Exploring Urban Greenery Through Standard and Novel Monitoring Optical Tools: Preliminary Findings in the Metropolitan City of Cagliari

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Abstract. Green spaces in urban areas play a fundamental role in shaping the cityscape, gaining increasing importance in a context of growing impact of extreme weather events, global warming, and urban pollution. Innovative strategies for urban green infrastructure planning and management are essential to foster a healthier urban ecosystem. This research focuses on employing a multifaceted strategy involving novel optical technologies and the acquisition of standard vegetation parameters to examine the physiological status of specific Mediterranean plant species (*Quercus Ilex* L., *Nerium Oleander* L., and *Prunus Cerasifera* Ehrh.) from different urban habitats (central and peripheral) of Cagliari as compared to a control site in the inner part of Sardinia. Preliminarily, historical data from air quality monitoring stations for the period 2019–2022 allowed to identify two timeframes to assess the relationship between plant physiological responses and environmental parameters as well as the effects determined by pollutants: one in the post-summer period and the other one in the post-winter period. Leaf area, fresh and dry leaf weight, and trunk size, were collected. At the same time portable Normalized Difference Vegetation Index (NDVI)-, fluorescence/transmission-, and Raman-based portable sensors were used to non-invasively monitor leaf pigment-related indices, showing variations based on species and urban zones. The responses observed were characterized by imbalances in chlorophyll levels and distinct variations in polyphenols and carotenoids as well as different biometric trends. In the next measurement campaigns, an analysis of the soil will be added to assess its potential influence on plant response as well as satellite data to obtain additional information on a local base such as traffic, land temperature variations and spread of pollutants. This preliminary study lays the groundwork for developing a strategy to conscientiously monitor and manage urban greenery, contributing to the establishment of a greener and more sustainable city.

Keywords: sustainable urban development · urban green space · optical techniques

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1 Introduction

The rapid increase in urban population represents one of the major challenges of our time, with more than half of the world's population currently residing in urban areas and a projected growth of up to 70% by 2050 [1]. This phenomenon is closely related to a series of significant environmental problems, which have a direct impact on human well-being, undermining the quality of life and endangering not only the environment subject to these issues but also people's health.

Indeed, urbanization is associated with a range of processes that exacerbate existing environmental problems in the area and intensify extreme climatic events due to ongoing climate change. Urbanization involves the extensive use of impermeable materials, altering the water cycle and increasing the risk of floods [2]. This impact on soil hydrology reduces water infiltration, altering flood dynamics, and influencing water resource availability [3, 4]. Moreover, urbanization intensifies energy demand, promoting the use of fossil fuels and contributing to increased greenhouse gas emissions [5], resulting in worsened air, water, and soil pollution [6, 7]. These emissions lead to increased greenhouse effect, causing longer periods of extreme heat, reduced precipitation, and intensified storms.

Global climate change is further fueled by urbanization, including significant alteration of climatic regulation within urban areas, creating urban heat islands characterized by increased land surface and air temperatures [8]. Record temperatures, floods, destructive hailstorms, droughts, and sudden fires are some of the most devastating effects of climate change impacting Italy and the rest of the world.

This complex scenario underscores the importance of adopting holistic approaches to address the challenges associated with urbanization and mitigate its negative impacts on human health and well-being. Until now, planning has mostly focused on managing human-induced transformations on the environment and territory, within a perspective where they were essentially available to humanity. Climate planning reverses this perspective, working to reduce human impacts on the ecosystem and adapt settlements to the transformations occurring in the natural environment of which we are part.

The need for urgent, strong, and cooperative action based on trust and mutual understanding has never been higher. Similarly, it is essential for countries to strengthen their capacity to understand, plan, and manage climate risks in an ongoing process, no longer treating them as unpredictable phenomena to be managed according to the logic of urgency and emergency, but integrating them into the ordinary dimension of policies, programming, planning, and design.

Local governments are often identified as key actors in the transition towards a more sustainable society as many local decisions can directly influence environmental quality, such as regulating local transportation, constructing buildings, spatial planning, and various economic aspects.

