A Bridge Between Soil Science and Photonics: A Novel Framework for Urban Green Space Assessment

Francesca Sanfilippo[1,2(✉)], Lorenza Tuccio[1], Lucia Cavigli[1], Francesca Rossi[1], Giorgio Querzoli[2], Ivan Blecic[2], Andrea Vacca[3], and Paolo Matteini[1]

[1] CNR-Institute of Applied Physics "Nello Carrara" (IFAC), Via Madonna del Piano, 10, 50019 Sesto Fiorentino (FI), Italy
f.sanfilippo@studenti.unica.it

[2] Department of Civil, EnvironmentalandArchitecturalEngineering(DICAAR), University of Cagliari, Via Marengo, 2 09123 Cagliari, Italy

[3] Department of Chemical and Geological Sciences, University of Cagliari, UniversityCampus, D - 09042 Monserrato, Block, Italy

Abstract. Urban green spaces mitigate key urbanization impacts such as pollution and climate change exacerbation; although optical technologies have predominantly focused on documenting plant stress responses to atmospheric drivers, the critical role of soil quality in mediating vegetation's physiological adaptations - spanning both primary, and secondary metabolism - remains understudied. The work develops an integrated methodology combining portable photonic tools (an NDVI sensor, a Dualex analyzer, and a Raman spectrometer) with soil analysis to assess *Quercus Ilex L.* metabolic status in the urban, periurban and rural areas. Our approach cross-validates optical measurements of physiological changes with soil variable analysis, enabling comprehensive plant health assessment. Preliminary results demonstrate significant soil-plant physiological correlations across both biometric and photonic parameters. The combined analysis enhances data robustness, confirming photonic measurements through soil diagnostics. This dual-method approach addresses a critical research gap in urban ecology by synergizing optical monitoring with edaphic factor analysis. The methodology provides deeper insight into urban ecosystems where plants face complex, unregulated stressors. Key findings include that soil quality significantly influences photonic-derived physiological indicators**,** optical measurements gain reliability when correlated with soil parameters**,** and urban vegetation management requires to be integrated soil-plant monitoring**.** This study provides insights to guide the implementation of photon-based tools in urban green space management. The integrated approach supports evidence-based policies for sustainable urban resilience, optimizing vegetation maintenance through combined optical and soil diagnostics. Our methodology offers a practical framework for monitoring urban tree status under multiple stress factors while maintaining scientific rigor in data collection and interpretation.

Keywords: Urban green spaces · edaphic analysis · photonic tools

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1 Introduction

Urban green spaces represent fundamental nature-based solutions for counteracting the negative effects of urbanization but too often, the focus is solely on the effects that urbanization has on the air compartment and assessing the exacerbation that this process causes on the impacts of climate change and atmospheric pollution [1–3]. In previous studies we investigated plant physiological responses to urban environmental stressors using advanced optical technologies. However, the role of soil quality was not sufficiently explored, focusing the experimental study at the leaf level, on the effects of the atmospheric compartment [4–6]. In the present study we propose a methodological approach, innovatively combining traditional biometric measurements with advanced photonic techniques, to capture both structural and functional responses. This dual perspective, integrating soil analysis, enables us to quantify adaptive strategies through correlation patterns, validate optical indicators against morphological changes, and identify threshold responses to environmental stressors. The study was conducted on Quercus ilex L. (QI) specimens in Cagliari, a rapidly expanding Mediterranean coastal city. The Mediterranean basin represents a critical hotspot for studying plant-environmental interactions, particularly for keystone species like QI, that dominate these ecosystems [7, 8]. The study specifically examines how QI manages the Mediterranean "stress triangle" of nutritional limitations, water deficit, and edaphic extremes through integrated morphological and biochemical adjustments. This evergreen sclerophyllous is our focal species, because it shows remarkable adaptability to diverse edaphic conditions, making it an ideal model for studying soil-plant relationships in stress-prone environments [9–16]. Our research is based on a dual assessment approach. On one hand, we conducted vegetation monitoring with portable photonic techniques, employing an NDVI sensor, a Dualex fluorescence analyzer, and a Raman spectrometer. This allowed us to measure photosynthetic efficiency, pigment dynamics, and the production of specific defense compounds. On the other hand, we performed soil profiling, evaluating essential nutrients such as organic carbon, nitrogen, and phosphorus, analyzing structural characteristics like texture and water retention capacity, and measuring potential contaminants including heavy metals and salts, revealing significant interactions. The innovative aspect of our method lies in comparing results obtained from optical techniques with soil analysis. This approach addresses two major limitations in urban plant studies. Optical instruments are often used to evaluate plants without considering the characteristics of the soil in which they grow. Furthermore, urban soils frequently present unique combinations of stress factors that differ from those found in natural environments [17, 18]. By analyzing QI specimens distributed along Cagliari's urbanization gradient, we were able to observe how soil quality influences the species' adaptation strategies [19–21]. Our results provide new insights into the species' plasticity in resource allocation and the reliability of non-invasive optical methods for stress detection. This study contributes to the advancement of urban ecology in several ways. First, it identifies practical reference points for applying optical techniques in human-modified soils, based on experimental findings. Second, it quantifies the physiological effects of urban soil stress factors on plants. Finally, it proposes an innovative method that can be adopted by municipal administrations to complement the monitoring of the status of green spaces. [22–24]. Overall, our integrated approach offers municipal managers practical support for improving urban

green space management - for example by optimizing soil amendment practices, selecting more resilient species based on soil characteristics, and implementing early warning systems that combine optical indicators with soil analysis. In line with these insights, it is evident that urban ecology must consider the interconnection between air pollution, soil quality, and plant adaptability to promote sustainable urban environments [25, 26]. Addressing these multifaceted aspects will be essential to enhance the resilience of urban green spaces, particularly in Mediterranean cities facing unique climatic challenges and anthropogenic pressures.

