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Cost-effective method for the estimation of tree crown density in urban settings using a smartphone

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ABSTRACT

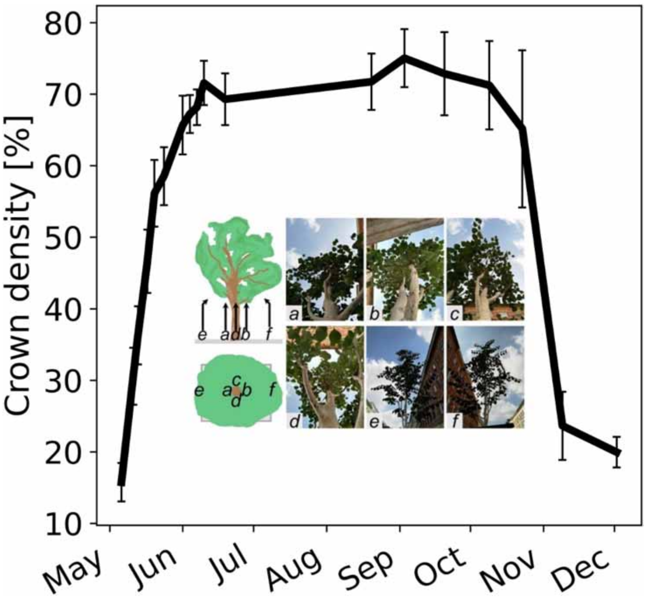
Urban trees provide vital ecosystem services, and assessing their health is crucial for managing urban infrastructure. Traditional methods of assessing crown density, an indicator of tree vitality, involve horizontal perspectives of unobstructed canopies. This study presents a novel method for estimating crown density in urban street trees that are surrounded by obstructing objects like buildings. The approach is based on photographs of the tree crown from defined positions using a smartphone. The method was validated on eight small-leaved lime trees in Leipzig during the 2021 vegetation period, demonstrating that crown density can be estimated by analyzing smartphone-photographs from various perspectives. The method provides data to quantify crown development and can be used to compare the vitality status of individual trees. The different perspectives are consistent in their estimates of crown density throughout the annual plateau phase of crown development. During the initial greening phase, crown photographs taken from angularly oriented positions showed a higher slope value than those taken from other positions. The method can also estimate the effect of blue-green infrastructures on tree vitality compared to regular urban tree planting methods. The approach is a practical and cost-effective tool for assessing tree vitality in spatially confined urban areas.

Key words: blue-green infrastructure, canopy, monitoring, street trees, tree swales, tree vitality

HIGHLIGHTS

- Crown densities were consistently estimated for eight street trees in 2021.
- The method can compare vitality, quantify temporal shift, and study climate change effects.
- Smartphone photography was used to estimate crown densities of street trees using different perspectives.
- The number of photos can be considerably reduced to optimize monitoring efforts.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Street trees provide numerous ecosystem services in cities, such as air quality, microclimate regulation, as well as noise reduction and contribute positively to the recreational aspects of urban life (van Stan *et al.* 2018). Thus, urban trees can be a significant factor in the quality of life of people living in urban areas (Bolund & Hunhammar 1999; Meili *et al*. 2021). Based on the assumption that an optimal provision of ecosystem services of urban trees depends on their optimal development, research regarding the interaction of environmental factors and tree development becomes more relevant for urban infrastructure planning (Bayer *et al.* 2018). Particularly in the context of blue-green infrastructure (BGI) development, trees can play a vital part regarding climate and stormwater runoff regulation (Carter & Kazmierczak 2010). At the same time, tree-based BGI necessitates monitoring to assess and evaluate the multifunctionalities of tree-based BGI in comparison to regular street trees as well as with other BGI.

The development of a tree is influenced by numerous biotic and abiotic factors that can vary across or even within regions. This complicates the projection of tree development and calls for better understanding of the structural development of different tree species in different growing environments from planting to maturity (Peper *et al.* 2014). Tree development status can be expressed as tree vitality at a given time. Tree vitality is influenced by several factors such as the age, predisposition and environmental factors, and is expressed in the tree's health status – especially in growth, crown structure and status of foliage – the adaptability to the environment, the resilience to disease and pests, and the regenerative ability (Roloff 2018). Individual tree vitality can only be assessed in relation to an adequate comparison group (Klug 2005). The adequacy of the comparison group in this context means that the trees have to be comparable regarding their age, species, breed, provenance and location. In the context of blue-green systems, rain gardens and tree trenches mitigate stormwater. At the same time, such systems also provide more water to vegetation. To better assess the effect of urban tree management in a blue-green context affordable and consistent monitoring is of high relevance.

Tree vitality can be assessed by several methods, e.g. by looking at the visual parameter of crown density (CD) (Klug 2005). According to Winn *et al.* (2010), CD is defined as the amount of sky area blocked by crown elements, expressed as a percentage of the total tree crown area. The assessment of tree vitality based on the condition of the foliage assumes that a higher CD reflects a higher vitality of the corresponding tree. That is because the leaves of deciduous trees are in most cases the most important organs for photosynthesis and thereby fulfill an essential physiological function (Roloff 2018). In forestry and tree-care practice, tree vitality is mostly determined by crown transparency (Roloff 2018). Standardized methods to estimate CD are often based on visual estimation (UNECE 2006; Roloff 2018). Thereby, these methods need trained personnel to deliver good quality data and are prone to subjective estimation. Visual tree crown status assessment methods like the visual vitality index described by