In such a complex and articulated framework, the importance of cities is also affirmed by Goal 11 of the UN 2030 Agenda [9], aiming to make "cities and human settlements inclusive, safe, resilient, and sustainable", as well as by the New Urban Agenda and the European Urban Agenda [10], sharing the objective of improving the social, cultural, and environmental well-being of all citizens with a focus on inclusion and cohesion. This commitment is also in agreement with Goal 13 of the 2030 Agenda on climate action and

entails integrating measures for adapting to and mitigating climate change into urban and territorial planning and development processes. The latter are internationally recognized for their capacity to strengthen environmental and socioeconomic resilience, improve both mitigation and adaptation to climate change, and manage natural and environmental risks [11–13]. At the EU level, the long-term strategy for 2050 [14] acknowledges that climate change is a concerning issue among European citizens, as it is reshaping the world by amplifying instability risks in all its forms.

Addressing climate change and its effects presents a multiple challenge where two priorities can be identified for an integrated and effective approach: 'mitigation', meaning limiting future climate changes by reducing greenhouse gas emissions; 'adaptation', meaning being prepared to face the impact of inevitable climate changes in the best possible way.

Territorial and urban planning is widely recognized internationally as a powerful tool in shaping urbanization to make cities truly resilient to various risks that make them fragile, especially through nature-based solutions. Plants, as integral bioindicators, respond to pollutants and play a fundamental role in improving air quality and mitigating the effects of urban heat islands [15].

In recent years, numerous physiological studies on plants have been conducted to better understand their adaptation and response to environmental conditions [16–26]. These studies have explored a wide range of physiological aspects of plants, providing valuable information on their well-being and adaptation strategies to the environment. Aspects such as variations in levels of photosynthetic pigments (chlorophyll, carotenoids), as well as levels of secondary metabolites, are linked to adaptation and defense mechanisms, adverse environmental conditions (cold, heat, excessive light radiation, drought, etc.), biotic attacks (pathogens, molds), as well as a plant's response to interactions with pollutants. Studies on the physiological responses of primary and secondary plant metabolites have employed a wide range of tools, techniques, and types of analysis to understand their adaptation mechanisms to the urban environment. Regarding specifically non-destructive optical techniques, studies have been conducted using chlorophyll level analyzers including the most commonly used ones such as the SPAD 502PLUS (Konica Minolta) [27], the Dualex (Force A), and the CCM-200 (Opti-Sciences Inc.) that provide an estimate of leaf chlorophyll through transmittance measurements on a single leaf [28]. Other instrumentation is based on fluorescence such as the Multiplex (Force A) [29] for measuring chlorophyll content on larger areas such as a cluster of leaves. Dualex and Multiplex also allow investigating the content of epidermal flavonoids and anthocyanins [30]. The PAM [31] is also based on fluorescence techniques but is used to analyze photosynthetic efficiency. All of the aforementioned techniques are widely used in agronomy, but few studies have been carried out in urban contexts, and the literature regarding non-destructive optical analysis techniques on urban greenery is rather lacking. Furthermore, techniques such as reflectance spectroscopy use hyperspectral data for the simultaneous evaluation of pigments such as chlorophyll, carotenoids, anthocyanins, and flavonoids. In the field of vibrational spectroscopy, portable systems based on Raman spectroscopy have recently been introduced, which potentially allow deriving information on the content of the main plant components [32]. Another type of technique used is Fourier-transform infrared spectroscopy (FTIR), which has been proposed

for the classification and prediction of the contents of secondary metabolites, including flavonoids, alkaloids, phenylpropanoids, terpenes, carotenoids, amino acids, and other phenolic compounds [33]. This research project, which involves the use of portable optical detection devices for the analysis of plant physiological responses, aims to test the efficiency of such devices in urban settings. Their use in this context is accompanied by that of traditional techniques such as destructive analyses for quantifying the levels of the main leaf compounds in order to validate the outcome of the results obtained with optical instrumentation. In addition to optical analyses, the measurement strategy includes the collection of fundamental parameters related to plant vitality and age, such as leaf area, fresh and dry leaf weight, height, and trunk dimensions. Specifically, we are evaluating the use of Dualex (as mentioned above) as well as a portable Raman spectrometer for non-invasive monitoring in situ or "close to the field" of the main leaf pigments and components, whose levels can reveal the characteristic responses of plants to variations in environmental conditions and pollution.

Adopting a multidisciplinary approach that includes also a detailed assessments of urban vegetation, along with analysis of soil characteristics and atmospheric conditions, can provide a more comprehensive understanding of the complex interactions between the urban environment and vegetation. The preliminary phases of this approach are here discussed and have included the adoption of more traditional as well as of innovative analytical tools that spam from the collection of biometric plant parameters to the use of portable optical devices aimed at scrutinizing the plant physiological status as a function of its localization in the urban environment and of external factors. This innovative methodology, downstream of a correlation with relevant data on pollution and atmospheric parameters, is aimed at providing an in-depth description of the state of health of particular areas of the city and help in undertaking targeted mitigation policies.

