from specific spectral bands which are used as indirect indicators for plant health (Rouse Jr., Haas, Schell, and Deering 1974). The Normalized Difference Vegetation Index (NDVI; Rouse Jr., Haas, Deering, et al. 1974; Tucker 1979) is one of the most widely applied (Bahe et al. 2021), where low NDVI values are associated with no vegetation, unhealthy, or stressed vegetation (Gupta et al. 2024). VIs derived from remotely sensed imagery reduce the need for labour-intensive on-site inspections, provide a simplified single value and therefore can support city administrations to implement timely actions in tree care.

However, VIs often lack sensitivity to subtle or early stress situations in trees, making it difficult to detect minor declines in health before they become more severe. Additionally, VIs can be challenging to interpret as their responses vary across different tree species (Hernández-Clemente et al. 2017), and distinguishing between different types of stress, such as water stress or pest infestation, is not readily achievable (Bahe et al. 2021). To address these limitations, hyperspectral imaging provides detailed reflectance data across numerous spectral bands. Although this can enable more precise diagnoses, especially in combination with machine learning methods and modeling approaches (Berger et al. 2021; Dao et al. 2021; Mederer et al. 2025), it increases the complexity of data analysis and data acquisition costs.

A common challenge when using multispectral or hyperspectral sensors in urban environments is that understories (Ewane et al. 2023) or non-vegetative surfaces, such as buildings, roads, or other infrastructure, introduce spectral noise. This can complicate the isolation of tree reflectance from surrounding materials and shadows, especially when sensor spatial resolution is lower. In addition, a high temporal resolution of observations is crucial for monitoring plant physiological changes, but atmospheric conditions, particularly cloud cover, frequently hinder the use of satellite imagery. Potential inconsistencies caused by varying environmental conditions can also complicate the analysis of drone data (Bahe et al. 2021). Additionally, regular data acquisition with aircraft or drones involves significant labour and financial costs.

Remote sensing provides high scalability for monitoring urban tree vitality. However, accurately distinguishing individual tree crowns remains challenging in areas with overlapping or adjacent canopies, even when using high-resolution imagery (Troles et al. 2024). Moreover, reflectance-based metrics are limited in their ability to detect early indicators of stress prior to the onset of visible changes at the leaf level (Figure 1), both make usability challenging.

3.2.2.3 | SIF via Remote Sensing. SIF offers a more direct and sensitive measure of photosynthetic activity compared to traditional VIs (Hernández-Clemente et al. 2017; Jonard et al. 2020). Hernández-Clemente et al. (2017) used SIF with three spectral bands to detect stress in *Quercus ilex* and found a significant relationship between the SIF and a physiological vegetation index (Hernández-Clemente et al. 2017). Nevertheless, its application in urban tree water stress monitoring is still developing.

Detecting SIF is challenging due to its weak signal, which is easily overshadowed by atmospheric interference. Particularly in urban environments, light scattering and shadowing from buildings and other structures can distort the measurements. Environmental factors such as remote-sensed soil moisture data should be compared alongside the water stress SIF analysis, as SIF shows seasonal (Jonard et al. 2020) and diurnal patterns (Zeng et al. 2022). Best practice should be the observation of several days at a fixed time to avoid the effects of daily changes (Zeng et al. 2022). Further research is needed to evaluate the scattering and reabsorption effects within the tree crown to separate the crown effects from changes in the photosynthetic cycle (Hernández-Clemente et al. 2017). Van Wittenberghe et al. (2014) showed that traffic-generated leaf deposits created a shading effect and reduced chlorophyll a/b levels, highlighting that SIF signal interpretation for urban trees requires careful consideration of specific site conditions (van Wittenberghe et al. 2014).

The high spectral resolution required for accurate SIF detection necessitates specialised imaging systems (e.g., Hyplant carried on aircraft) or high-precision spectrometers (e.g., AirSIF carried on drones; Aasen et al. 2019). However, these systems are costly and technically challenging to implement. The relatively low spatial resolution of satellite data (e.g., FLuorescence EXplorer satellite, FLEX) can limit the accuracy of SIF measurements (Hernández-Clemente et al. 2017) for detecting water stress at the tree level. Despite these limitations, FLEX data hold promise for large-scale monitoring, particularly when combined with other remote sensing data sources like unmanned aerial vehicles (UAVs) or higher-resolution satellite imagery for finer detail.

In conclusion, SIF is a direct indicator of photosynthetic activity and, compared to active ChlF, does not require a dark adaptation period. However, SIF is currently not applied in urban drought stress detection (Figure 4). First research studies are conducted, but there is no ready-to-use system for practitioners. The high technical requirements of imaging systems and the lack of robustness towards external conditions of the SIF signal limit its broader application.