Johnstone *et al.* (2012) or the estimation of the proportion of visual sky area within the top 30% of the tree crown in steps of 5% following the European standardized procedure widely used in tree care described by Roloff (2018) are by nature prone to subjective influence or inconsistencies in data recording. Photography has demonstrated its applicability for non-invasive measurements of CD (Winn *et al.* 2010). Nonetheless, the application of photography as a monitoring tool for visible tree crown traits faces many challenges in complex urban areas such as man-made obstructions or light conditions (Kleinn *et al.* 2020). Today, common smartphone cameras provide photographs of sufficient quality for tree crown analysis (Tichý 2016). Existing terrestrial photographical tree CD or volume assessment methods often depend on horizontal perspectives into the tree crowns. For these methods to work in tree CD assessment, a representative portion of the tree crown must remain clear of background obstructions from a horizontal perspective into the tree crowns (Winn *et al.* 2010; Miranda-Fuentes *et al.* 2015). Whereas methodologies for tree assessment (cf. Roloff 2018) and crown estimation from photography (cf. Tichý 2016) are available, to our knowledge, these have not yet been adapted for urban settings. Instead, those methods are classically applied in forested regions, urban parks, or solitary trees. Street tree locations are at roadsides or in close vicinity to buildings and facades which necessitates a methodology rooted in classic approaches but adapted to urban settings. This makes those photographical CD assessment methods inapplicable when the trees stand in locations surrounded by obstructing objects like buildings.

In this paper, we present a novel method to measure tree CD as an indicator of tree vitality based on smartphone photography. This approach is non-invasive and was designed for application in urban areas with a high degree of background obstruction. The method was developed to be intuitive in its application, and therefore, not relying on a high level of training in measuring personnel. Thereby, the factor of subjective influence on the derived data had to be avoided. Also, the approach was designed to be independent of cost intensive devices, to provide an opportunity for later adaptation to citizen collection of tree crown status data. The method was tested on a set of eight street trees in an urban residential area through repeated measurements throughout one vegetation period in the City of Leipzig, Germany. We therefore hypothesize that the CD of urban solitary trees can be measured by processing and analyzing smartphone-photographs taken from vertical and angular oriented perspectives into the tree crowns. Furthermore, we assumed that the data derived by the application of this method over a vegetation period reflects and quantifies the progression of crown development of the surveyed trees. CD estimates of urban trees based on photographs were analyzed with the aims (i) to highlight differences and variability of urban trees and (ii) to identify which recording positions are required for consistent monitoring. The latter was motivated by the intention to reduce the data sampling effort by reducing the number of recording positions per tree.

3. METHODS

3.1. Setup and site of study

The measurements were conducted on a set of eight street trees lining the eastern section of Kasseler street in the urban residential district Gohlis in the City of Leipzig (51°21′46.00″N, 12°21′30.00″O). The street is flanked by four storey residential buildings. All eight small-leaved lime trees (*Tilia cordata* MILL.) of the breed 'Greenspire' were planted in 2020 in the course of road reconstruction. Figure 1 shows the locations of the study trees. Trees 1, 3, and 5 were planted in tree trenches. The tree trenches of trees 1 and 5 are equipped with a retention layer to improve the water storage properties. In contrast, no retention layer was installed in the tree trench of tree 3. All

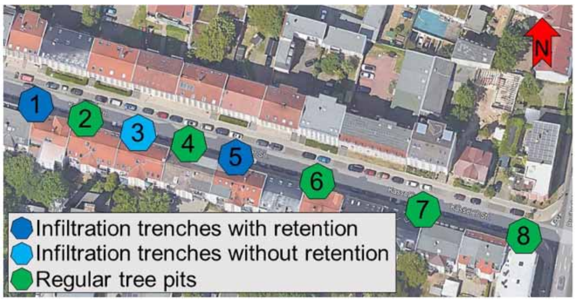


Figure 1 | Location plan of study trees.

other study trees were planted in regular tree pits. Further information on the study trees is summarized in Table 1.

3.2. Frequency and period of measurements

In 2021, a total of 18 monitoring days from 2021-05-06 (after bud burst) until 2021-12-02 (defoliation completed) were conducted. The individual measurements were done at different times of day and under diverse weather conditions (see Table 2). Hereinafter the individual measurements will be referenced by their chronological number of the monitoring days.

Table 1 | Study group of trees

Tree number	Type of tree site	Stem diameter at breast height (cm)	Mean crown radius (cm)	Height (m)
1	Infiltration trench with retention layer	6.6	58.8 (± 8.2)	4.9 (± 0.4)
2	Regular tree pit	6.3	60.3 (± 12.9)	5.0
3	Infiltration trench without retention layer	6.4	58.9 (± 15.8)	4.7 (± 0.3)
4	Regular tree pit	6.9 (± 0.1)	57.3 (± 12.9)	4.7 (± 0.6)
5	Infiltration trench with retention layer	6.4	74.1 (± 20.4)	4.8 (± 0.5)
6	Regular tree pit	6.3	53.8 (± 13.9)	4.4 (± 0.2)
7	Regular tree pit	6.5 (± 0.2)	61.8 (± 13.1)	5.4 (± 0.4)
8	Regular tree pit	6.4[a]	42.0	4.9
9	Regular tree pit	6.5 (± 0.1)	63.1 (± 10.0)	5.7

Tree numbers, type of tree site, stem diameters, crown radii, and tree height measurements. Mean values of measurements on 2021-05-06 and 2022-01-25 with the measurement range in brackets.

[a] No fluctuation range is given for tree 8 because of missing data.