2 Methodology

In the initial phase of our research, we selected two different areas within the urban context of the metropolitan city of Cagliari: a central neighborhood and a neighborhood situated in a more peripheral location. This selection was aimed at capturing the variety of urban landscapes and enabling an in-depth investigation of the diverse ecological facets of the Mediterranean environment of Cagliari (see Fig. 1).

The selection was also dictated by the positioning of monitoring stations under the control of the regional environmental protection agency, referred to as ARPAS, which in turn were strategically placed in various locations within the metropolitan city of Cagliari to capture the diverse urban fabric of the metropolis in question.

The station located at Via Cadello, indeed, termed as an urban traffic station in the municipality of Cagliari, offers several advantages over the others: it is centrally located relative to the urban core; it is a four-lane road (2 lanes per direction) experiencing medium to high traffic volumes; it is situated near a heavily urbanized area and is representative of pollution generated by high traffic volumes, akin to other significant thoroughfares (such as Via Dante, Via Sonnino, Viale Trieste, etc.); to the east and west, it intersects with other heavily trafficked arteries: 300 m to the east with the New Median Axis Road and 500 m to the west with Via Campania and Via Is Mirrionis; on

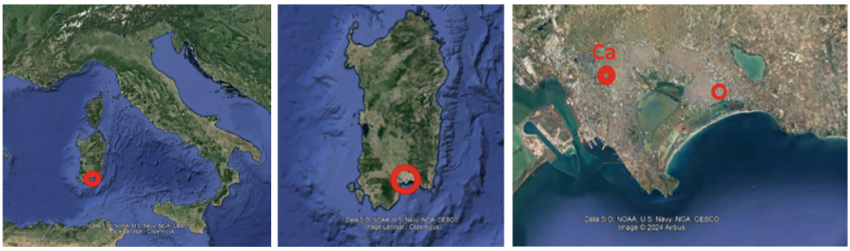

Fig. 1. Study area in southern Sardinia (left and central images) and identification of two selected sub-areas (right image) from Google Earth: a Cagliari central area (Ca) and a peripheral zone of the city situated in Quartu Sant'Elena (Qu).

the southern side, it borders a recreational green area (Monte Claro Park) that allows for the dispersion of pollutant sources (port area) and thus is not directly interfered with by sources other than traffic.

The urban background monitoring station located on Via Perdalonga in the municipality of Quartu Sant'Elena, represents a more peripheral situation. The chosen site is indeed a municipal area free from specific pollution sources such as vehicular traffic (Viale Cristoforo Colombo and Via Fiume, two roads characterized by significant traffic flows, are located at distances of 300 and 600 m from the site, respectively) or nearby industrial or artisanal emissions. Furthermore, the urban fabric of the surrounding area is very homogeneous (as required by specific APAT criteria; APAT is a national government agency for environmental protection and technical services) and densely populated. The location appears optimal for determining the levels of urban background pollution experienced by the residents of Quartu. Although this location was later replaced by another peripheral one (see below) responding better to the requirements of our research, this area has proven an exceedingly valid test field to setting up our measurement protocol.

Starting from the air quality monitoring stations, we have defined a field of action that extends up to a maximum distance of 1 km from the monitoring station. Beyond this distance, the data recorded by the station are less representative of the area (see Fig. 2).



Fig. 2. On the left is the central area of the city of Cagliari where the urban traffic monitoring station is located; on the right is the peripheral area of the city where the urban background monitoring station is located.

Firstly, we analyzed the historical data recorded by the monitoring stations from 2019 to 2022. Through the analysis of the trends of environmental parameters and pollution levels over the past four years, we were able to identify suitable time windows in which it was most feasible to observe a physiological response of the species under examination in relation to pollution and environmental stressors (see Fig. 3).

