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Towards regenerative city models

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An innovative tool for supporting urban policies: assessing the health of mediterranean urban greenery with portable optical technologies and vegetation metrics

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Abstract

Urban green spaces are crucial for cityscapes, particularly in the context of escalating extreme weather, global warming, and pollution. They provide essential ecosystem services, including air quality improvement, cooling effects, and natural stormwater management. In this context, effective policy frameworks and innovative planning and design solutions of urban green infrastructure are critical. This study proposes utilizes advanced optical technologies and standard vegetation metrics to assess the physiological status of Mediterranean plant species (Quercus Ilex L. and Nerium Oleander L.) across various urban habitats of Cagliari (Italy), compared to a control site in Sardinia's interior.

Analysis of historical air quality data (2019-2023) identified two key periods—post-summer and post-winter—for evaluating plant responses to environmental factors and pollutants. Metrics such as leaf area, fresh and dry leaf weight, and trunk diameter were recorded. Additionally, portable sensors for Normalized Difference Vegetation Index (NDVI), fluorescence/transmission, and Raman spectroscopy were employed to non-invasively monitor leaf pigments. The results revealed species and location-specific variations in chlorophyll, polyphenols, and carotenoids, alongside different biometric trends.

Future research will integrate soil analysis and satellite data to assess local factors like traffic density, land surface temperature, and pollutant distribution. This preliminary study aims to develop a comprehensive strategy for monitoring and managing urban greenery, ultimately fostering a greener and more sustainable city environment.

Keywords

Urban greenery; Urban planning and management; Impact assessment; Climate change

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1. Introduction

Urban Green is increasingly recognized as a key indicator of sustainability, particularly in rapidly growing cities where balanced urban development policies are often lacking. The New Urban Agenda (Habitat III - UN, 2016) and the Sustainable Development Goals (SDGs - UN, 2015), especially Goal 11, emphasize the importance of urban green spaces for creating inclusive, safe, resilient, and sustainable cities. These spaces combat pollution, safeguard biodiversity, improve microclimates, and enhance individual well-being. The presence of urban green spaces significantly improves urban life quality (e.g., Braubach et al., 2017; Byrne & Sipe, 2010; Kabisch et al., 2017; Lyytimäki & Sipilä, 2009; Sadeghian & Vardanyan, 2013), contributing to ecological balance, public health, and social cohesion.

Urban green spaces also play a crucial role in climate action, aligning with Goal 13, by absorbing carbon dioxide and other pollutants, thereby improving air quality and reducing greenhouse gas emissions. Plants and trees act as natural air filters, mitigating pollution and benefiting public health, as highlighted by Sadeghian & Vardanyan (2013).

Urban greenery regulates city temperatures through shading and evapotranspiration, effectively cooling urban areas and combating the urban heat island phenomenon, exacerbated by climate change (Byrne & Sipe, 2010). Urban green is now an essential strategy for cities to adapt to and mitigate climate impacts, requiring policies that analyze and integrate green spaces as active tools for urban regeneration, sustainability, and resilience (Ingaramo & Negrello, 2024).

As global warming intensifies, cooling has become a critical resource, leading to "cooling poverty," a form of inequality linked to income, energy costs, housing, and infrastructure. Inadequate access to cooling infrastructure heightens vulnerability to extreme heat. Equitable access to urban green spaces can bridge socio-economic gaps, promote social inclusion, and mitigate the harmful effects of urbanization, which exacerbate climate change challenges (Mazzone et al., 2023)

Urban green spaces are not only evaluation objects but also serve as bioindicators, providing valuable data on urban-vegetation interactions for policymaking (Scheiber & Zucaro, 2023). Their integration as bioindicators and mitigation tools is essential for sustainable and resilient cities. Plants enhance urban aesthetics and offer continuous environmental monitoring, responding to pollution and environmental changes through biochemical, biophysical, and physiological adaptations. Monitoring urban greenery helps understand how cities adapt to changing conditions.

This research project, developed by a multidisciplinary team from the University of Cagliari and the Institute of Applied Physics of the National Research Council of Italy, evaluates the effectiveness of portable optical instruments for monitoring plant physiological responses in urban environments. While existing literature highlights the importance of urban greenery for sustainability and resilience, there is a gap in methods for detecting detailed physiological changes in urban plants, as photonic techniques have not been widely applied in this context.