Table 2 | Dates, time periods, and weather conditions of measurements

Measurement number	Date	Time period	Weather conditions
1	2021-05-06	03:22 pm–06:22 pm	Variable cloudiness, rainy, windy
2	2021-05-11	11:54 am–01:28 pm	Slightly cloudy
3	2021-05-13	00:36 pm–01:59 pm	Cloudy, rainy
4	2021-05-17	00:21 pm–01:37 pm	Cloudy with cloud gaps
5	2021-05-20	00:41 pm–02:16 pm	Slightly cloudy with cloud gaps
6	2021-05-24	06:31 pm–07:33 pm	Cloudy, slightly windy
7	2021-06-01	05:30 pm–06:34 pm	Cloudy with cloud gaps, windy
8	2021-06-04	01:58 pm–03:03 pm	Cloudy with cloud gaps, slightly windy
9	2021-06-07	00:58 pm–02:01 pm	Slightly cloudy, slightly windy
10	2021-06-10	11:08 am–00:02 pm	Slightly cloudy, clear weather, slightly windy
11	2021-06-19	01:17 pm–05:18 pm	Slightly cloudy with cloud gaps, slightly windy
12	2021-08-20	02:00 pm–03:20 pm	Slightly cloudy with cloud gaps, slightly windy
13	2021-09-03	01:35 pm–02:37 pm	Slightly cloudy, clear weather, slightly windy
14	2021-09-20	00:50 pm–02:07 pm	Cloudy, slightly windy
15	2021-10-09	03:56 pm–04:50 pm	Clear weather, slightly windy
16	2021-10-23	03:34 pm–04:37 pm	Cloudy with cloud gaps, rainy, windy
17	2021-11-09	04:07 pm–04:54 pm	Clear weather
18	2021-12-02	02:16 pm–03:12 pm	Cloudy

3.3. Data sampling

At each measurement a series of photographs of the study trees crowns was recorded with a smartphone (Nokia, model TA-1052) with a resolution of 13.0 megapixels. A set of six photographs was taken per tree and day. The canopy photographs were taken from defined positions and perspectives (*a*–*f*) around the trees (see Table 3 for definition of recording positions). In Figure 2, a schematic illustration of the recording positions layout is given as well as an exemplary set of unprocessed canopy photographs. For positions *a*–*d* photographs were recorded from four points located in different directions around the tree stem with the camera pointing vertically upwards into the tree crown. The camera lens was positioned in a distance of 13 cm to the tree stem in a height of 2.15 m above ground. The four directions were selected to represent the street, building and left and right sides of the infiltration trench tree's crowns, as seen from the sidewalk on southwestern side of the street. For positions *e* and *f*, photographs were taken from two points located in different directions around the tree stems. The photographs were taken with the camera pointing upwards into the tree crown at an angle of 45° and with the camera lens positioned at a distance of 1.7 m from the tree trunk at a height of 1.87 m above the ground. The directions to positions *e* and *f* from the tree stem are identical to those of vertical recording positions *a* and *b*. To fix the position of the smartphone during recording, the device was mounted on a leveled tripod.

3.4. Image processing

The canopy photographies were rotated uniformly so that the tree tops in the images were oriented to the left for recording position *a*, upwards for recording positions *b*, *c*, *e*, *f* and to the right for recording position *d*. Thereafter,

Table 3 | Definition of crown photograph-recording positions

Position identifier	Perspective into tree crown	Direction to recording position from trees	Distance of camera lens from the tree (m)	Height of camera lens above ground (m)
a	Vertically upwards	285° WNW	0.13	2.15
b	Vertically upwards	105° ESE	0.13	2.15
c	Vertically upwards	15° NNE	0.13	2.15
d	Vertically upwards	195° SSW	0.13	2.15
e	Tilted 45° upwards	285° WNW	1.7	1.87
f	Tilted 45° upwards	105° ESE	1.7	1.87

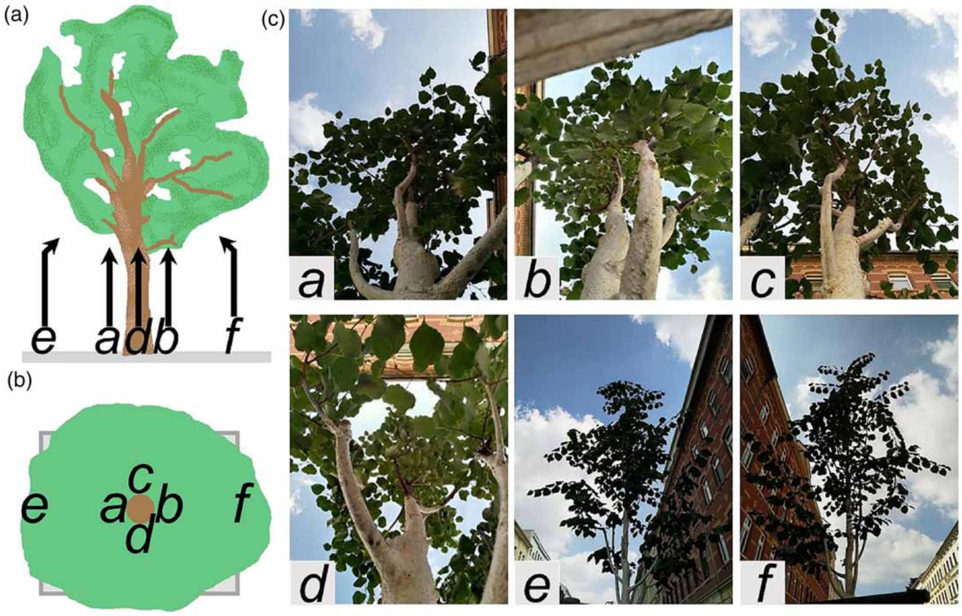


Figure 2 | (a) Side view illustration of recording positions, (b) plan illustration of recording positions, and (c) unprocessed photograph series of tree 4 from measurement date #13 from all recording positions.

the photographs were cropped to images that show only tree crown elements and sky area in the background (excluding e.g. house facades) by using the image-processing program IrfanView (v 4.57; Skiljan 2022). To do so, the photographs were cropped uniformly for each recording position by using stencils defined by pixel coordinates (see Table 4). The cropping stencils were defined so that a representative (as representative as possible regarding spatial confinement) portion of the tree crowns was unobstructed by background objects. Figure 3 shows the image-processing steps exemplarily for one crown photograph. In the next step, the cropped images were converted from RGB into 16-Bit greyscale images by use of the image-processing program imageJ (v 1.53e; ImageJ 2022). The greyscale images were converted into binary images using a brightness threshold manually adjusted for each individual image to ensure that the binarization facilitated the highest precision possible in the separation of image area occupied by tree crown elements and background sky area.