3.2.3 | Soil Water Monitoring

3.2.3.1 | Monitoring of Soil Moisture and Matric Potential. Monitoring of the amount of water stored in soils (volumetric soil water content, VWC_{soil}) or of the soil water potential (matric potential, Ψ_{soil}) is among the most fundamental methods in soil hydrology, and both methods have been applied in many studies (Figure 4). The information on the water status of the soil can provide indirect evidence of the condition of the hydrological system and the amount of water available for plants. Hence, it is an indirect indicator of water stress. Generally, a particular plant is not able to extract water from the soil anymore if Ψ_{soil} is greater than Ψ_{root}. The permanent wilting point for plants is defined with a matric potential value of pF 4.2 (or ~16 000 hPa). Once Ψ_{soil} reaches this value, no more water uptake by plants is possible. Hence, measuring Ψ_{soil} or VWC_{soil} for optimal plant water supply can be incredibly useful for irrigation purposes.

The most common way of measuring VWC_{soil} is by inserting sensors, which are connected to a data logger into the soil or substrate to be monitored at the desired soil depth. Soil moisture sensors exist in different forms and shapes (e.g., 2/3 parallel metallic rods of different lengths, plates) and are operated mainly based on two principles, namely frequency-domain reflectometry (FDR) and time-domain reflectometry (TDR). FDR (also called 'capacitance') sensors are the most widely employed method to measure soil water content (Topp 2003).

For optimal installation, a hole must be excavated, and the sensors should be placed horizontally in undisturbed soil. Limited space and sealing around the tree pit make the installation in urban areas difficult, however. Often only the upper 50 cm of the soil are measured (Marchin et al. 2022; Stratópoulos et al. 2019), but it can be assumed that the trees root much deeper. Therefore, a soil moisture setup ideally should be implemented, when a tree is newly planted (Schütt, Becker, Gröngröft, et al. 2022).

The hydration of a soil can also be determined by measuring its suction tension, that is, the force at which water particles are held by the soil. This force is called soil water or soil matric potential (Ψ_{soil}). Fully saturated soil has a soil matric potential of 0 [hPa]. The drier a soil gets, the higher the binding force of the water particles to the soil matrix and the higher, that is, more negative Ψ_{soil} becomes. Ψ_{soil} is measured with tensiometers or gypsum/ceramic blocks, by recording the changes in voltage induced by the increased force of the soil matrix and relating it to its corresponding water potential. While soil tensiometers often only work in a limited range of pF values up to 2.5 to 3.0 (i.e., under wet conditions), there are a number of indirect soil matric potential sensors allowing monitoring of soil matric potential over a large range (pF 0–6; Durner 2023). The advantage of measuring soil water potential is that the soil water status can be directly inferred from it: Field capacity corresponds to a matric potential of ~−33 kPa and the permanent wilting point corresponds to a matric potential of ~−1500 kPa regardless of the soil type. Disadvantages of monitoring soil matric potential are the currently higher costs and a smaller integration volume within the soil compared to VWC_{soil} sensors.

In conclusion, the application of soil moisture sensors is well established in research and in practice (Figure 4). However, soil moisture sensors are point measurements and sensor installation is challenging, which limits their scalability. When the soil type is unknown, the matric potential should be measured because it allows conclusions to be drawn on field capacity and the wilting point.

3.2.3.2 | Geoelectric Soil Moisture Monitoring. The soil is often described as a 'black box'. Geophysical methods can offer insights into rock types, ground water levels and variations in soil moisture. Geophysical methods offer the possibility of investigating larger areas in the subsurface while being minimally invasive. Results of conventional invasive direct measurement methods can thus be supplemented and extended to larger scales.

Measuring the soil moisture content is possible through Electrical Resistivity Tomography (ERT; Binley and Kemna 2005; Michot et al. 2003). ERT is a geophysical imaging technique that measures the electrical resistivity of the subsurface through electrodes (e.g., steel bars) attached to the ground surface. In its simplest form, ERT employs four electrodes: two for injecting current into the subsurface and two for measuring the resulting voltages in the subsurface. Using Ohm's Law, these quantities can be used to determine the electrical resistivity. There is a direct connection between electrical resistivity and soil moisture content, as explained by Archie's Law, which generally indicates that electrical resistivity decreases as soil moisture content increases (Archie 1942). Geoelectrical monitoring has been utilised in various small-scale studies for precision farming, enabling more efficient water management and crop optimization (Michot et al. 2003; Srayeddin and Doussan 2009) or to investigate tree root water uptake and also to provide insights into the impacts of drought conditions (Jayawickreme et al. 2014; Mary et al. 2020; Nijland et al. 2010).