2 Methodology

This research was conducted in two differentiated environments within the metropolitan area of Cagliari: a densely populated central district and a more sparsely developed peripheral zone. The selection of these sites was guided by the strategic positioning of air quality monitoring stations managed by the Regional Environmental Protection Agency (ARPAS), ensuring representative coverage of the city's pollution gradients. The central monitoring station was in Cagliari along Via Cadello, while the peripheral station was situated in the municipality of Monserrato. To establish a baseline for natural background conditions, an additional control site was included 3 km far from the town of Seulo, designated by ARPAS as a "maintenance area" due to its minimal anthropogenic influence and suitability for monitoring long-range atmospheric transport of pollutants [27–31]. Within each zone, 6 individual QI specimens were selected for analysis. This species was chosen for its ecological dominance in Mediterranean urban landscapes and its well-established role as a reliable bioindicator of air quality [32].

The analysis of five-year environmental data (2019–2023) identified late October 2024 as the optimal period for sampling, a choice driven by the need to jointly evaluate: the combined effects of atmospheric pollution and summer climatic stress (characterized by high temperatures, intense solar radiation, and reduced precipitation) on both soil and plant physiology; the acute and chronic responses of QI to these multiple pressures, within a climate change context that cannot be separated from the analysis of Mediterranean urban ecosystems. Field measurements employed three complementary optical techniques to non -destructively assess plant stress responses. The normalized difference vegetation index (NDVI) was acquired using a handheld GreenSeeker sensor (Trimble) to evaluate canopy health at the whole-plant level. Leaf-level physiological status was characterized using a Dualex instrument (Force-A, Orsay, France) that measures chlorophyll fluorescence denoted DxChl, epidermal flavonols and anthocyanins, compounds directly involved in photoprotection and oxidative stress mitigation, reported under the acronyms DxFlav, DxAnth and finally DxNBI, that was used to estimate the nitrogen nutritional status of the plant [33–35]. Molecular composition was further analyzed using a Mini-Raman Power portable spectrometer (Lightnovo) equipped with a 785 nm excitation laser, which detected vibrational modes characteristic of carotenoids (RI1526 in the text refers to the intensity of the 1526 cm^{-1} Raman band that is characteristic of carotenoids) and of polyphenols (RI1626 that is the intensity of the 1626 cm^{-1} band ascribed to phenolic compounds) [36–38]. Our research team developed the measurement protocol, a comprehensive sampling of each tree's southeastern aspect to control solar exposure

effects. For the Dualex measurements, twenty leaves per tree were analyzed (totaling 120 leaves per site), while Raman spectroscopy was performed on ten leaves per tree (60 leaves per site). Each specimen also received a single NDVI measurement to maintain consistency in canopy-scale assessment. Complementary biometric analyses included determinations of leaf area and fresh-to-dry weight ratios to evaluate potential morphological adaptations to pollution stress. The measurements were conducted in situ without destructive sampling, except for Raman analysis, conducted indoors within 2 h of leaf harvesting. Regarding soil, all operational phases—from soil sample collection to subsequent laboratory analyses—were conducted in strict compliance with the provisions of the Decreto Ministeriale 13 Settembre 1999 («Metodi ufficiali di analisi chimica del suolo»), issued by the Ministry of Agricultural Policies [39].

Soil sampling was performed at the base of each selected tree at a depth of 50 cm. As each study area included 6 trees, this operation generated 6 individual samples per site. In Cagliari, where trees were distributed across two distinct zones, a specific strategy was adopted to optimize analysis: samples collected beneath 3 trees from the first area were thoroughly mixed to form a single 1 kg composite sample ("Soil A"), while 3 samples from the second area were combined to create "Soil B". This approach pre-served each zone's distinctive characteristics while reducing laboratory analyses. Moreover, it ensured full sample representativeness as required by ministerial regulations. This phase proved critical for guaranteeing the reliability of subsequent laboratory tests. In Monserrato, all trees fell within a homogeneous area. Here, the 6 initial samples were combined into a single 1 kg representative sample ("Soil C"), reflecting the site's natural soil variability. A similar approach was applied in Seulo, where specimens were clustered within 3 m of each other in a uniform pedological context. All subsamples were homogenized to produce "Soil D", maintaining the representativeness of the entire area. This methodology offered dual advantages: it preserved natural soil heterogeneity across zones while optimizing analytical processes without compromising data reliability. Composite sampling notably minimized localized errors, providing robust insights into each site's pedological features. For the preparation and physicochemical characterization of composite samples (A, B, C, D), all analyses followed official protocols [40]. Sample preparation included standardized drying, crushing, and sieving procedures. Granulometric characterization involved both skeleton determination (separation of particles > 2 mm) and fine fraction analysis via pipette sedimentation [41]. Soil reaction (pH) was measured in water using a glass electrode, strictly adhering to the decree's procedural specifications [42]. Beyond these fundamental analyses, all additional physicochemical tests—including organic matter content and cation exchange capacity—were performed using certified, standardized methods in full compliance with ministerial guidelines.

3 Results

Table 1 shows the physicochemical properties of soils A-D, with color-coded values: red (exceeds legal limits, D.Lgs. 152/2006), black (moderate ranges), and green (low ranges), according to the Sardinia Region guidelines [43, 44]. The dataset encompasses chemical properties (pH, carbonates, organic carbon, nitrogen), nutrient availability, water retention parameters, and heavy metal concentrations, providing a comprehensive assessment of edaphic conditions. For each soil parameter, we chose to report only physical and physiological responses that had a moderate to high R correlation value of at least: ± 0.60 [45]. In this way, we focused on an actual adaptation response of QI to that value of the investigated parameter.

Table 1. Comparative analysis of soil characteristics (pH, TCaCO3: Total Calcium Carbonate ACaCO3: Active Calcium Carbonate, SOC: Soil Organic Carbon, TN: Total Nitrogen, C/N ratio: Carbon to Nitrogen ratio, AP: Available Phosphorus, EX Ca: Exchangeable Calcium, EX Mg: Exchangeable Magnesium, EX K: Exchangeable Potassium, EX Na: Exchangeable Sodium, CEC: Cation Exchange Capacity, EC: Electrical Conductivity, FC: Field Capacity, PWP: Permanent Wilting Point, PAW: Plant Available Water, As: Arsenic, Cd: Cadmium, Cr: Chromium, Hg: Mercury, Ni: Nickel, Pb: Lead, Cu: Copper, Zn: Zinc) and QI performance metrics (morphological, photosynthetic and secondary metabolites) across four soil classes (A-D): LA = leaf area, FW = fresh weight, DW = dry weight, LMA = LMA = leaf mass per area, SLA = specific leaf area, DxChl = chlorophyll index, DxFlav = flavonol index, DxAnth = anthocyanin index, DxNBI = nitrogen balance index, NDVI = normalized difference vegetation index, RI1526 = Raman intensity of the 1526 cm^{-1} band, RI1626 = Raman intensity of the 1626 cm^{-1} band).