Following the binary conversion, a template modification of the crown images was conducted. To this end a template of the maximum crown coverage throughout the whole time series was generated by superimposing all binary images for each individual tree-position combination. The maximum crown coverage template thereby ensures that all sky areas are excluded. CD values are therefore calculated as area percentages of crown elements within the template area for each individual crown photograph. The template modification resulted in an average absolute increase in CD values of 3.2% (ranging from 0.0 to 15.5%) in comparison to CD values based on the cropped photograph alone (Figure 3(c)). Due to the differences of up to 15.5%, only the template modified crown densities were used.

3.5. Data availability and data flagging

From a total of 864 photographs that were planned (18 measurements of eight trees in six recording positions) 23 photographs could not be recorded due to inaccessible recording positions (such as parked vehicles). 114 photographs were discarded due to overexposure or reflections that inhibited the analysis of the photographs. A total of 727 photographs could be used to calculate crown densities. A detailed overview of the data coverage per tree and recording position is shown in Figure 4. Recording position *e* showed the highest number of valid photographs with 130, while recording position *b* displayed the lowest number of 111.

Recording positions *b* and *a* had the highest number of discarded photographs, followed by *c* and *d*, while the lowest number of photographs had to be sorted out for recording positions *f* and *e*. The distribution of discarded

Table 4 | Pixel coordinates for photograph recording position specific cropping stencils

Recording position identifier	*X*-position	*Y*-position	Width	Height	Total image area
a	349	283	1,283	1,157	1,484,431
b	246	433	1,194	953	1,137,882
c	60	511	1,356	849	1,151,244
d	391	14	885	1,426	1,262,010
e	470	688	488	613	299,144
f	470	688	488	613	299,144

Positions are defined originating from the upper left corner of the stencil in the original photograph. nit is in number of pixels.

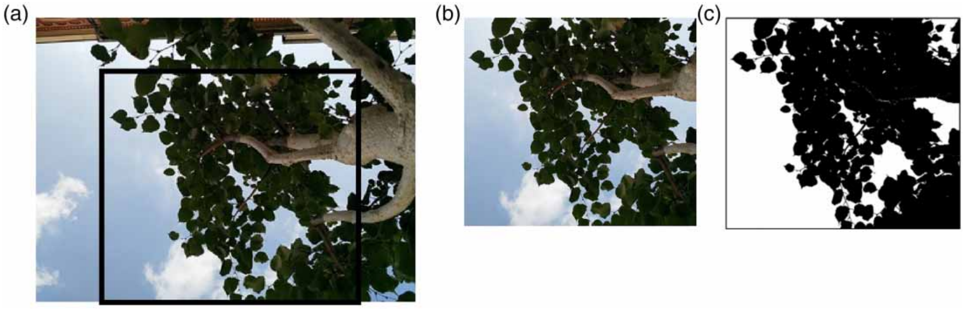


Figure 3 | Image-processing steps shown on photograph of tree 4, recording position *a* from 2021-09-03. (a) Original photograph with framed cropping stencil area, (b) the cropped photograph, and (c) the binarized photograph.

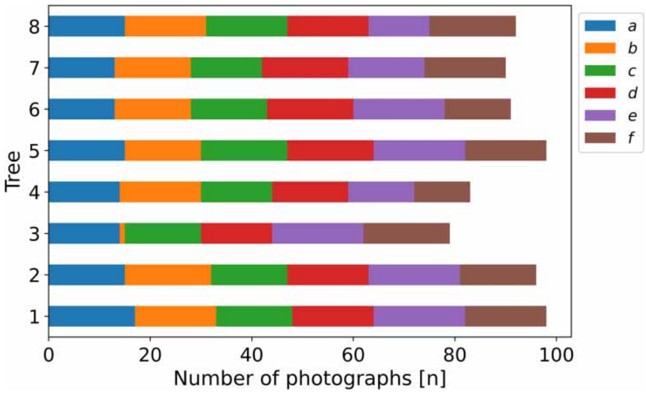


Figure 4 | Quantity of tree crown photographs analyzed per individual tree of the study group and recording position accumulated throughout the measurement series.

photographs among the individual study trees – under consideration of all recording positions – shows that tree 3 had the highest amount of 28 discarded photographs. The recording position *b* for tree 3 had the highest amount of 16 discarded photographs for a single recording position of an individual tree within the whole distribution.

3.6. Statistical assessment of CD data

3.6.1. Separation of data series

The CD data were divided into two characteristic phases – the greening phase (increasing CD) and the plateau (stabilized CD). To identify the turning point between the two phases a sixth-degree polynomial regression was fitted to the CD data averaged across the trees and recording positions. The moment of first sign change in the polynomial regression curve was taken as the turning point between the two phases. Measurements 1–10 were defined as the rising phase of annual crown development. Measurements 11–16 were defined as the plateau phase of annual crown development. Measurements 17 and 18 represent the defoliation phase of annual crown development but were not defined analytically.

3.6.2. Time stability analysis

Temporal stability analysis (Vachaud *et al.* 1985) is a method used to assess the stability of temporal patterns or trends in a dataset. It is commonly employed in ecological and environmental research to examine changes over time in variables such as species abundance or environmental conditions. Originally used to statistically assess which soil moisture locations within a field are consistently wetter or drier over time we apply temporal stability to our CD dataset. We therefore assess the relative deviations of individual image positions and study trees from the mean values of the individual comparison groups. The aim was to identify and quantify structural differences in temporal persistence of CD development among the group of study trees and separately among the individual photograph recording positions. Based on the temporal stability method introduced by Vachaud *et al.* (1985) the respective CD data were standardized. Depending on the data subset, the mean and standard deviation of the positions (either tree or recording position) were calculated using the standardized values. For the time stability plots the means were ranked and each position was visualized using the mean and the standard deviation as error bars.