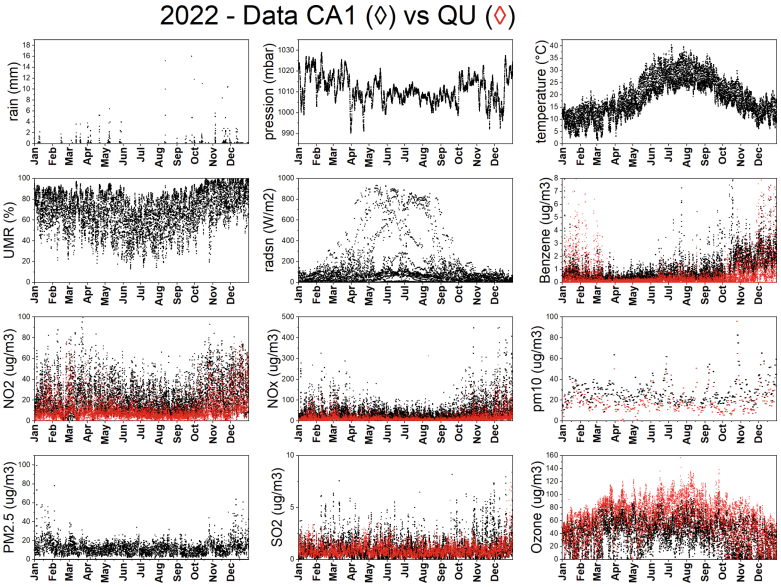

Fig. 3. An example of data analysis provided by the monitoring station of the regional environmental protection agency ARPAS for the year 2022 in the central area of the city of Cagliari and in the peripheral area of Quartu.

We identified an initial time window towards the end of February and a second time window at the end of October. These are two significant periods for conducting our measurements during a planned two-year campaign (2024–2025). The first period falls at the end of the winter season, during which typically higher levels of pollutants are observed due to domestic heating and vehicular traffic. The second period was identified at the end of the summer season, chosen following cycles of extreme meteorological events such as high temperatures, intense solar radiation, and low precipitation.

The year 2023, during which we also conducted two measurement campaigns, served to refine the protocol. Throughout this period, we made several adjustments based on the results obtained and field analyses, ultimately leading to a reliable protocol as applied in the third measurement campaign, conducted at the end of February 2024, whose results will be also briefly summarized in the followings.

Regarding the selection of species to monitor, our choice turned to plant species that were widely present in the locations considered and that were most representative of the urban context. The selected species included *Quercus Ilex* L. and *Nerium Oleander* L.,

which are evergreen arboreal and shrubby plants, respectively. Initially, the deciduous tree *Prunus Cerasifera* Ehrh. was also considered.

In the two measurement campaigns conducted in 2023, 3 plant subjects were identified for each species in each considered area, for a total of 9 subjects per study area. The use of portable detection devices, including a Normalized Difference Vegetation Index (NDVI)-based device (GreenSeeker Handheld sensor, Trimble), a leaf transmission/fluorescence analyzer [30] (Dualex, Force A) and a Raman spectrometer [32] (Mini-Raman Power Dual LightNovo with 660 and 785 nm lasers) enabled an in situ or close to field non-invasive monitoring of main leaf pigments and components whose levels can reveal characteristic plant responses to variations in environmental and pollutant conditions (see Fig. 4).



Fig. 4. Portable optical instruments used in the field to monitor plant physiological response: Greenseeker (on the left), Dualex (in the center), Raman spectrometer (on the right).

In particular, the main Dualex indices such as Chl, Flav, and Anth were collected from a total of 20 leaves per plant, focusing on the southeast orientation of the species relative to sunlight. These optical indices are proportional to the concentration of chlorophyll, epidermal flavonols (a type of flavonoids mainly involved in protection against oxidative stressors), and anthocyanins, respectively, present in the leaf [34–36]. Furthermore, selected Raman peaks were considered as representative of carotenoids and total phenols [37, 38]. For Raman spectroscopy-based analysis, 4 leaves per SE orientation subject were considered, totaling 12 leaves analyzed. A single NDVI acquisition per subject was also carried out.

It is worth specifying that in the preliminary measurement campaigns conducted in 2023, we also considered the northwest orientation of the selected subjects for the analysis. However, as no statistically significant differences between different orientations were observed on the basis of chlorophyll indexes, we finally selected the southeast orientation for future measurements. This decision was made both to ensure a more homogeneous comparison among the different sites and to better appreciate possible metabolic changes in polyphenol levels due to excessive solar radiation in the summer periods.

In addition to optical analyses, our measurement strategy included the collection of fundamental parameters related to plant vitality and age, such as leaf area, fresh and dry leaf weight, and trunk size.