	Ph	LA	FW	DW	LMA	NDVI
A	7.4	56.53	0.19	1.10	0.02	0.62
B	7.1	68.15	0.23	1.35	0.02	0.56
C	6.8	84.67	0.30	1.78	0.02	0.56
D	7.2	109.13	0.33	1.82	0.02	0.59

	TCaCo3 g/Kg	LA	LMA	SLA	Flav	Anth	RI_{1526}	RI_{1626}
A	97.5	56.53	0.02	51.61	1.36	0.07	33.48	3.28
B	20	68.15	0.02	51.20	1.48	0.13	34.81	3.01
C	59.6	84.67	0.02	48.03	1.34	0.07	34.56	3.36
D	241	109.13	0.02	60.29	1.27	0.07	37.57	3.61

	ACaCo3 g/Kg	LA	LMA	SLA	Flav	Anth	RI_{1526}	RI_{1626}

(*continued*)

Table 1. (*continued*)

A	25	56.53	0.02	51.61	1.36	0.07		
B	1.3	68.15	0.02	51.20	1.48	0.13	34.81	3.01
C	13.8	84.67	0.02	48.03	1.34	0.07	34.56	3.36
D	53.8	109.13	0.02	60.29	1.27	0.07	37.57	3.61

	SOC g/Kg	LA	FW	DW	Chl	Flav	RI_{1526}	RI_{1626}
A	13	56.53	0.19	1.10	61.58	1.36	33.48	3.28
B	16.4	68.15	0.23	1.35	45.94	1.48	34.81	3.01
C	29.5	84.67	0.30	1.78	51.25	1.34	34.56	3.36
D	35.3	109.13	0.33	1.82	42.17	1.27	37.57	3.61

	TN g/Kg	LA	FW	DW	Chl	Flav	RI_{1526}	RI_{1626}
A	1.14	56.53	0.19	1.10	61.58	1.36	33.48	3.28
B	1.39	68.15	0.23	1.35	45.94	1.48	34.81	3.01
C	2.34	84.67	0.30	1.78	51.25	1.34	34.56	3.36
D	2.91	109.13	0.33	1.82	42.17	1.27	37.57	3.61

	C/N ratio	LA	FW	DW	NDVI
A	11.4	56.53	0.19	1.10	0.62
B	11.8	68.15	0.23	1.35	0.56
C	12.6	84.67	0.30	1.78	0.56
D	12.1	109.13	0.33	1.82	0.59

	AP mg/Kg	LMA	SLA	NDVI
A	6.5	0.02	51.61	0.62
B	11.8	0.02	51.20	0.56
C	24.8	0.02	48.03	0.56
D	5.48	0.02	60.29	0.59

	EX Ca mg/Kg	Chl	NBI	RI_{1526}
A	342	61.58	45.28	33.48
B	572	45.94	31.11	34.81

(*continued*)

Table 1. (*continued*)

C	376	51.25	38.46	34.56
D	544	42.17	33.13	37.57

	EX Mg mg/Kg	Chl	Anth	NBI
A	50	61.58	0.07	45.28
B	96	45.94	0.13	31.11
C	17	51.25	0.07	38.46
D	69	42.17	0.07	33.13

	EX K mg/Kg	LMA	SLA	Flav	Anth	NDVI	RI_{1626}
A	26	0.02	51.61	1.36	0.07	0.62	3.28
B	73	0.02	51.20	1.48	0.13	0.56	3.01
C	48	0.02	48.03	1.34	0.07	0.56	3.36
D	15	0.02	60.29	1.27	0.07	0.59	3.61

	EX Na mg/Kg	LA	FW	DW	Flav	Anth	RI_{1626}
A	36	56.53	0.19	1.10	1.36	0.07	3.28
B	39	68.15	0.23	1.35	1.48	0.13	3.01
C	32	84.67	0.30	1.78	1.34	0.07	3.36
D	32	109.13	0.33	1.82	1.27	0.07	3.61

	CECmeq/100 g	Chl	NBI	RI_{1526}
A	13.9	61.58	45.28	33.48
B	25.5	45.94	31.11	34.81
C	14.4	51.25	38.46	34.56
D	23.9	42.17	33.13	37.57

	EC dS/m	LA	FW	DW	Flav	Anth	RI_{1626}
A	2.142	56.53	0.19	1.10	1.36	0.07	3.28
B	2.524	68.15	0.23	1.35	1.48	0.13	3.01
C	0.973	84.67	0.30	1.78	1.34	0.07	3.36
D	0.661	109.1	0.33	1.82	1.27	0.07	3.61

(*continued*)

Table 1. (*continued*)

	FC %	LA	FW	DW	LMA	SLA	Chl	RI_{1526}	RI_{1626}
A	25.1	56.53	0.19	1.10	0.02	51.61	61.58	33.48	3.28
B	26.6	68.15	0.23	1.35	0.02	51.20	45.94	34.81	3.01
C	28	84.67	0.30	1.78	0.02	48.03	51.25	34.56	3.36
D	32.8	109.1	0.33	1.82	0.02	60.29	42.17	37.57	3.61

	PWP %	LA	FW	DW	LMA	SLA	Chl	RI_{1526}	RI_{1626}
A	13.4	56.53	0.19	1.10	0.02	51.61	61.58	33.48	3.28
B	14.3	68.15	0.23	1.35	0.02	51.20	45.94	34.81	3.01
C	15.1	84.67	0.30	1.78	0.02	48.03	51.25	34.56	3.36
D	18	109.1	0.33	1.82	0.02	60.29	42.17	37.57	3.61

	PAW	LA	FW	DW	LMA	SLA	Chl	RI_{1526}	RI_{1626}
A	11.7	56.53	0.19	1.10	0.019	51.61	61.58	33.48	3.28
B	12.3	68.15	0.23	1.35	0.020	51.20	45.94	34.81	3.01
C	12.9	84.67	0.30	1.78	0.021	48.03	51.25	34.56	3.36
D	14.8	109.1	0.33	1.82	0.017	60.29	42.17	37.57	3.61