The time stability analysis performed for the individual study trees was conducted to determine which of the individual study trees showed consistently low or high CD values within the study group throughout the plateau phase. The time stability analysis conducted for the individual recording positions was motivated by the objective of reducing the effort in data sampling by lowering the number of recording positions per study tree.

3.6.3. Slope analysis

The slope values for CD development throughout the greening phase were determined for each individual study tree (mean of all recording positions per study tree and measurement) and for each individual recording position (mean of study trees per recording position and measurement) were determined to detect differences in the annual foliation progression among study trees and recording positions. Time stability analysis was then applied onto the sets of slope values for the group of study trees and the recording positions separately.

3.7. Additional measurements

In addition to the crown photographs other tree development parameters of the study group of trees were recorded at the beginning on 2021-05-06 and on 2022-01-25 after the end of the series of CD measurements. The additional parameters encompassed tree height, tree diameter at breast height and horizontal crown extension in four directions corresponding to the directions of the photograph recording positions *a*–*d* as seen from the tree stems (Table 1). All additional parameters were measured using a tape measure; in addition, for tree height an inclinometer was used, and for horizontal crown extension a pole was used to project the crown area to the ground. For variability, the measurement ranges are reported in Table 1.

4. RESULTS

4.1. CD data

Figure 5(a) shows the curve progression of CD of tree 4 over the entire measurement series as an individual example from the measurement group of trees. The curve of the CD derived from the individual recording positions of tree 4 is shown as well as the curve of the CD averaged over the recording positions *a*–*f*. Additionally, the photographs of recording position *a* of tree 4 recorded throughout the measurement series are exemplarily displayed in Figure 5(b). The curve progressions of the individual recording positions as well as of the average curve evince a steep increase in CD during approximately the first month of the measurement period. After

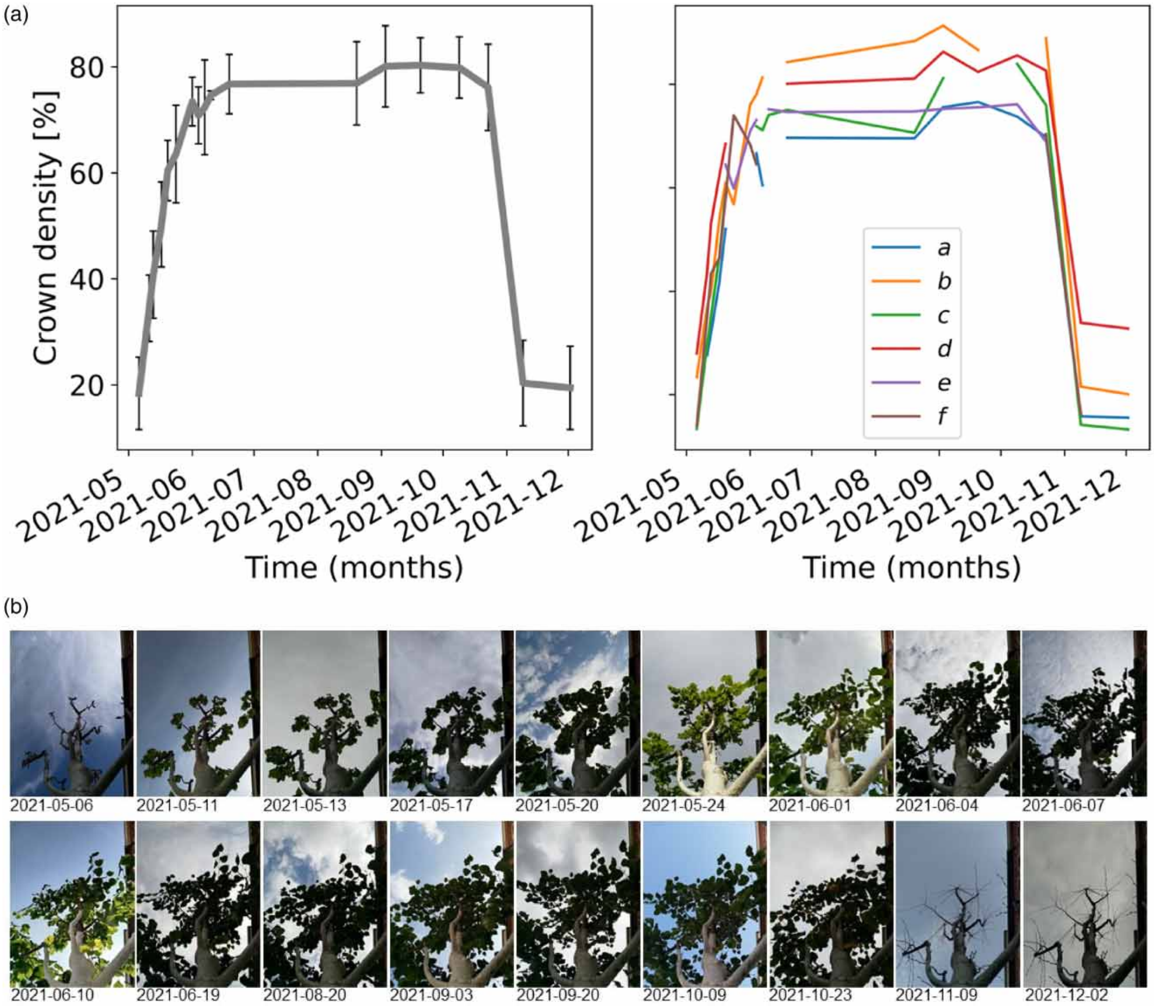


Figure 5 | (a) Mean CD percentages of tree 4 throughout the measurement series, individual recording positions and average curve, (b) corresponding series of unprocessed photographs from recording position *a* (corresponding series of cropped and binarized photographs are shown in Supplementary material, Figure S2 and S3). The grey line is the average of all recording positions; the colored lines correspond to the individual recording positions.

that the curves flatten out and show only a relatively slight increase in CD values until the measurement at the end of October when values are beginning to rapidly decrease until the curves are eventually approaching their initial levels. The data gaps in Figure 5 result either from inaccessible recording positions at the time of the measurement or from discarded photos in the assessment process (see section 3.6.).