The refined measurement protocol, finalized and implemented in the third measurement campaign of 2024, saw substantial changes compared to the two campaigns conducted in 2023. In this last measurement campaign, we decided to focus on a different peripheral area of the metropolitan city of Cagliari, *i.e.* that of Monserrato (Mo), where another ARPAS station for air quality monitoring is located. This station provides a more comprehensive information compared to the station located in the Quartu area because it collects a more complete selection of daily pollution data and atmospheric parameters. Furthermore, the Monserrato station is used by the regional authority as a reference station for the urban background, which also motivated us to choose this site as peripheral area to analyze. Another factor that led us to prefer the Monserrato area over the Quartu area is that, during field analyses, we noticed that the plant subjects in Quartu were not of the same age as those distributed in Cagliari and Monserrato, which represents an aspect of particular relevance for making comparable evaluations. Finally, we preferred to consider the Monserrato area instead of Quartu to exclude factors related to marine aerosols that inevitably can affect the Quartu area due to its closer proximity to the coast (see Fig. 5).

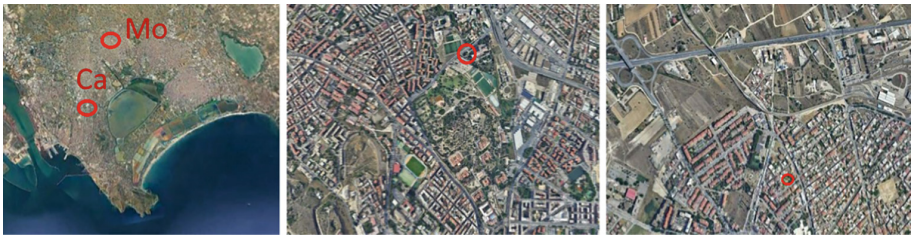

Fig. 5. In the new protocol, the central area in Cagliari (Ca) as previously considered (central image) and the new peripheral area in Monserrato (Mo, right image) are identified. Both areas (Ca and Mo) are reported in the left image.

During the third measurement campaign, we further added a background area (Se) where an ARPAS monitoring station is located, in what the regional authority calls the "Maintenance Area". This station is capable of monitoring background pollutant levels resulting mainly from natural sources and long-range transport phenomena. This area is considered a control zone. The positioning was defined by the fact that it is a relatively uncontaminated area and far from significant sources. Annual average levels of NO_2, PM10 and PM2.5 of about 1 $\mu g/m^3$, 13 $\mu g/m^3$ and 6 $\mu g/m^3$ (year 2022), respectively indicate the almost absence of pollution sources. The station is located about 3 km from the nearest inhabited center: Seulo, a village of fewer than 1000 inhabitants, 70 km north of Cagliari, at an altitude of about 700 m, located within a natural area accessible from the SS198, a road with limited traffic flow; the neighboring municipalities, well-spaced, have similar characteristics and the entire region is characterized by hilly and mountainous terrain with extensive forested areas; no significant industrial plants or dusty areas are

reported. In particular, an area cleared of trees (firebreak zone) and overlooking the valley below was identified: in this way, the station is not interfered with obstacles and also the anemometric pole can measure meteorological parameters optimally. The site had already been used previously for mobile monitoring stations, providing high-quality data, and also presents low simulated pollutant concentration values (see Fig. 6).



Fig. 6. On the left, the new and third control area added in the new measurement protocol located in Seulo, and on the right, a magnified view of the zones under analysis.

Based on the statistical analysis of the initial campaigns, it was decided to expand the number of subjects to be considered in the third campaign from 3 to 6 (of comparable size and age; *Quercus Ilex* L. subjects showing a trunk circumference within the 40–60 cm range) to reduce intraspecies variability, while simultaneously obtaining a larger representativeness of each area. Additionally, we excluded *Prunus Cerasifera* Ehrh. (not present in Monserrato and Seulo sites) to focus only on the two most widespread urban species: *Quercus Ilex* L. and *Nerium Oleander* L. (see Fig. 7).



Fig. 7. The species analyzed in the third campaign: *Quercus Ilex* L. (left image), and *Nerium Oleander* L (right image).

The number of analyses based on Raman spectroscopy was also increased (from 4 leaves to 10 leaves per subject), while the number of measurements performed with the Dualex device remained the same. It is important to emphasize that in the third campaign, Raman spectroscopy measurements were performed on collected leaves within a short (after 2 h) timespan from the in-situ measurements, while in the preparatory campaigns, the analysis was conducted in the laboratory after 1–2 days from leaves collection.

We utilized one-way ANOVA with Tukey post hoc test and a significance level of 0.05 to statistically analyze the groups corresponding to the identified zones for each chosen index. Statistical results as reported in the paper were performed under Origin Pro 2022 based on intraspecies grouping.

