Original Articles

Foliar optical traits indicate that sealed planting conditions negatively affect urban tree health

Kang Yu[a,*], Maarten Van Geel[b], Tobias Ceulemans[b], Willem Geerts[b], Miguel Marcos Ramos[c], Nadine Sousa[c], Paula M.L. Castro[c], Pierre Kastendeuch[d], Georges Najjar[d], Thierry Ameglio[e], Jérôme Ngao[e], Marc Saudreau[e], Olivier Honnay[b], Ben Somers[a]

[a] Department of Earth & Environmental Sciences, KU Leuven, 3001 Heverlee, Belgium
[b] Department of Biology, KU Leuven, 3001 Heverlee, Belgium
[c] Universidade Católica Portuguesa, CBQF – Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia, Rua Arquiteto Lobão Vital, 172, 4200-374 Porto, Portugal
[d] Laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie, Strasbourg University, Illkirch, France
[e] Université Clermont Auvergne, INRA, PIAF, F-63000 Clermont Ferrand, France

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ABSTRACT

Urban trees play a key role in mitigating environmental problems in cities, but they often face harsh environmental conditions as they generally grow in sealed soils that have small rooting space and low water availability. In this context, rapid monitoring and assessment of tree health status is critical to maintain urban trees and secure the provisioning of urban ecosystem services. Across three European cities we selected 187 *Tilia tomentosa* trees growing under following planting conditions: (i) *sealed*, trees planted in small soil pits or strips surrounded by highly sealed surfaces (concrete, pavement or asphalt); and (ii) *unsealed*, trees planted in roomy soil surfaces (e.g. parks). We measured leaf reflectance and fluorescence and derived a set of optical traits from the measurements. We examined whether these non-destructively measured optical traits differ between planting conditions and whether they correlate with leaf functional traits, e.g. specific leaf area (SLA), leaf water content (LWC) and leaf water per area (LWA). Compared to the *unsealed* trees, *sealed* trees showed decreased SLA and LWC while increased LWA. Leaf optical traits differed between the *unsealed* and *sealed* trees. Highly sealed soils accelerated leaf senescence of the *sealed* trees compared to the *unsealed* trees, embodied in the temporal trend of optical traits. Sealed planting conditions negatively affect urban tree health status and phenology. These negative effects can be estimated by leaf optical traits, demonstrating the great potential of optical traits in assessing tree health status. Our findings provide insights into facilitating urban green management using optical traits and remote sensing data.

1. Introduction

Urban trees play key roles in providing ecosystem services and mitigating environmental problems in urban areas in the form of air quality improvement, microclimate regulation, noise reduction, moderation of the urban heat island effect and providing recreational and cultural values (Bolund and Hunhammar, 1999). Yet, urban trees generally grow in soils sealed by buildings and urban infrastructures and face harsh environmental conditions, including limited soil volume, soil compaction and low soil moisture (Clark and Kjelgren, 1990; Sanders and Grabosky, 2014). Lack of rooting space, water and nutrient holding capacity will affect the development of urban trees, which leads to reduction in growth and health and imposing high risks of tree mortality (Grabosky and Bassuk, 1995). For instance, street trees planted in pits often have smaller canopies than trees planted in linear strips (Sanders and Grabosky, 2014). Moreover, urban trees are more prone to water deficits than forest trees, making them very susceptible to pathogens and pests (Clark and Kjelgren, 1990; Dale and Frank, 2017). All

Table 1
Results of linear mixed models for testing the effect of different planting conditions (soil sealing conditions) on variations in leaf functional traits and optical traits. We set the two variables *City* and *Site* as random effect factors and used the Dataset 1 (Table S2) for the mixed models. Bold font highlights the statistical significance of each test (p < 0.05).

Dependent variable	Model statistics		Post-hoc test (Tukey's HSD)					
	F-value	P-value	Boxed – Linear		Unlimited – Boxed		Unlimited – Linear	
			estimate	p-value	estimate	p-value	estimate	p-value
SLA	6.318	**0.002**	−0.605	0.535	4.235	**0.002**	3.63	**0.008**
LMA	7.773	**0.001**	0.315	0.383	−1.942	**< 0.001**	−1.627	**0.004**
LWC	7.721	**0.001**	−1.399	**0.031**	4.156	**0.002**	2.757	0.051
LWA	3.923	**0.023**	−0.089	0.926	−1.208	**0.033**	−1.297	**0.019**
mSR705	5.708	**0.005**	−0.294	0.12	0.856	**0.008**	0.562	0.101
mND705	6.221	**0.004**	−0.029	0.062	0.072	**0.007**	0.043	0.141
NDWI	2.114	0.126	0.002	0.301	−0.004	0.188	−0.002	0.559
WI	1.067	0.349	−0.0002	0.934	0.002	0.318	0.002	0.409
MDWI	5.674	**0.004**	0.004	0.441	−0.026	**0.003**	−0.021	**0.017**
WI2	6.772	**0.002**	0.064	0.329	−0.345	**0.001**	−0.28	**0.01**
PRI	13.568	**< 0.001**	−0.011	**0.009**	0.035	**< 0.001**	0.023	**0.005**
PSRI	1.124	0.329	0.003	0.311	−0.001	0.983	0.002	0.734
SIPI	2.809	0.063	0.006	0.097	−0.007	0.185	−0.002	0.913
Fv/Fm	2.795	0.07	−0.007	0.222	0.015	0.106	0.008	0.488
PI	7.181	**0.001**	−0.257	0.612	2.103	**0.001**	1.845	**0.004**

this, in turn, will reduce the ecosystem services provided by trees in urban environments (Bolund and Hunhammar, 1999; Dale and Frank, 2017). In this context, monitoring urban tree health and, especially, water status is crucial to secure the provisioning of urban ecosystem services.