	As mg/kg	LMA	SLA	RI_{1526}	RI_{1626}
A	3.06	0.019	51.61	33.48	3.28
B	0.001	0.020	51.20	34.81	3.01
C	0.001	0.021	48.03	34.56	3.36
D	8.15	0.017	60.29	37.57	3.61

	Cr mg/kg	LA	FW	LMA	SLA	Chl	Flav	RI_{1526}	RI_{1626}
A	29.8	56.53	0.19	0.019	51.61	61.58	1.36	33.48	3.28
B	27.6	68.15	0.23	0.020	51.20	45.94	1.48	34.81	3.01
C	27.9	84.67	0.30	0.021	48.03	51.25	1.34	34.56	3.36
D	18	109.1	0.33	0.017	60.29	42.17	1.27	37.57	3.61

	Ni mg/kg	LA	FW	DW	Chl	NBI	NDVI	RI_{1526}
A	21.4	56.53	0.19	1.10	61.58	45.28	0.62	33.48
B	11.8	68.15	0.23	1.35	45.94	31.11	0.56	34.81
C	15.5	84.67	0.30	1.78	51.25	38.46	0.56	34.56

(*continued*)

Table 1. (*continued*)

D	10.9	109.1	0.33	1.82	42.17	33.13	0.59	37.57

	Pb mg/kg	LMA	SLA
A	24.3	0.019	51.61
B	7.14	0.020	51.20
C	67.3	0.021	48.03
D	10.1	0.017	60.29

	Cu mg/kg	LMA	SLA
A	22.1	0.019	51.61
B	15.5	0.020	51.20
C	62.8	0.021	48.03
D	9.13	0.017	60.29

	Zn mg/kg	LMA	SLA
A	75.7	0.019	51.61
B	58.6	0.020	51.20
C	160	0.021	48.03
D	32.3	0.017	60.29

Table 2 presents Pearson's correlation matrix quantifying relationships between these edaphic factors and plant response variables across four distinct levels: vegetative metrics (LA, FW, DW), leaf morphological characteristics (LMA, SLA), physiological indicators (chlorophyll content - DxChl, nitrogen balance index - DxNBI, normalized difference vegetation index - NDVI), and secondary metabolites such as flavonoids (DxFlav), anthocyanins (DxAnth), carotenoids (RI1526), polyphenols (RI1626). This two-tiered approach enables the identification of not only the distinctive environmental features of each soil type, but, more importantly, the functional relationships between specific edaphic factors and QI adaptive strategies, as evidenced by the correlation patterns.

4 Discussion

This research examines the interactions between soil properties and QI responses through an integrated analytical approach. In general, pH represents a crucial factor for nutrient availability, with extreme values (pH $<\ <$ 7 acidic or $>\ >$ 7 alkaline) limiting absorption [46, 47]. Soil A (pH 7.4) exhibits lower values of LA, FW, and DW, which correlate negatively with pH ($R = -0.56$ and -0.66). The lower LMA ($R = -0.53$) may

Table 2. R Pearson's correlation matrix between edaphic parameters and morpho-physiological responses in QI. The analysis examines relationships between soil characteristics (chemical properties, nutrient availability, water retention, heavy metals) and plant traits (growth metrics, leaf morphology, photosynthetic indicators, and secondary metabolites.

	pH	T $CaCO_3$	A $CaCO_3$	SOC	T N	C/N
LA	−0.32	0.75	0.69	0.97	0.98	0.64
FW	−0.56	0.58	0.53	0.99	0.99	0.83
DW	−0.66	0.46	0.42	0.97	0.96	0.89
LMA	−0.53	−0.93	−0.90	−0.46	−0.51	0.19
SLA	0.46	0.91	0.87	0.50	0.55	−0.14
DXChl	0.36	−0.35	−0.25	−0.66	−0.68	−0.48
DXFlav	−0.01	−0.83	−0.86	−0.74	−0.75	−0.37
DXAnth	−0.17	−0.66	−0.74	−0.44	−0.45	−0.15
DXNbi	0.35	−0.08	0.03	−0.41	−0.42	−0.34
NDVI	0.90	0.47	0.54	−0.30	−0.26	−0.72
RI_{1526}	−0.06	0.79	0.72	0.81	0.84	0.36
RI_{1626}	0.03	0.90	0.91	0.80	0.82	0.37
	A P	**EX Ca**	**EX Mg**	**EX K**	**EX Na**	**CEC**
LA	0.00	0.44	−0.06	−0.43	−0.74	0.39
FW	0.29	0.28	−0.28	−0.31	−0.82	0.22
DW	0.40	0.27	−0.31	−0.20	−0.79	0.20
LMA	0.77	−0.45	−0.38	0.72	0.31	−0.48
SLA	−0.74	0.54	0.43	−0.65	−0.29	0.56
DXChl	0.02	−0.88	−0.46	−0.14	0.18	−0.84
DXFlav	0.09	0.27	0.54	0.88	0.93	0.29
DXAnth	0.10	0.59	0.68	0.90	0.81	0.59
DXNbi	0.00	−0.94	−0.62	−0.41	−0.12	−0.91
NDVI	−0.75	−0.38	0.01	−0.74	−0.01	−0.31
RI_{1526}	−0.30	0.68	0.29	−0.40	−0.48	0.65
RI_{1626}	−0.16	−0.11	−0.40	−0.87	−0.90	−0.13
	EC 25 °C	**FC p.F 2.5**	**PWP p.F 4.2**	**PAW**	**As**	**Cd**
LA	−0.88	0.98	0.98	0.99	0.65	N/A
FW	−0.92	0.89	0.89	0.90	0.43	N/A
DW	−0.89	0.83	0.83	0.84	0.31	N/A
LMA	0.43	−0.75	−0.76	−0.74	−0.97	N/A

(*continued*)