The devices tested include a portable reflectance sensor (GreenSeeker, Trimble) based on the Normalized Difference Vegetation Index (NDVI), a leaf transmission/fluorescence analyzer (Dualex, Force A), and a Raman spectrometer (MiniRaman Power Dual LightNovo). These tools enable in situ monitoring of key pigments and foliar components, offering insights into plant responses to environmental changes and pollution.

The introduction of photonic instruments represents a significant advancement in urban vegetation studies, providing operational and scientific advantages over traditional methods for analyzing plant physiological responses. This project aims to enhance environmental monitoring through innovative, precise, and rapid approaches, enabling real-time, non-invasive analysis of urban green spaces. By combining traditional and cutting-edge optical tools, it delivers detailed insights into plant health, supporting informed decisions for urban green space management. As cities expand and the demand for sustainability grows, these tools will be crucial for ensuring the vitality and resilience of urban greenery.

The paper is structured into five sections:

- Introduction: Highlights urban greenery's role in sustainability, traditional monitoring tools, and the need for innovative, real-time approaches;
- Literature Review: Summarizes prior research on urban vegetation monitoring, focusing on optical tools and their importance;
- Methodology: Introduces an innovative monitoring protocol using advanced optical technologies;
- Case Studies: Examines selected urban areas with varying environmental and pollution levels;
- Results and Discussion: Presents findings on plant responses to urban stressors, evaluates the protocol's potential for sustainable planning, and suggests improvements for urban green space management.

This approach aims to bridge the gap between scientific data and urban policy, fostering sustainable and resilient cities.

2 Literature Review

Numerous studies highlight the benefits of urban green spaces (UGSs) in enhancing environmental, social, and economic sustainability, particularly in urban biodiversity, ecological connectivity, and ecosystem services (Lepczyk et al., 2017; Savard et al., 2000; Almeida et al., 2018; Green et al., 2016; Lazzarini et al., 2024). UGSs improve public health, mental well-being, and physical activity (Fischer et al., 2018; Barton & Rogerson, 2017; Douglas et al., 2017; Gascon et al., 2015; Houlden et al., 2018; Ambrey, 2016; Coombes et al., 2010; Lachowycz & Jones, 2011; Lovasi et al., 2013), improve local microclimate (Aram et al., 2019; Farhadi et al., 2019) and mitigate environmental issues like air pollution (Bottalico et al., 2016; Escobedo & Nowak, 2009), urban heat islands (Bowler et al., 2010; Gill et al., 2007), and stormwater management (Bolund & Hunhammar, 1999). Tools and indicators assess UGS accessibility, considering multiple transportation modes and distance-decay functions (Dony et al., 2015; Li et al., 2019; Xing et al., 2018; Almohamad et al., 2018; Giles-Corti et al., 2005; Guan et al., 2020), with detailed micro-urban analyses (Blečić et al., 2020; Blečić & Saiu, 2021). Studies also examine accessibility disparities across demographic groups (Almohamad et al., 2018; Breuste & Rahimi, 2015; Ferguson et al., 2018; Ward Thompson et al., 2012) and the impact of UGSs on urban vitality through Jane Jacobs's theory (Jacobs, 1969). Furthermore, recent research highlights the importance of identifying spatial variations in the values of urban green at the city level (Giannakidou & Latinopoulos, 2023).

These assessments combine extrinsic factors (urban area vitality) with intrinsic factors (park design and organization), providing tools for urban planning and policy development to optimize green spaces for community engagement and social cohesion (Pantaloni et al., 2024). Emerging photonic technologies, using advanced monitoring protocols, enable faster, more accurate environmental data collection, offering insights into green space health, soil quality, and air pollution levels (Butt et al., 2024). This approach reduces delays in traditional assessments, supporting agile decision-making and sustainable urban development. By integrating these technologies, cities can optimize green space management, enhancing long-term environmental sustainability.

To fully grasp the role of urban green spaces in sustainable planning, it is essential to analyze plant adaptation to urban stressors such as pollution and climate variations. Physiological studies offer valuable insights into these processes, guiding the design of resilient green spaces that deliver lasting ecological and social benefits. This integrated approach promotes healthier, smarter, and more sustainable cities by aligning urban policies with scientific understanding.