Water stress often leads to leaf morphological changes (Farooq et al., 2009; Fernández et al., 2002), such as reduced cell growth and small leaf area (Farooq et al., 2009). These morphological changes will induce variations in the observed functional traits such that a reduction in specific leaf area (SLA) and leaf water content (LWC) is observed during water stress (Xu et al., 2009), which further affects whole plant growth (Farooq et al., 2009; Fernández et al., 2002). Therefore, the stress response is a complex of changes in traits that reflect plant strategies for coping with the stress (Farooq et al., 2009; Fernández et al., 2002; Wellstein et al., 2017). Water stress can also induce leaf senescence and alter tree phenology (Xie et al., 2015), disturbing ecosystem nutrient cycling and net primary production (Estiarte and Peñuelas, 2015). Therefore, quantitative determination of changes in leaf functional traits and changes related to leaf phenology during water stress is essential to understand plant strategies related to water stress.

Efficient assessment tools for monitoring urban tree health status and measuring plant functional traits are still limited. Traditional approaches are mainly based on visual assessments and need additional effort to standardize the data protocol and to account for subjective bias in the data collected by different investigators (Roman et al., 2017). Visible symptoms of certain stresses, however, may take a long time to appear, whereas at the same time tree growth may have already been seriously inhibited (Smoleń, 2012). Thus, efficient monitoring approaches are needed so that one can estimate the stress before visible symptoms appear. Normally, stresses alter leaf biochemical characteristics before visible symptoms (Petrova et al., 2014; Smoleń, 2012). It is possible to detect stresses by measuring plant biochemical parameters (e.g., pigment, nutrient element) as stress indicators. However, these analyses are destructive, costly and time-consuming (de la Riva et al., 2016; Petrova et al., 2014), making continuous monitoring of tree health status infeasible.

Advances in optical sensing technologies provide a means to quantify optical properties of leaves and characterize their optical traits (Ollinger, 2011; Ustin et al., 2009). Leaf reflectance and fluorescence measurements both allow for a rapid extraction of leaf optical traits of interest related to plant health or vitality (Buschmann, 2007; Delalieux

et al., 2009; Gamon et al., 1992; Sims and Gamon, 2002). The former measures the passively reflected light energy whereas the later measures the actively emitted energy by leaves, and both are of great potential as alternatives of lab analyses for plant health assessment (Lichtenthaler et al., 1998). Reflectance- and fluorescence-based techniques are non-destructive and have great repeatability, which enables to monitor plant health *in situ* readily by analyzing plant optical traits (Gitelson et al., 2003; Lausch et al., 2016) and allows for remotely assessing ecosystem functions (Pettorelli et al., 2017).

A reflectance-based approach for monitoring plant health typically employs spectral indices (Rouse et al., 1974). Since decades, a diverse set of spectral indices has been developed and validated for the estimation of plant biological traits such as leaf pigments, area, water, nitrogen and photosynthesis (Gamon et al., 1992; Gao, 1996; Gitelson et al., 2003; Peñuelas et al., 1997; Sims and Gamon, 2002). Many of these spectral indices have been well recognized as optical traits or surrogates of biological traits (Ollinger, 2011; Ustin et al., 2009). High spectral resolution sensors further enhance the estimation of plant biological traits by providing high fidelity data (Ustin et al., 2009), allowing for capturing subtle changes in spectral signatures as a response to changes in plant physiology and phenology (Gamon et al., 1992; Merzlyak et al., 1999; Peñuelas et al., 1995). For instance, hyperspectral reflectance spectra have been successfully used to estimate leaf pigments based on their unique absorption features in the visible region (Peñuelas et al., 1995; Sims and Gamon, 2002; Ustin et al., 2009) and to estimate leaf water content based on the water absorption features in the near infrared (NIR) and short-wave infrared (SWIR) spectral regions (Eitel et al., 2006; Gao, 1996; Gutierrez et al., 2010; Serrano et al., 2000). Facing the challenge of climate change mitigation, rapid detection of plant water stress using reflectance spectra is becoming increasingly critical (Maimaitiyiming et al., 2017; Zhang et al., 2017).

Leaf chlorophyll fluorescence (ChlF) is part of the light energy dissipated by non-photochemical processes, mainly in the form of red and far-red radiation (Buschmann, 2007; Lichtenthaler et al., 1998). Biotic or abiotic stresses often affect the photosynthetic performance of a leaf, and thus alter the intensity of ChlF emitted from the leaf (Buschmann, 2007; Lichtenthaler et al., 1998). Similar to leaf reflectance spectra, optical traits extracted from a leaf ChlF emission spectrum are widely used to estimate plant health status (Delalieux et al., 2009). Furthermore, combined use of reflectance- and fluorescence-based optical traits allows for a simultaneous quantification of multiple changes in leaves and plants (Delalieux et al., 2009; Yu et al.,