Figure 6 shows the progression of the average curve of photograph recording positions *a*–*f* throughout the measurement series for each individual study tree as well as an overall average curve of all study trees combined. As in Figure 5 the curve progressions show an initial steep increase, an interim flattening followed by a rapid decrease of CD which is eventually approaching the initial levels again. To visualize the differences of CD curve progression throughout the measurement series between the individual trench trees 1, 3, and 5 and the trees standing in regular tree pits the curves of the trench trees are depicted as dashed lines in Figure 6. Throughout the plateau phase the values of trees 1, 3, and 5 are mostly surpassed by the average of the regular tree pits. This is applicable for all measurements from measurement 9 on aside from measurements on 2021-10-23 where trees 1 and 5 surpass the average of the regular tree pits. The values of tree 3 are outside of the standard deviation of the overall average curve for all measurements throughout the plateau phase of crown development.

4.2. Time stability and slope analysis of individual trees

The results of the time stability analysis of the CD data collected from individual study trees during the plateau phase averaged over the recording positions *a*–*f* are shown in Figure 7. Within this comparison, tree 3 had the

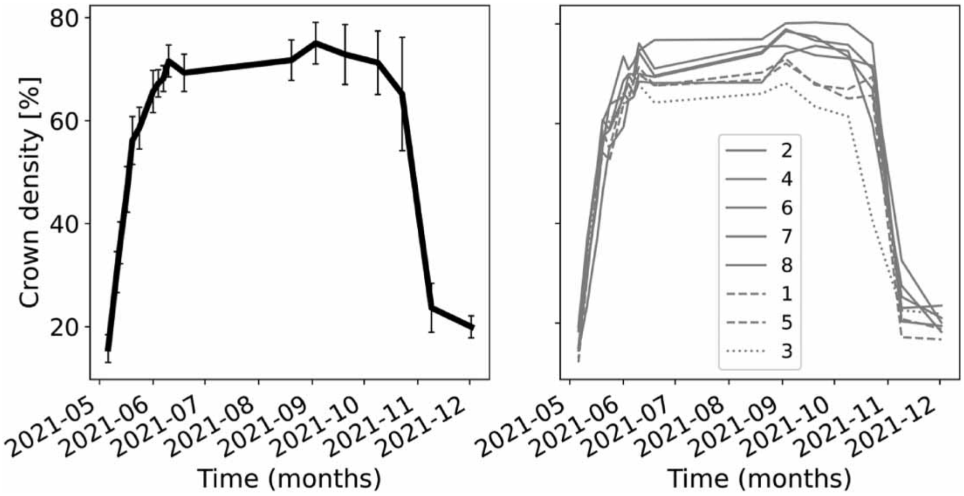


Figure 6 | Mean curve of study trees 1–8 throughout the measurement series (left) and average CD percentages of recording positions *a*–*f* for the individual study trees 1–8 (right, the solid grey lines correspond to regular tree pits; the dashed grey lines correspond to the tree trenches).

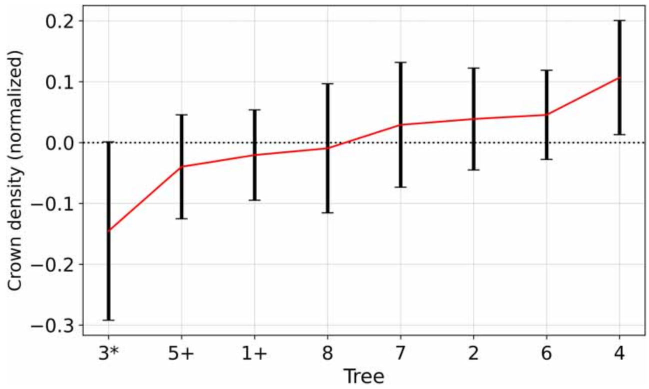


Figure 7 | Time stability of CD for the individual study trees 1–8 averaged over photograph-recording positions *a*–*f* throughout the time period of the plateau phase. Infiltration trench trees with retention elements are marked with [+], infiltration trench trees without retention elements are marked with [*].

only distinctly lower standardized CD, followed in the ranking by trees 5 and 1. Here, only tree 4 shows a distinct positive difference compared with the other trees. Tree 3 also shows the highest degree of variation.

Time stability slope analysis of the CD data collected from individual study trees 1–8 throughout the greening phase averaged over the recording positions *a*–*f* revealed that none of the study trees had a distinctly higher or lower standardized slope in CD development throughout the greening phase as depicted in Figure 8. Here, tree 2 shows the lowest standardized slope values within the comparison followed in the ranking by trees 3, 1, 5, 7, 6, 8, and 4. Trees 7 and 2 display the highest degree of variation within this comparison.

4.3. Time stability and slope analysis of photograph recording positions

Figure 9 depicts the results of the time stability analysis performed to assess the relationship between the sets of CD data collected from the individual photograph recording positions throughout the plateau phase averaged over the study trees. Within this comparison no distinct positive or negative deviations of any individual photo recording positions were found. Here, position *c* showed the lowest standardized CD values, followed by position *a*. After that the ranking continues with positions *f*, *d*, *e*, and *b*.

To visualize the relationship between the types of recording positions throughout the measurement series the corresponding average CD curves across the study trees are plotted in Supplementary material, Figure S1.