Table 2. (*continued*)

	pH	T $CaCO_3$	A $CaCO_3$	SOC	T N	C/N
SLA	−0.44	0.79	0.80	0.79	0.95	N/A
DXChl	0.40	−0.78	−0.78	−0.78	−0.32	N/A
DXFlav	0.90	−0.68	−0.68	−0.68	−0.73	N/A
DXAnth	0.69	−0.35	−0.34	−0.35	−0.58	N/A
DXNbi	0.10	−0.54	−0.54	−0.54	−0.08	N/A
NDVI	0.09	−0.11	−0.10	−0.11	0.57	N/A
RI_{1526}	−0.67	0.97	0.98	0.97	0.75	N/A
RI_{1626}	−0.91	0.79	0.78	0.79	0.80	N/A
	Cr	**Hg**	**Ni**	**Pb**	**Cu**	**Zn**
LA	−0.92	N/A	−0.70	0.00	−0.06	−0.17
FW	−0.76	N/A	−0.64	0.27	0.23	0.12
DW	−0.68	N/A	−0.65	0.35	0.32	0.21
LMA	0.87	N/A	0.37	0.63	0.73	0.80
SLA	−0.91	N/A	−0.47	−0.65	−0.73	−0.80
DXChl	0.76	N/A	0.99	0.33	0.28	0.36
DXFlav	0.61	N/A	−0.03	−0.27	−0.12	−0.04
DXAnth	0.29	N/A	−0.41	−0.37	−0.21	−0.16
DXNbi	0.55	N/A	0.98	0.42	0.32	0.37
NDVI	−0.04	N/A	0.61	−0.35	−0.47	−0.45
RI_{1526}	−0.99	N/A	−0.80	−0.37	−0.41	−0.51
RI_{1626}	−0.73	N/A	−0.12	0.15	0.00	−0.09

result from micronutrient deficiencies. Even with reduced growth, a slightly alkaline pH corresponds to higher NDVI values (R = 0.90; highest in Soil A: 0.62, Table 1), showing that QI keeps a good vegetative state. The highest chlorophyll concentration is observed in plants grown in these soils, though the correlation remains weak (DxChl, R = 0.36), confirming that pH is not the determining factor. More neutral soils (B: pH 7.1; C: 6.8; D: 7.2) show a better balance between growth and nutrient availability, and here too, given the low correlation, pH does not emerge as the driver of vegetative growth.

The texture influences water retention, aeration, and vegetative growth. Clay soils (A) limit growth (low LA, FW, DW) improve photosynthetic efficiency (high NDVI and DxChl). Loamy–sand soils (D) favor more robust growth (high LA, FW, DW) but with lower photosynthetic efficiency (low NDVI and DxChl). Intermediate textures (B/C) show intermediate vegetative performance.

$TCaCO_3$ and $ACaCO_3$ greatly affect nutrient availability, influencing both growth and secondary metabolism. TCa CO3 correlates positively with LA (R = 0.75), polyphenols (RI1626, R = 0.90), carotenoids (RI1526, R = 0.79), and specific leaf area (SLA,

R = 0.91), but negatively with LMA (R = −0.93), flavonoids (DxFlav, R = −0.83), and anthocyanins (DxAnth, R = −0.66). ACa CO3 shows similar effects: positive on LA (R = 0.69), RI1626 (R = 0.91), RI1526 (R = 0.72), and SLA (R = 0.87), negative on LMA (R = −0.90), DxFlav (R = −0.86), and DxAnth (R = −0.74), indicating changes due to environmental stresses like nutrient deficiency.

SOC is a key factor for fertility and growth, with strong positive correlations with LA (R = 0.97), FW (R = 0.99), DW (R = 0.97), RI1526 (R = 0.81), and RI1626 (R = 0.80).

Minor negative effects on DxChl (R = −0.66) and DxFlav (R = −0.74) are observed. Soil D (the richest in carbon) shows the best plant growth, while soil A (the poorest) shows the worst growth.

TN is essential for both vegetative development and protein synthesis, as shown by its strong positive correlations with LA, FW, and DW (R > 0.96).

A high correlation is also found with RI1526 (R = 0.84) and RI1626 (R = 0.82), indicating a positive action on carotenoids and polyphenols synthesis. However, an excess of TN (>2.2 g/kg), such as that observed in soil D, inhibits chlorophyll, as shown by the negative correlation with DxChl (R = −0.68), probably due to a balance between chlorophyll synthesis and other nitrogen compounds; there is also a decrease in flavonoid synthesis and DxFlav (R = −0.75), which negatively affects some aspects of secondary metabolism.

The C/N Ratio is an indicator of soil quality and nutrient availability, as it affects organic matter decomposition and nitrogen mineralization, with positive correlations with LA (R = 0.64), FW (R = 0.83), and DW (R = 0.89), but negative with NDVI (R = −0.72). This suggests that a high ratio can favor vegetative growth due to better organic carbon availability but limits photosynthetic efficiency due to lower nitrogen availability, confirming its role as a primary growth driver.

AP increases leaf density (LMA, R = 0.77) but moderately, likely due to phosphorus's role in protein and cell membrane synthesis. High phosphorus levels reduce leaf expansion (SLA, R = −0.74) and NDVI (R = −0.75), indicating a trade-off between structural growth and photosynthetic efficiency.

Exchangeable calcium (EX-Ca) correlates positively with carotenoids (RI1526, R = 0.68), but negatively with chlorophyll (DxChl, R = −0.88), likely due to nutritional imbalances or inhibitory effects. The correlation is also negative with nitrogen balance index (DxNBI, R = −0.94), which could be explained with a negative interaction between calcium and nitrogen that limits nitrogen absorption or use by QI. Magnesium (EX – Mg) shows a negative correlation with chlorophyll (DxChl, R = −0.46), despite the role of this element in chlorophyll synthesis, which can be ascribed to nutritional imbalance or interaction with other nutrients. This nutrient stimulates anthocyanins (DxAnth, R = 0.68) and, to a lesser extent, flavonoids, essential pigments for stress defense. Magnesium also shows a negative correlation with DxNBI, due to a negative interaction between magnesium and nitrogen that limits nitrogen absorption.