Depending on the objectives, different electrical monitoring approaches can be employed. Using permanently installed

TABLE 1 | Overview of methods for detecting stress in urban trees and trade-off assessment.

	Literature search				Trade-off assessment			
					Invaseness	Scalability	Availability on the market	Usability for practitioners
	Methods	Tools, sensors, techniques	Observed parameters	Citation	Yes, No	Leaf, tree/ street, quarter/city	Research purposes: +, market entry: ++, commercially available: +++	Difficult: –, medium: ~, easy: +
Tree Monitoring	Water potential	Pressure chamber	Leaf water potential	Zhang et al. (2022) Marchin et al. (2022) Konarska et al. (2023)	Yes	Leaf	+	–
		Microtensiometer	Stem water potential	Blanco and Kalcsits (2021)	Yes	Tree/Street	+,++	+
	Leaf gas exchange	Open and closed leaf gas exchange systems	Transpiration rates, stomatal conductance, net-photosynthesis	Gillner et al. (2017) Brunetti et al. (2019) Ahongshangbam et al. (2023)	No	Leaf	+	–
	Sap Flow	Heat pulse and thermal dissipation sensors	Sap flux density, transpiration	Rahman et al. (2017) Thomsen et al. (2020) Ahongshangbam et al. (2023)	Yes	Tree/Street	+	–,~
Tree Monitoring	Stem water content	Dendrometers, TDR and sap flow sensors	Volumetric water content, stem water storage	Werner et al. (2021) Song et al. (2023) Kühnhammer et al. (2023)	Yes, No	Tree/Street	+	–
	Leaf relative water content	Weight	Leaf relative water content	Wang et al. (2023) Selig and Bohne (2017) Ahongshangbam et al. (2023)	Yes	Leaf	+	–
	Microwave radiation	Radiometers	Vegetation water content	Gente and Koch (2015) Konings et al. (2019) Konings et al. (2021)	No	Tree/Street	+	–
	Stem diameter variations	Band and point dendrometer	Radius, circumference	Stratópoulos et al. (2019) Marchionni et al. (2019) Moser-Reischl et al. (2019)	Yes, No	Tree/Street	++	~
	Terrestrial Laser Scanning	Terrestrial Laser Scanner	Branch length, crown volume, crown shape changes	Lecigne et al. (2018) Jacobs et al. (2021) Heidenreich et al. (2024)	No	Tree/Street, Quarter/City	+++	~
	Active ChlF	Handheld ChlF devices	Maximum and minimum fluorescence, quantum yield of PSII, performance indices	Swoczyna et al. (2015) Gillner et al. (2017) Brunetti et al. (2019)	No	Leaf	++	~
	SIF (Passive ChlF)	Handheld SIF devices	Maximum variable chlorophyll fluorescence yield in the light-adapted state, the photochemical efficiency of PSII	Hernández-Clemente et al. (2017) Baraldi et al. (2019) Jonard et al. (2020)	No	Leaf	+	–

(Continues)

TABLE 1 | (Continued)

	Literature search				Trade-off assessment			
					Invasiveness	**Scalability**	**Availability on the market**	**Usability for practitioners**
	Methods	**Tools, sensors, techniques**	**Observed parameters**	**Citation**	**Yes, No**	**Leaf, tree/ street, quarter/city**	**Research purposes: +, market entry: ++, commercially available: +++**	**Difficult: −, medium: ~, easy: +**
Airborne Monitoring	Thermography	Thermal cameras	Canopy temperature	Leuzinger et al. (2010) Gillner et al. (2017) Fuentes et al. (2021)	No	Tree/Street, Quarter/City	+	~
	Reflectance	Multi- and hyperspectral cameras	NDVI, Ratio of reflected radiation to the incoming radiation for a specific wavelength (range)	Degerickx et al. (2018) Ewane et al. (2023) Kyaw et al. (2024)	No	Tree/Street, Quarter/City	++	~
	Sun-induced chlorophyll fluorescence (SIF)	SIF cameras	SIF_{687}, SIF_{760}, SIF_{ratio}, fluorescence quantum yield	Hernández-Clemente et al. (2017) Aasen et al. (2019) van Wittenberghe et al. (2014)	No	Tree/Street, Quarter/City	+	−
Soil monitoring	Soil moisture sensors	TDR/FDR sensors	Volumetric water content	Chen et al. (2012) Stratópoulos et al. (2018) Ahongshangbam et al. (2023)	Yes	Tree/Street, Quarter/City	+++	~
		Tensiometer, matrix sensors	Matric potential	Moser et al. (2017) Thomsen et al. (2020) Schütt, Becker, Gröngröft, et al. (2022)	Yes	Tree/Street, Quarter/City	+++	~,+
	Geoelectric soil moisture monitoring	Electrical Resistivity Tomography	Electrical Resistivity	Srayeddin and Doussan (2009) Michot et al. (2016) Slater and Binley (2021)	No	Tree/Street	+	−