Time stability slope analysis of the CD data collected from individual recording positions *a*–*f* throughout the greening phase averaged over the study trees show that recording position *c* has a distinctly lower standardized slope than the other recording positions as depicted in Figure 10. Recording positions *e* and *f* displayed distinct positive deviations regarding their standardized slope throughout the corresponding time period.

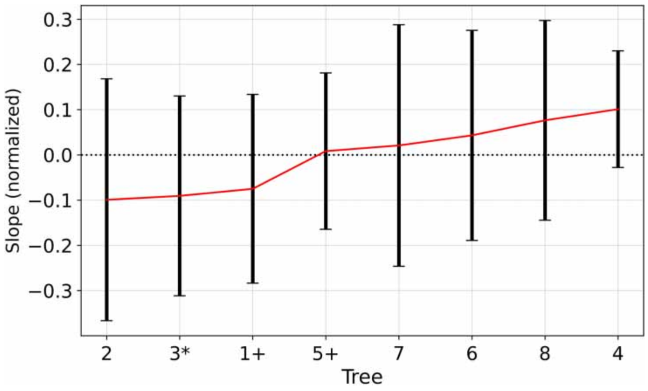


Figure 8 | Time stability of slopes of CD for the individual study trees 1–8 averaged over the recording positions *a*–*f* throughout the time period of the greening phase. Infiltration trench trees with retention elements are marked with [+], infiltration trench trees without retention elements are marked with [*].

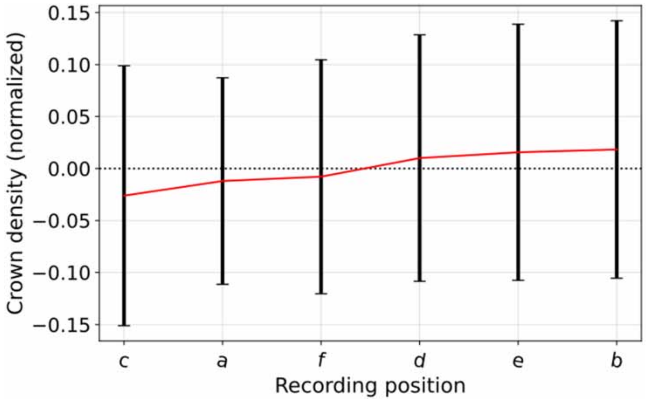


Figure 9 | Time stability of CD for the individual photograph recording positions *a*–*f* averaged over study trees 1–8 throughout the time period of the plateau phase.

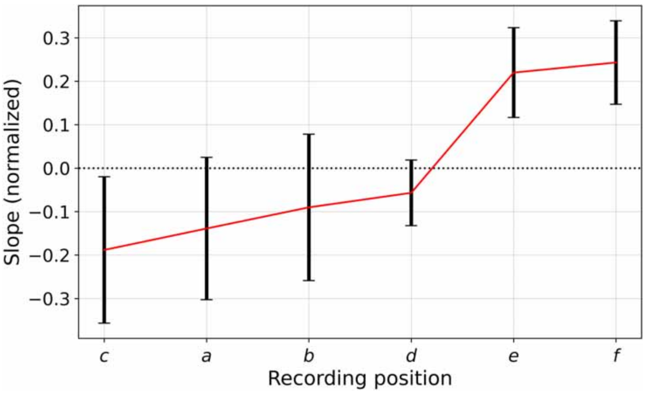


Figure 10 | Time stability of slopes of CD for the individual photograph recording positions *a*–*f* averaged over study trees 1–8 throughout the time period of the greening phase.

5. DISCUSSION

Both types of recording positions (vertical perspectives and 45°-tilted perspectives into the tree crowns) resulted in plausible CD data compared to visual inspection of the tree crowns. Smartphone photography has thereby proven its applicability for photographic assessment of CD of urban solitary trees under the spatially confined conditions of the study site as shown in Figures 5 and 6. The data plausibly reflect and quantify the annual development of individual tree crowns over the time period of the measurement series by clearly depicting characteristic phases of annual crown development. Those phases are characterized by an initial steep increase of CD roughly throughout the course of the first one and a half months of the measurement period (2021-05-06 to 2021-06-19), followed by a plateau with only slight increase in CD values of roughly four months (2021-06-19 to 2021-10-23) and an eventual rapid decrease until the curves are eventually approaching their initial levels from 2021-10-23 to 2021-12-02. The occurrent implausible fluctuation of data, i.e. CD values lower than a corresponding preceding value during the greening phase of annual crown development, are most likely a result of windy conditions at certain measurements that caused tilting and movement in the leaves which influenced the image area occupied by crown elements. This occurrent implausible fluctuation of data is, for the most part, compensated by the averaging of the individual recording positions per tree and measurement as apparent in Figure 5.

Throughout the plateau phase, the values of infiltration trench trees 1, 3, and 5 were for the most part above the average of the comparison group. Here, tree 3 showed the lowest values outside of the standard deviation of the average curve for all measurements throughout the plateau phase. The lower crown densities for the infiltration trench trees and in particular that of tree 3 throughout the plateau phase could possibly be a result of waterlogging in its root zone (Vaughn Grey *et al.* 2018). The latter could have been caused by a combination of relatively high annual precipitation amounts (780 l/m² in the State of Saxony compared to the mean of the international reference period 1961–1990 of 699 l/m²) (DWD 2021) and the retention effect of the tree trenches. Time stability analysis of the individual trees CD data of the plateau phase revealed structural differences in temporal persistence of CD development among the study group of trees (see Figure 7). Here, the infiltration trench trees 3, 5, and 1, respectively, displayed the lowest standardized CD values. This difference was only distinct for tree 3 which additionally showed the highest degree of scatter among the comparison group. The latter evinces a lower stability of relative CD values for tree 3. In contrast, the study trees standing in regular tree pits showed consistently higher values. Tree 4 displayed the highest values and the only distinct positive deviation from the comparison group mean regarding its standardized CD values.