Potassium (EX K) boosts flavonoids (R = 0.88), anthocyanins (R = 0.90), and LMA (R = 0.71), helping leaf density and defense pigments, but oddly lowers polyphenols (RI1626, R = −0.90), perhaps due to complex nutrient interactions. Concerning NDVI

($R = -0.74$) and SLA ($R = -0.64$), potassium shows an inhibitory effect on photosynthetic efficiency and leaf expansion. Sodium (EX Na) increases DxFlav ($R = 0.88$) and DxAnth ($R = 0.90$) as a stress response but damages growth (negative FW, DW, LA) and inhibits polyphenol production ($R = -0.90$).

CEC enhances carotenoid production (RI1526, $R = 0.65$) but strongly reduces the nitrogen balance index (DxNBI, $R = -0.92$), possibly due to competition between exchangeable cations and nitrogen uptake by the plant. The correlation is also negative with DxChl ($R = -0.84$), due to nutritional imbalances or highlighting complex interactions between exchangeable cations and chlorophyll synthesis.

EC: seems to reduce growth (negative LA, FW, DW) and polyphenols (RI1626, $R = -0.90$) but stimulates DxFlav ($R = 0.90$) and DxAnth ($R = 0.69$) as defense, a trend particularly observed in soils A and B.

FC, PWP, PAW show strong positive correlations with LA, FW, DW, SLA, RI1526, and RI1626 ($R > 0.78$), but negative with LMA, DxChl, and DxFlav, suggesting that greater water availability favors growth at the expense of some defense mechanisms like flavonoids, which are likely deemed unnecessary for combatting water stress.

Heavy metals (As, Cr, Ni, Pb, Cu, Zn) are present at low concentrations, with limited impact on growth but notable adaptive responses in plant metabolism. At very low concentrations, As increases SLA, indicating a peculiar adaptation to moderate abiotic stress. The reduction in leaf thickness (LMA, $R = -0.97$) can be explained as follows: at sub-toxic concentrations, As can activate adaptive responses similar to hormesis, where mild stress temporarily stimulates growth, leading QI to invest in leaf expansion (↑ area, ↓ thickness) to maximize photosynthesis, increase transpiration to reduce the toxic substance, compensating for metabolic stress. An increase in carotenoid and polyphenol concentrations is noted as a response to stress associated with leaf thickening.

At low doses, Cr stimulates LMA and DxChl ($R = 0.87$ and 0.76, respectively), though it does not activate carotenoid and polyphenol synthesis, likely because the stress level is too mild to trigger such responses. However, a "light" defense pathway is activated with an increase in flavonoids as a precaution, without full oxidative alarm, supporting the fact that defense mechanisms are active and functional.

Ni displays a typical pattern of metals with dual nutrient/toxicity roles; it shows a positive correlation with DxChl ($R = 0.99$), where QI prioritizes photosynthetic activity (also improving DxNBI and NDVI) over leaf expansion, sacrificing structural growth (LA, FW, DW show negative correlations). At very low concentrations, nickel does not produce enough reactive oxygen species (ROS) to trigger the synthesis of carotenoids, which normally act as antioxidants.

Pb, Cu, and Zn appear to induce thicker leaves (positive LMA) to limit oxidative damage, amplifying its sclerophyllous nature, but reducing SLA, with Zn being the most marked ($R = -0.80$). This reduction can occur because growth in area is sacrificed in favor of robustness. Additionally, Pb, Cu, and Zn alter water absorption, leading to more compact leaves (↑ LMA) but less cell expansion (↓ SLA).

QI reacts differently to soil traits, adapting based on environmental conditions. Leaf growth and biomass (LA, FW, DW) are primarily influenced by organic carbon and nitrogen availability, which act as true engines of vegetative development. A soil rich in organic matter with a good carbon-nitrogen balance (optimal C/N ratio) favors broader

leaves and greater biomass. Conversely, alkaline pH and high salinity limit growth, though not necessarily compromising plant vitality, as evidenced by high NDVI values in alkaline soils. Regarding photosynthetic efficiency, parameters like chlorophyll, NDVI, and nitrogen balance are particularly affected by water availability and calcium carbonate presence, which e.g. can improve leaf reflectance (and thus NDVI readings) even under reduced growth conditions. However, excess phosphorus or calcium may inhibit photosynthesis, likely due to nutritional imbalances altering chloroplast functionality. Secondary metabolites (flavonoids, anthocyanins, carotenoids, total polyphenols) respond to more specific stresses. Soils rich in calcium carbonate promote the production of polyphenols and carotenoids. In contrast, high levels of potassium and sodium increase flavonoids and anthocyanins, reflecting a defensive reaction to ionic stress. Heavy metals like lead, copper, and zinc result in thicker (high LMA) and more compact leaves, reducing leaf expansion (SLA) to limit toxic uptake. In contrast, nickel and arsenic at low doses show dual effects: the former favors chlorophyll but inhibits carotenoids, while the latter triggers a hormetic response, temporarily increasing SLA and antioxidant metabolites.

Ultimately, QI demonstrates great adaptive plasticity: in fertile soils, it prioritizes growth, while in harsher conditions (poor, calcareous, or contaminated soils), it invests in structural and metabolic defenses. This flexibility explains its success in Mediterranean ecosystems, where it faces multiple environmental stressors.

5 Conclusions

The collected data demonstrates that QI modulates its physiology in distinct ways depending on soil characteristics, with clearly distinguishable responses at both structural and biochemical levels. Soil properties—particularly organic carbon content (SOC), nitrogen (TN), calcium carbonate, and water availability—directly influence leaf architecture. Nutrient-rich soils promote greater leaf expansion (LA) and biomass accumulation (FW, DW), whereas calcium carbonate-rich soils induce thinner leaves (low LMA, high SLA), likely as an adaptation to optimize photosynthetic efficiency under potential nutrient stress. Simultaneously, optical analyses reveal that these same edaphic conditions also affect physiological parameters. Soils with high SOC and TN, while stimulating growth, appear to reduce photosynthetic efficiency per unit area, as indicated by lower chlorophyll (DxChl) levels and increased carotenoids (RI1526), which may serve as supplementary protection against light stress. Conversely, calcareous soils, while reducing the synthesis of certain secondary metabolites like flavonoids (DxFlav), enhance other polyphenols (RI1626), suggesting a targeted defensive response against specific abiotic stressors. A particularly interesting aspect is the role of water availability (PAW), which emerges as the primary driver of foliar growth while having a limited impact on stress-related metabolites. This indicates that while water primarily influences vegetative development, other soil factors trigger more refined physiological mechanisms, detectable through optical measurements.