3 Results and Discussion

The variances noticed among the chosen plant varieties within the two designated urban areas - urban traffic site of Cagliari (Ca) and background urban site of Quartu Sant'Elena (Qu) - in the post-summer campaign provide initial perspectives into how urban vegetation reacts to its immediate surroundings (see Figs. 8 and 9). An imbalance in Dualex chlorophyll indexes (Dx Chl, see Fig. 8) between Ca and Qu sites is observed in the case of *Quercus Ilex* L. (QI), which was instead absent in *Nerium Oleander* L. (NO) and in *Prunus Cerasifera* Ehrh. (PC) This observation can suggest a peculiar response of QI as a function of the location inspected. Flavonols Dualex index (Dx Flav) kept comparable values upon different sites for NO and PC while an opposite variation with respect to Chl index was observed for QI between the two locations.

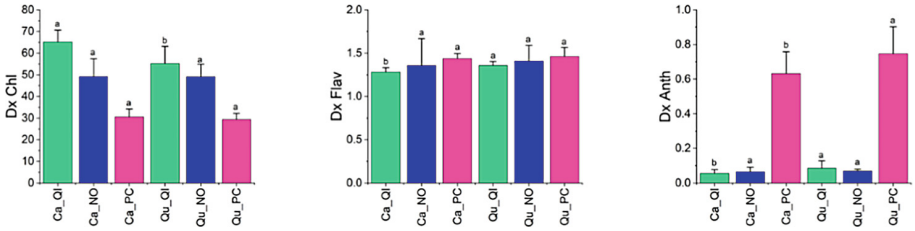

Fig. 8. Dualex analysis of the physiological responses of pigments in *Quercus Ilex* L. (QI), *Nerium Oleander* L. (NO) and Prunus Cerasifera Ehrh. (PC) in Cagliari (Ca) and in Quartu Sant'Elena (Qu). Each value represents the mean ± SD. Different letters indicate significant differences at $P < 0.05$.

Raman measurements (see Fig. 9) indicated an increase in phenols in the case of PC subjects from the Qu site, probably driven by a substantial increase in the level of anthocyanins as detected by Dualex analysis (Dx Anth, see Fig. 8). A larger Dx Anth index value was also observed for QI in the same location (Qu). The production of phenolic compounds such as flavonols and anthocyanins is generally involved in photoprotection and free radical scavenging activities, indicating a possible adaptation mechanism of the plant against environmental agents.

The results of the third measurement campaign in the post-winter window show that there is a significant increase in chlorophyll levels observed in the case of QI and to a

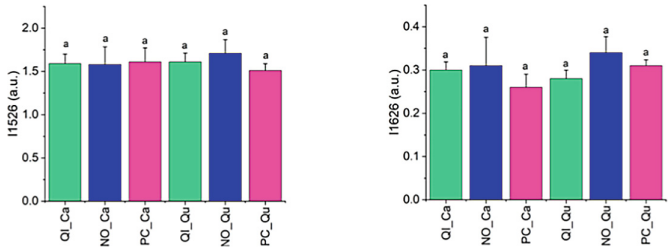

Fig. 9. Raman signal intensities at 1526 cm^{-1} (I1526) ascribed to carotenoid content (on the left) and at 1626 cm^{-1} (I1626) ascribed to total phenols content (on the right) in *Quercus Ilex* L. (QI), *Nerium Oleander* L. (NO) and *Prunus Cerasifera* Ehrh. (PC) in Cagliari (Ca) and in Quartu Sant'Elena (Qu). Each value represents the mean ± SE.

much lesser extent for NO at the Ca location compared to the peripheral (Mo) and control (Se) locations (see Fig. 10). This behavior is not uncommon for urban trees and highlights a plant response to a "mild pollution" effect, as previously noted [39]. It is hypothesized that below a certain level of air contaminants, chlorophyll content is positively affected due to compensatory mechanisms [40]. Indeed, this result is well in agreement with NOx levels for Ca (33 $\mu g/m^3$ annual average NOx in 2023) around the critical threshold for vegetation protection (i.e. 30 $\mu g/m^3$), accompanied by substantially higher levels of PM10 and PM2.5 for this location (30 $\mu g/m^3$ and 13 $\mu g/m^3$ annual average PM10 and PM2.5 in 2023, respectively) even compared to the peripheral site (7 $\mu g/m^3$, 27 $\mu g/m^3$, 7 $\mu g/m^3$ annual average NOx, PM10 and PM2.5 in 2023, respectively) and notably higher than in Se (<1 $\mu g/m^3$, 13 $\mu g/m^3$, 6 $\mu g/m^3$ annual average NOx, PM10 and PM2.5 in 2023, respectively). The result is also supported by measurements for QI from the post-summer campaign, where higher chlorophyll levels were recorded for the metropolitan site (Ca) compared to the peripheral one (Qu) as already mentioned above (see Fig. 8).