In recent years, numerous physiological studies have explored plant adaptation and responses to environmental conditions (Ramon et al., 2019; Park et al., 2021; Falcioni et al., 2020; Furlanetto et al., 2020;

Clemente et al., 2021; Gould et al., 2018; Fine et al., 2021; Sinanoglou et al., 2018; Baranovi et al., 2018; Ge et al., 2019; Franca et al., 2022). These studies have examined aspects such as photosynthetic pigments (chlorophyll, carotenoids) and secondary metabolites, linked to adaptation and defense mechanisms against environmental stressors (cold, heat, drought) and biotic attacks (pathogens, fungi), as well as interactions with pollutants.

Studies on plant physiological responses to environmental adaptation have utilized various non-destructive optical tools and techniques. Chlorophyll level analyzers such as the SPAD 502PLUS (Konica Minolta) (Falcioni et al., 2017), Dualex (Force A), and CCM-200 (Opti-Sciences Inc.) estimate leaf chlorophyll through transmittance measurements (Shibaeva et al., 2020). The Multiplex (Force A) (Almansoori et al., 2021) measures chlorophyll over larger areas, while Dualex and Multiplex also analyze flavonoid and anthocyanin content (Tuccio et al., 2022). The PAM (Agati et al., 2020) assesses photosynthetic efficiency. Reflectance spectroscopy evaluates pigments like chlorophyll, carotenoids, anthocyanins, and flavonoids using hyperspectral data. Portable Raman spectroscopy systems (Figueroa et al., 2021) and Fourier-transform infrared (FTIR) spectroscopy (Saletnik et al., 2021) classify and predict secondary metabolite content. Although advanced, these tools have not yet been widely applied to urban environmental studies.

Traditional urban greenery monitoring relies on satellite technologies or fixed sensors, which provide static and costly data unsuitable for dynamic monitoring. Techniques like solvent extraction (Lichtenthaler, 1987; Porra, 1989), mass spectrometry, and chromatography require invasive sampling and specialized labs, limiting real-time analysis. In contrast, portable photonic instruments enable non-invasive, on-site, and real-time measurements. When combined with traditional methods for validation, these devices allow direct monitoring of plant conditions in urban settings, overcoming the limitations of conventional approaches.

Integrating green spaces into urban policies and understanding plants' physiological responses to environmental factors form a unified approach to sustainable city planning. Advanced technologies like reflectance spectroscopy and chlorophyll fluorescence allow for precise, non-destructive monitoring of plant health in urban conditions, such as air pollution and heat islands. These tools provide accurate vegetation data, supporting environmental impact assessments and sustainability policies. Continuous monitoring fosters resilient planning by considering the social, ecological, and climatic benefits of green spaces. This approach bridges public health improvement with urban biodiversity protection, ensuring decisions are informed by scientific data and advanced analytical tools.

3 Methodology

We analyzed historical data from ARPAS monitoring stations (2019-2023) to identify key periods for observing plant responses to pollution and environmental stressors. Two-time windows were selected for the two-year campaign (2024-2025): end of February (higher pollutant levels due to heating and traffic) and end of October (extreme weather like high temperatures and low precipitation). Plants were studied in three areas:

- Central urban area (Cagliari): Near traffic monitoring stations;
- Suburban area (Monserrato): Near an urban background monitoring station;
- Rural control area: Far from pollution sources, for comparison.

The goal was to correlate plant physiological responses with ARPAS data on environmental parameters and pollutant levels. For species selection, we chose Quercus Ilex L. (QI) and Nerium Oleander L. (NO) (Fig.1), evergreen species representative of urban contexts. Six plants of each species were analyzed per area, totaling twelve plants per study area.

Fig.1 Plant species examined: Quercus ilex L. (QI, right image) and Nerium oleander L. (NO, left image)

In 2023, two measurement campaigns were conducted to refine our protocol. Adjustments based on results and field analyses led to a reliable protocol applied in the third campaign in February 2024, with results summarized in subsequent sections. Portable devices (Fig.2), including the GreenSeeker Handheld sensor, a transmission and fluorescence-based leaf analyzer (Dualex, Force A) (Agati et al., 2020), and a Raman spectrometer (MiniRaman Power Dual LightNovo with 660 and 785 nm lasers) (Saletnik et al., 2021), were used to non-invasively monitor leaf pigments, assessing chlorophyll, carotenoids, and polyphenols in response to pollution and environmental factors.