Note: Scalability describes the object, which can be assessed with the given technology and refers to the methods ability to be effectively applied across large areas or in diverse environments. Scalability is divided into three categories: Leaf, Tree/Street and Quarter/City. Availability on the market indicates how accessible or commercially available the method is and is divided into three categories: Research purposes (specialised knowledge needed for application), market entry (tools that are entering the market but are not yet widely applied), commercially available (tools that are already applied in urban areas). Usability for practitioners is divided into three categories: Difficult (can only be applied to selected samples and labour intensive), medium (easy handling but labour intensive), easy (easy handling and interpretation after setup), and evaluates how user-friendly and practical the method is for those in the field. Practitioners are here defined as municipalities and companies that provide data analysis tools to municipal governments.

profiles, electrical resistivity and soil moisture content can be monitored with high temporal resolution (e.g., with hourly measurements; Uhlemann et al. 2016). Other approaches are limited to individual comparative measurements spanning intervals ranging from days to years (Blanchy et al. 2020; Srayeddin and Doussan 2009). Since changes in electrical resistivity are often small, it is crucial to ensure that the setup remains completely identical during repeated measurements (Slater and Binley 2021), e.g., leaving the electrodes in the ground between measurements. In urban areas, this is often challenging, as vandalism and construction work can disrupt the measurement setup. Another challenge is the coupling of the electrodes at sealed sites. Without good electrode coupling, a high noise level can occur, making it difficult to resolve small changes in electrical resistivity and soil moisture content (Ingeman-Nielsen et al. 2016).

Geoelectric soil moisture monitoring has been applied to measure moisture around trees and investigate drought stress, but it has not yet been utilised specifically for urban tree drought stress detection (Figure 4). The scalability of this method is limited to individual sites, but it can include several trees. The data analysis requires expert knowledge and a stable measurement setup, which is challenging in urban areas. Hence, the method is mainly used for research purposes.

3.2.4 | Trade-Off Assessment

There are several methods to detect drought stress on urban trees. However, there are also large challenges when it comes to city-wide application and usability for practitioners. Our key findings regarding methodological trade-offs are summarised in Table 1.

4 | Discussion

Urban areas are highly heterogenic environments, which prioritise human needs. Trees often grow under unfavourable conditions (Czaja et al. 2020). Drought stress detection is a major challenge in urban areas because municipal resources are limited, equipment needs to be secured against theft and vandalism, and safety and privacy concerns have to be considered. Soil-based, tree-based and airborne stress detection methods were compared in order to identify drought stress detection tools that are efficient, scalable, applicable and well-established (Table 1).

Two methods (soil moisture sensors and microtensiometer) are considered mid-easy in their usability for practitioners. The plant water potential measured through microtensiometer provides valuable information, but the sensor is single-tree based. The soil moisture monitoring with sensors is a commonly used method, but it is only an indirect measurement and not directly linked to the tree stress level. To this end, incorporating matric potential monitoring, which has not been systematically done in urban tree studies up to date, might be useful, because it allows for a direct and soil-type-independent assessment of whether plant-available water is present in the soil (i.e., a certain tension observed corresponds to the same water availability independent of the soil type).

Only three tree-based methods (sap flow, dendrometer and active chlorophyll fluorescence devices) and three street/city wide application methods (terrestrial laser scanner, reflectance and thermography) were identified to be medium in their usability. Municipalities and tree inspectors have an expertise in visual tree health assessments, but have limited resources for urban drought stress detection. Thus, external contractors that offer advanced data analysis tools may be needed to support these efforts. Recent advances in surveying technology have brought the use of airborne methods into focus. Airborne techniques for stress detection in urban trees are still rare, and published studies mainly focus on detecting broad indicators of tree vitality rather than acute tree stress. Satellite based remote sensing currently produces data at spatial and spectral resolution that makes individual tree stress detection challenging. UAVs have been used to address this issue in forest and horticulture systems, but, despite of the great potential, their adoption in urban areas is strongly regulated and their use limited in many parts of the world due to safety and privacy concerns.