While it is well known that soil conditions affect plant status, the novelty of this work lies elsewhere: the consistency and complementarity between edaphic and photonic data is a key finding, which also reveals the limitations of photonic instruments. Optical analyses in fact record only the physiological state of plants, without digging deeper into the

reasons behind the observed responses; edaphic analyses, on the other hand, inform us about the causes underlying the behavior recorded by optical instruments. Considering this, an integrated approach is recommended. Through this methodological integration it is possible to obtain a complete understanding of plant responses, especially in complex and variable environments such as urban ones. This study also allows us to verify how the responses recorded by optical instruments correspond to morphological variations in leaves. This correlation demonstrates for the first time how such modifications can be effectively monitored through innovative optical approaches. This validates the reliability of optical techniques in detecting real physiological states, free from artifacts, while also highlighting their user-friendly application. Their simplicity of use—requiring minimal training and no destructive sampling—positions them as a promising tool for rapid, scalable plant health monitoring. In summary, QI exhibits a sophisticated response capacity: it prioritizes structural adaptations (leaf growth, thickness) when soil resources (water, nutrients) are limited while activating biochemical responses (synthesis of pigments and antioxidants) in the presence of specific stressors such as high pH or metal accumulation. This duality not only fully justifies the optical observations but also suggests that integrating photonic sensors with edaphic analyses could offer an innovative approach to studying plant adaptation in complex environmental conditions. The next stages of the research will focus on more in-depth statistical analyses aimed at evaluating to what extent soil characteristics influence the data acquired through advanced photonic instrumentation. However, while soil represents one of the factors potentially modulating the physiological responses of QI, we hypothesize that its influence should be interpreted conditionally, within the broader environmental context. This cautious approach appears particularly relevant when comparing data from different locations, where multiple confounding factors may coexist. Therefore, the next phase will systematically extend the investigation to other environmental compartments. This integrated approach will allow for a comprehensive understanding of the influence exerted by each compartment on the species' physiological responses under the three different environmental conditions (urban, suburban, and rural). In this way, it will be possible to achieve a more robust validation of the results obtained through photonic techniques, whose data—as already observed for the soil—are supported by consistent and well-justified evidence.

References

1. Tucci, F., Giampaoletti, M., Nava, F., Tulelli, V.: Verso la neutralità climatica di architetture e città green (2023)
2. Nieuwenhuijsen, M.J.: New urban models for more sustainable, liveable and healthier cities post covid19; reducing air pollution, noise and heat island effects and increasing green space and physical activity. Environment International. 157, p. Article 10685 (2021)
3. Brears, R.C.: Nature-Based Solutions to 21st Century Challenges, 1st ed., Routledge (2020)
4. Ramos-González, O.M.: The green areas of san juan, puerto rico. Ecology and Society **19**(3) (2014)
5. Li, F., et al.: Spatio-temporal patterns of the use of urban green spaces and external factors contributing to their use in central beijing. Int. J. Environ. Res. Public Health **14**(3), 237 (2017)

6. Badiu, D.L., et al.: Is urban green space per capita a valuable target to achieve cities' sustainability goals? romania as a case study. Ecol. Ind. **70**, 53–66 (2016)
7. Liyaqat, I., et al.: Xylogenesis responses to a mediterranean climate in holm oak (quercus ilex l.). Forests **15**(8), 1386 (2024)
8. Giorgi, F.: Climate change hot-spots. Geophysical Research Letters **33**(8) (2006)
9. Agnelli, A., et al.: Holm oak (quercus ilex l.) rhizosphere affects limestone-derived soil under a multi-centennial forest. Plant and Soil **400**(1–2), 297–314 (2015)
10. Barquero, J., et al.: Biogeochemical prospecting of metallic critical raw materials: soil to plant transfer in sw ciudad real province, spain. Environ. Sci. Pollut. Res. **31**(20), 29536–29548 (2024)
11. Bogdziewicz, M., Fernández-Martínez, M., Espelta, J., Ogaya, R., Peñuelas, J.: Is forest fecundity resistant to drought? results from an 18-yr rainfall-reduction experiment. New Phytol. **227**(4), 1073–1080 (2020)
12. Cubera, E., Moreno, G.: Effect of single quercus ilex trees upon spatial and seasonal changes in soil water content in dehesas of central western Spain. Annals of Forest Science **64**(3), 355–364 (2007)
13. Díez-Hermano, S., et al.: Rhizosphere mycobiome diversity in four declining mediterranean tree species. Frontiers in Forests and Global Change **6** (2023)
14. Hoff, C., Rambal, S.: An examination of the interaction between climate, soil and leaf area index in a quercus ilex ecosystem. Ann. For. Sci. **60**(2), 153–161 (2003)
15. Limousin, J., Rambal, S., Ourcival, J., Rocheteau, A., Joffre, R., Rodríguez-Cortina, R.: Long-term transpiration change with rainfall decline in a mediter- ranean quercus ilex forest. Glob. Change Biol. **15**(9), 2163–2175 (2009)
16. Souad, E., Amraoui, M.: Effect of soil properties on growth of quercus ilex l. in humid and cold mountains of morocco. Appl. Environ. Soil Sci. **2020**, 1–9 (2020)
17. Прокофьева, T. B., et al.: Inclusion of soils and soil-like bodies of urban territories into the russian soil classification system. Eurasian Soil Science **47**(10), 1276–1287 (2014)
18. Liu, L., et al.: Impact of urbanization on soil microbial diversity and composition in the megacity of shanghai. Land Degradation & Development **33**(2), 282–293 (2021)
19. Rolo, V., Moreno, G.: Shrub species affect distinctively the functioning of scattered quercus ilex trees in mediterranean open woodlands. For. Ecol. Manage. **261**(11), 1750–1759 (2011)
20. García-Fayos, P., Monleón, V.J., Espigares, T., Ibarra, J.M.N., Bochet, E.: Increasing aridity threatens the sexual regeneration of quercus ilex(holm oak) in mediterranean ecosystems. PLoS ONE **15**(10), e0239755 (2020)
21. Pardos, M., Calama, R.: Adaptive strategies of seedlings of four mediterra- nean co-occurring tree species in response to light and moderate drought: a nursery approach. Forests **13**(2), 154 (2022)
22. Roman, L.A., Scatena, F.N.: Street tree survival in New York City: comparing species, site conditions, and planting programs. Urban Forestry & Urban Greening **10**(2), 99–106 (2011)
23. Li, T., Meng, L., Herman, U., Lu, Z., Crittenden, J.: A survey of soil enzyme activities along major roads in Beijing: the implications for traffic corridor green space management. Int. J. Environ. Res. Public Health **12**(10), 12475–12488 (2015)
24. Sonti, N.F., Pregitzer, C.C., Hallett, R.A.: Native tree seedling growth and physiology responds to variable soil conditions of urban natural areas. Restor. Ecol. **30**, e13653 (2022)
25. Hopkins, L.P., January-Bevers, D.J., Caton, E.K., Campos, L.A.: A simple tree planting framework to improve climate, air pollution, health, and urban heat in vulnerable locations using non-traditional partners. Plants, People, Planet **3**(2), 166–182 (2021)
26. Bankole, A.O., et al.: Air quality assessment of ubeji community near petroleum-related activities. Open Journal of Air Pollution **13**(02), 57–71 (2024)