However, time stability analysis of the individual trees slopes in CD data recorded throughout the greening phase of annual crown development revealed no distinct relative deviation of any study tree from the mean among study trees. Possibly, the variable of greening slope could become more significant for the comparing assessment of the study trees vitality reflected in their crown status in the future, when their root systems have developed further. Here, infiltration trench trees 3 (second rank), 1 (third rank), and 5 (fourth rank) were ranked relatively low again while tree 4 showed the highest standardized greening slope in CD development throughout the plateau phase. Time stability analysis of the recording positions showed no distinct differences between the individual recording positions across the plateau phase and study trees. This finding contributes to the assumption that the number of recording positions could be reduced by excluding individual positions from the measuring protocol for measurements throughout the corresponding annual crown development phase. In contrast to this, the time stability analysis of slope values throughout the greening phase and study trees showed distinctly higher values for the recording positions *e* and *f* when compared with the other recording positions.

Matching this finding, the mean absolute difference between the separately averaged CD values of the vertical perspective photograph recording positions *a–d* and the 45°-tilted perspective recording positions *e* and *f* throughout the measuring period and the study trees amounts to 5.3% with the highest absolute differences of 9.1% at the initial measurement of the series and 8.2% at the eighth's measurement of the series (see Supplementary material, Figure S1). The mean CD values derived from the recording positions *a–d* started at a higher level of 20.6% and rose to 69% while the corresponding values of recording positions *e* and *f* developed from a lower starting point of 11.5–75.9% throughout the greening phase. At the last measurement of the greening phase, the absolute difference between the average values of the two sets of recording positions mean values amounted to 6.9%. This difference could be due to a combination of the complex and irregular three-dimensional structure of the tree crowns and the different view angles into the crowns. Furthermore, the two different types of recording positions could be influenced by differing view angles onto the foliage. An analysis of the amounts of discarded photographs showed that 45°-tilted recording positions were less prone to failure by compromised photograph usability due to overexposure or reflections. This is an argument for the use of these recording positions if a reduction of effort in the measuring procedure is needed. The observed difference in susceptibility to insufficient photograph quality that resulted in exclusion of the photographs in the evaluation between vertical and 45°-tilted photographs is presumably related to the difference in intensity and occurrence of light reflections on crown elements. The especially high amount of sorted out photographs for recording position a of tree 3 was caused by the repeated obstruction of the tree crown from the recording positions perspective by the trees strutting. The template modification resulted in an increased representation of the tree crown elements as opposed to background area in the cropped photographs.

Although crown assessment based on horizontal photography has been tested in different studies (Winn *et al.* 2010; Miranda-Fuentes *et al.* 2015), it was not suitable for application under the conditions of an urban study site. With the non-horizontal recording perspectives, our method is applicable on trees situated in spatially confined urban areas where other comparable methods for measuring CD based on photography like the software tool urban crowns (Winn *et al.* 2010) are inapplicable due to optical foreground or background obstruction by parking cars or buildings or due to inaccessibility of positioning required to obtain the necessary horizontal perspectives on the trees. Visual tree crown status assessment methods (e.g. Johnstone *et al.* 2012; Roloff 2018) are prone to subjective influence or inconsistencies in data recording. Our method can be understood as an approach toward automatization of the CD estimations contained in stated methods. The statistical relationships between visual crown traits and other vitality indicators like bark chlorophyll fluorescence and leaf water potential in deciduous trees have been confirmed by different studies (Johnstone *et al.* 2012; Callow *et al.* 2018). Under consideration of the definition of tree vitality given in the introduction section and the fact that the crown photographs do not depict the complete tree crowns but only parts of them, the derived CD values cannot be used as an absolute unit of measurement for individual tree vitality but can be used as a relative proxy for crown status. Thereby the data are functional as an indicator of tree vitality within a comparison group of trees. Thus, the method allows an explorative and relative assessment of tree crown status across an adequate comparison group (comparable regarding age, species, breed, provenance, and location). By only depending on smartphone photography, the developed method is cost-effective in its application and has potential for future adaptation e.g. in citizen participation.

6. CONCLUSIONS

CD data was collected for a set of eight street trees during the vegetation period of 2021. Crown photographs were taken repeatedly from defined recording positions and analyzed digitally regarding area percentages of crown material relative to background area. Smartphone photography was found to be sufficient for tree crown assessment. The crown status of the surveyed trees could be analyzed both from vertical and 45°-tilted perspectives into the tree crowns. The data series reflects the crown development of the study group of trees. Thereby, it allows the chronological recording of different phases of the visible crown development in annual cycle. The data can be used to compare the study trees in terms of crown development status as an indicator of relative vitality status. For example, the trees in infiltration trenches showed generally lower greening slopes throughout the greening phase as well as relatively lower CD values throughout the plateau phase of annual crown development as compared to the trees standing in regular tree pits. The vertical and the 45°-tilted perspective recording positions showed no distinct differences in temporal stability throughout the plateau phase. Thus, a reduction of effort in data sampling by excluding any of the recording positions throughout the corresponding annual crown development phase seems reasonable. In contrast, distinctly higher slope values were detected for the 45°-tilted recording positions throughout the greening phase.

Future steps in the modification of the method consist in the automatization of the threshold setting in image processing. Also, the standardization and automatization of photograph cropping between individual recording positions in the image processing is of high importance to simplify the photograph processing procedure. In addition to assessing the overall developmental status of the tree crown, the method can be used to quantify the temporal shift of the annual developmental phases of urban trees over a multi-year series of measurements. It can be used to collect comparable and quantitative data on canopy status. Therefore, the method could contribute to research on effects of climate change on urban trees if associated to further environmental observations. In view of blue-green systems our method provides affordable and quantifiable monitoring. Especially for planning and decision making it is important to clearly assess the performance of blue-green systems and their functionalities.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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