Based on the studies we reviewed, there is a scale mismatch when it comes to the practical use of the methods. On one hand, there are methods that work at the city scale, but downscaling their results to the individual tree is still an open issue. On the other hand, there are sophisticated and species-specific tree stress monitoring methods operating at the leaf scale, which are difficult to scale up to the plant, not to mention the city-wide scale. We perceive an urgent need for studies that close the gap between plant-based stress monitoring methods and airborne stress detection methods. One way forward would be to combine soil-based (e.g., matrix potential), tree-based (e.g., sap flow, microtensiometer) and airborne measurements (thermography) to gain comprehensive and scalable results. Gupta et al. (2024) also identified scalability as one of the major challenges and suggested that one solution for a tree health assessment could be sensors mounted on vehicles (Gupta et al. 2024). In addition, stress detection combined with suitable models may be a way of scaling from individual measurements to groups of trees and even city-wide assessments (Dao et al. 2021; Kluge and Kirmaier 2024). Lastly, engaging the public could be a way forward. People constantly cross through urban areas with smartphones that could serve as recording devices, and smart city management could benefit from this. The first citizen-supported tree health assessments were documented by Roman et al. (2017) in the United States and Sweden and Hallett and Hallett (2018) in the United States. With the *Mein Baum* App, there is a simple phone application on the German market that can be used by the public to document trees (BUND Naturschutz, n.d.).

Limitation of the study:

This review has some methodological and thematic constraints. One major limitation is that the systematic search was conducted with two search strings: 'urban AND tree AND drought' and 'urban AND tree AND water stress'. However, there are more papers available when searching for the individual method term and the drought stress; for example, "urban AND tree AND 'water potential'" results in 129 sources (08.09.25 on Web of Science), "urban AND tree AND drought AND 'water potential'" results in 87 sources (08.09.25 on Web of Science). Hence, the search for the individual methods could lead to more results.

Therefore, the second literature search followed that path and we searched for individual method terms.

Water stress was solely assessed in terms of water shortage. We have neglected the fact that water stress can be enhanced when several stress factors occur simultaneously and that drought can make it easier for some pests and pathogens to spread. Both can result in more severe water stress symptoms. In cities, multiple stress symptoms, for example, caused by heat plus limited water plus high salt level, occur at the same time, leading to the detection of a combined stress detection rather than the detection of one stress factor only.

We excluded several methods, such as tree ring analysis and tree coring, as they only allow a retrospective observation; isotopic, hormone and pigment analysis, as they are destructive and require extensive analytical methods; and biomass analysis, which requires the removal of the plant, as it is destructive and will never be applied as a stress monitoring system. All the aforementioned techniques require extensive work and only provide insights on a limited sample size.

Further, we neglected the aspect of the cost in this review. First, the cost of a widespread application of a detection method depends on the frequency and scale of its application. The costs per tree could vary strongly depending on the number of trees under assessment. In addition, technology changes fast, making cost assessments based on certain products and required monitoring frequencies short lived. Airborne methods might be more suitable when determining where in the city drought stress can be observed, because large areas are easily covered. When aiming to observe the water stress on newly planted trees, plant-based and soil-based methods may be more suitable, because the crowns are small and harder to process in airborne imagery, but can be reached directly for manual measurements. Moreover, soil sensors are easier to integrate into newly planted tree sites. Hence, depending on the objective of the drought stress detection, the method and measurement frequency and therefore the attached costs will vary.

In the literature, the majority of urban tree studies are conducted in North America and Europe. In Asia, most studies are from China or Japan. This leads to a bias with regard to the examined tree taxa. Drought stress of urban trees in Asian countries outside of China and Japan, in Africa, or South America is either understudied or underreported in English research literature. Thus, effort should be made to close this knowledge gap in the future.

5 | Conclusions

Drought detection of urban trees will gain importance under changing climate conditions and in growing urban areas. We reviewed literature on drought stress detection in trees with soil-based, tree-based and airborne stress detection tools to identify promising methods but also research gaps, drawing on urban, but also forestry and horticultural literature. Although today's toolbox of water-stress sensors and analyses is diverse, no single approach meets the requirement for rapid, nondestructive, city-wide monitoring of a large number of trees yet. Bridging the gap between remote sensing and on-site measurements remains an open challenge. However, systematic stress detection can still contribute to urban tree health by guiding decision making from selecting drought-tolerant species to optimizing planting sites and irrigation regimes. Moving forward, pilot implementations alongside cost–benefit studies will be vital to bridge the gap between research tools and practical application.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** hyp70298-sup-0001-TableS1.xlsx.