27. Falcioni, R., et al.: Classification and Prediction by Pigment Content in Lettuce (Lactuca sativa L.) Varieties Using Machine Learning and ATR-FTIR Spectroscopy. Plants **11**(24), 3413 (2022)
28. Alfani, A., Baldantoni, D., Maisto, G., Bartoli, G., Virzo De Santo, A.: Temporal and spatial variation in C, N, S and trace element contents in the leaves of Quer- cus ilex within the urban area of Naples. Environ. Pollut. **109**, 119–129 (2000)
29. Alfani, A., Maisto, G., Prati, M.V., Baldantoni, D.: Leaves of Quercus Ilex L. as bio-monitors of PAHs in the air of Naples (Italy). Atmos. Environ. **35**, 3553–3559 (2001)
30. Maisto, G., Alfani, A., Baldantoni, D., De Marco, A., Virzo De Santo, A.: Trace me-tals in the soil and in Q. ilex L. leaves at anthropic and remote sites of the Campania Region of Italy. Geoderma **122**, 269–279 (2004)
31. De Nicola, F., Maisto, G., Prati, M.V., Alfani, A.: Temporal variations in PAH con-centrations in Quercus ilex L. (holm oak) leaves in an urban area. Chemosphere **61**, 432–440 (2005)
32. De Nicola, F., Maisto, G., Prati, M.V., Alfani, A.: Leaf accumulation of trace elements and polycyclic aromatic hydrocarbons (PAHs) in Quercus ilex L. Environmental Pollution **153**, 376–383 (2008)
33. Cerovic, Z.G., Masdoumier, G., Ghozlen, N.B., Latouche, G.: A new optical leaf-clip meter for simultaneous non-destructive assessment of leaf chlorophyll and epidermal flavonoids. Physiol. Plant. **146**, 251–260 (2012)
34. Agati, G., et al.: Nondestructive optical sensing of flavonols and chlorophyll in white head cabbage (Brassica oleracea L. var. capitata subvar. alba) grown under different nitrogen regimens. J. Agricult. Food Chem. **13**, 85–94 (2016)
35. Lo Piccolo, E., et al.: Multiple Consequences Induced by Epidermally-Located Anthocyanins in Young, Mature and Senescent Leaves of Prunus. Frontiers in Plant Science **9**, 917 (2018)
36. Akpolat, H., et al.: High-throughput phenotyping approach for screening major carotenoids of tomato by handheld Raman spectroscopy using chemo- metric Methods. Sensors **20**(13), 3723 (2020)
37. Traksele, L., Snitka, V.: Surface-enhanced Raman spectroscopy for the characterization of Vaccinium myrtillus L. bilberries of the Baltic-Nordic regions. European Food Res. Technol. **248**, 427–435 (2022)
38. Matteini, P., Distefano, C., de Angelis, M., Agati, G.: Assessment of nitrate levels in greenhouse-grown spinaches by Raman spectroscopy: A tool for sustainable agriculture and food security. J. Agricult. Food Res. **21** (2025)
39. Ministry of Agricultural Policies: Ministerial Decree of 13/09/1999. Approval of the "Official Methods of Chemical Analysis of Soil". In: Gazzetta Ufficiale, Suppl. Ordin. n° 248, pp.21/10/1999
40. Colombo, C., Miano, T.: Metodi di analisi chimica del suolo. 1a ed. Collana di Agronomia, vol. 12. FrancoAngeli, Milano (2023)
41. Indorante, S.J., Follmer, L.R., Hammer, R.D., Koenig, P.G.: Particle-size analysis by a modified pipette procedure. Soil Sci. Soc. Am. J. **54**, 560–563 (1990)
42. Conyers, M.K., Davey, B.G.: Observations on some routine methods for soil pH determination. Soil Sci. **145**, 29–36 (1988)
43. Repubblica Italiana, Parlamento: Decreto Legislativo 3 aprile 2006, n. 152 (2006). Norme in materia ambientale. Gazzetta Ufficiale n. 88 del 14 aprile 2006, Suppl. Ordinario n. 96, Roma
44. Agris, Regione Autonoma della Sardegna, Settore Suolo, Territorio e Ambiente (2016). Linee Guida all'Interpretazione delle Analisi del Suolo. Agenzia Regionale per la Ricerca Scientifica e l'Innovazione in Agricoltura, Cagliari
45. Schober, P., Boer, C., Schwarte, L.A.: Correlation coefficients: appropriate use and interpretation. Anesth. Analg. **126**(5), 1763–1768 (2018)
46. George, P., et al.: Divergent national-scale trends of microbial and animal biodiversity revealed across diverse temperate soil ecosystems. Nat. Commun. **10**(1), 1107 (2019)

47. Feng, X., Sun, X., Li, S., Zhang, J., Hu, N.: Relationship study among soils physicochemical properties and bacterial communities in Urban Green Space and promotion of its composition and Network Analysis. Agron. J. **113**, 515–526 (2021)