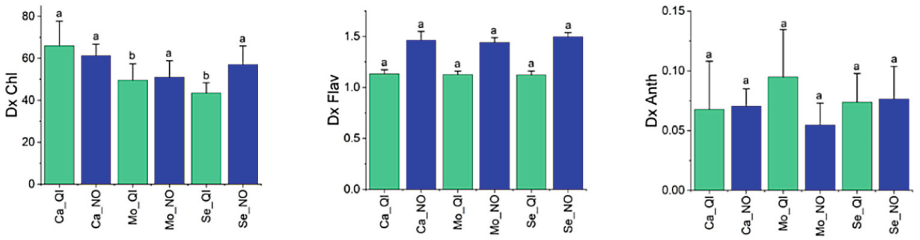

Fig. 10. Dualex analysis of the physiological responses of pigments in *Quercus Ilex* L. (QI), *Nerium Oleander* L. (NO) in Cagliari (Ca), Monserrato (Mo) and Seulo (Se). Each value represents the mean ± SD. Different letters indicate significant differences at $P < 0.05$.

The measured levels of Dx Flav exhibit a homogeneous intraspecies behavior during the post-winter campaign, which is further corroborated by Raman data I1626 (see Fig. 11). The absence of variations in both Dx Flav index and Raman I1626 suggests the absence of a defense response based on an accumulation of secondary metabolites by the

plant, eventually indicating the utilization of alternative adaptation mechanisms to urban stress situations, as observed in the case of QI for Ca, where chlorophyll levels increased. The Dx Anth index indicates very low levels of anthocyanins that remain constant across different locations, confirming the absence of a response at the secondary metabolism level of the plant.

Moreover, the levels of carotenoids highlighted by the Raman I1526 show minimal differences across locations, with an increasing trend from the metropolitan areas (Ca, Mo) to the control zone (Se) possibly indicating a partial impairment of photosynthetic centers in the former site (significative for NO of Ca), which is compensated by other plant adaptation mechanisms, as suggested above.

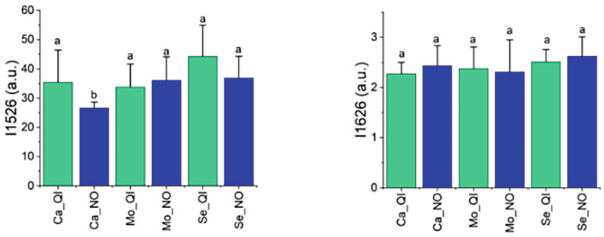

Fig. 11. Raman signal intensities at 1526 cm^{-1} (I1526) ascribed to carotenoid content (on the left) and at 1626 cm^{-1} (I1626) ascribed to total phenols content (on the right) in *Quercus Ilex* L. (QI), *Nerium Oleander* L. (NO) in Cagliari (Ca), in Monserrato (Mo), and in Seulo (Se). Each value represents the mean ± SE.

NDVI measurements (see Fig. 12) find a certain alignment with Raman observation evidencing moderately worse vegetation conditions (reduced plant vigor and/or foliage canopy density) in the case of the subjects from Ca and Mo.

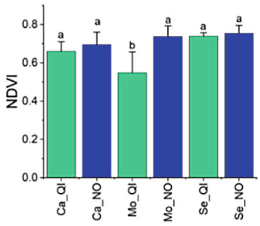

Fig. 12. NDVI measurements in Cagliari (Ca), in Monserrato (Mo), and in Seulo (Se). Each value represents the mean ± SE.

Finally, biometric data (see Fig. 13) highlight a reduced leaf expansion of both QI and NO accompanied by a lower fresh and dry weight in NO subjects from the metropolitan locations.

Overall, these results outline a fair tolerance of both plant species under examination to the higher levels of pollution observed in the metropolitan area, to which they respond through compensatory mechanisms by either an imbalance in photosynthetic pigments

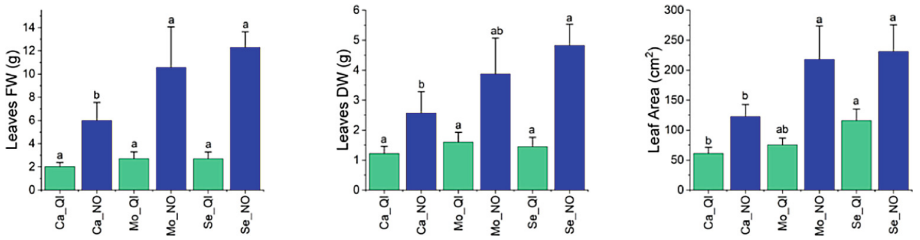

Fig. 13. Leaves fresh weight (FW), dry weight (DW) and leaf area in Cagliari (Ca), in Monserrato (Mo), and in Seulo (Se). Each value represents the mean ± SE.

(both chlorophyll and carotenoids), which is the case of QI, or reducing leaf growth levels and lushness, as observed in both QI and NO.

4 Conclusions

Cities are central to efforts aimed at addressing climate change, optimizing resources, and enhancing sustainability and resilience. The way cities are planned, built, governed, and managed directly impacts not only their own sustainability but also their broader role within interconnected systems. The main challenge lies in adopting a lifestyle that harmonizes with natural resources, recognizing their crucial role for humanity's future. When managed wisely, cities can drive human progress rather than merely being centers of problems [41, 42]. It's essential to recognize ecosystemic and ecological dynamics as integral to urban development and fully integrate them into city planning.

Within this framework, the use of simple, portable tools for rapid monitoring represents a significant step forward in assessing the conditions of urban greenery, allowing for a more detailed and precise evaluation of the physiological response of urban vegetation to environmental conditions. This data can then be promptly used to inform urban planning policies and strategies aimed at promoting more sustainable and resilient cities. The integration of innovative technologies into urban planning is essential to address the global ecological crisis and promote sustainable urban development worldwide, with a particular emphasis on the role of urban greenery in achieving this goal.

This preliminary investigation thus marks the initiation of a comprehensive exploration aimed at developing an innovative approach for monitoring urban greenery, leveraging the potential of a multifacted protocol including consolidated and novel analytical technologies. The ultimate goal is to establish a robust information framework conducive to future planning efforts, aimed at enhancing the sustainability of urban ecosystems and strengthening their adaptability. By utilizing advanced analytical tools like the optical technologies tested here, capturing detailed physiological responses of plant species to the urban environment becomes easily accessible. The real-time data generated by these cutting-edge technologies will facilitate a deeper understanding of how greenery interacts with its surroundings, suggesting how urban greenery can be managed consciously and intelligently to achieve sustainability and resilience goals, thereby attributing a positive connotation to the city in the intricate fight against climate change and urban pollution. The adoption of innovative technologies in green monitoring and management can

contribute to ensuring better air quality and mitigating the negative impacts of climate change, promoting healthier and more adaptable cities for future generations. Greater attention to green management, to which this work partly contributes, can lead cities to display functional, aware, and resilient environments, in a perspective of sustainability and inclusiveness that reflects the changing needs of contemporary society.

In future developments of this research, several avenues can be pursued to enhance its impact and applicability. Firstly, longitudinal data analysis could be implemented to track the long-term effects of urban vegetation on environmental quality and human well-being. By collecting data over extended periods, researchers can better understand the dynamics of urban ecosystems and assess the effectiveness of green infrastructure in mitigating pollution and climate change impacts. Secondly, the application of the methodology to a wide range of plant species would enrich the understanding of how different plants respond to urban conditions and pollutants. By studying various species, researchers can identify resilient species suitable for urban environments and tailor urban greening initiatives accordingly. Additionally, replicating the methodology in diverse urban contexts would strengthen the robustness of the study's conclusions and recommendations. Different cities exhibit unique environmental challenges, and applying the research methodology across various urban settings would provide insights into the universality of its findings and the adaptability of green infrastructure solutions.

Analyzing data collected through portable optical devices can provide detailed information on the health and responses of plants to local environmental conditions, enabling policymakers and urban planners to assess the effectiveness of existing policies and implement targeted interventions, allowing for the identification of best practices and solutions tailored to each urban context.

In summary, the results of this research can be used to inform and guide policy and planning decisions in various areas, including urban planning, environmental management, and climate change mitigation. Their integration into participatory and evidence-based decision-making processes can contribute to creating more sustainable, resilient cities that meet the needs of local communities.

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