Fig.2 Field-monitoring of plant physiological responses is conducted using portable optical instruments: Greenseeker (left), Dualex (center), and Raman spectrometer (right)

We collected the main Dualex indices (Chl, Flav, Anth) from 20 leaves per plant, totaling 240 leaves analyzed. These indices reflect chlorophyll, epidermal flavonols, and anthocyanin concentrations (Cerovic et al., 2012; Agati et al., 2016; Lo Piccolo et al., 2018). Additionally, we analyzed Raman peaks for carotenoids and total phenols (Akpolat et al., 2020; Traksele et al., 2022). For Raman spectroscopy, 10 leaves per plant were analyzed, with each plant also receiving a single NDVI reading. Fundamental parameters like leaf area, fresh, and dry weight were measured to assess plant vitality. Statistical analysis used one-way ANOVA with Tukey post hoc test ($p<0.05$) to evaluate zone-specific groups for each index, performed in Origin Pro 2022, focusing on intraspecies grouping. The study's methodology involves key steps to optimize monitoring urban plants' physiological responses to environmental changes and pollutants. The research procedure, including historical data analysis, measurement window identification, and selection of study areas and plant species, is summarized in the flowchart (Fig.3).

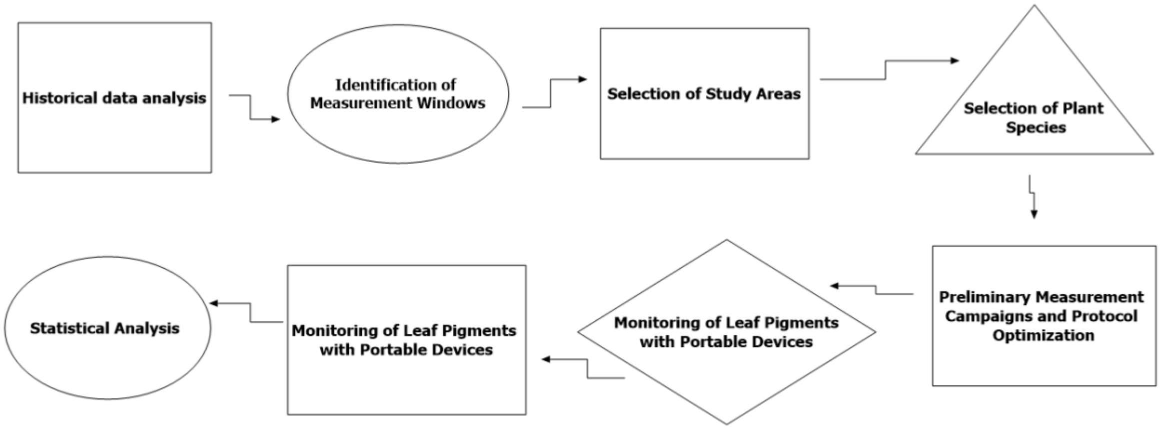

Fig.3 Flowchart

This flowchart (Fig.3) outlines the methodological process, combining innovative tools for urban green monitoring with statistical analysis to enhance understanding of plants' physiological responses to environmental stressors in diverse urban settings.

3.1 Description of case study

At the start of our research, we selected two distinct areas in the metropolitan city of Cagliari: a central neighborhood and a peripheral one (Fig.4). This choice aimed to cover a range of urban landscapes, enabling a thorough examination of Cagliari's Mediterranean ecological aspects. The selection was guided by the locations of ARPAS monitoring stations, strategically placed across the city to capture its diverse urban fabric. We defined a study area extending up to 1 km from each station, as data beyond this range becomes less representative.

Fig.4 The central area in Cagliari (Ca) and an urban peripheral area in Monserrato (Mo). The newly added third control area in the updated measurement protocol, located in Seulo (Se)

During the third measurement campaign, an additional background area (Se) was included, housing an ARPAS monitoring station in the "Maintenance Area." This station tracks background pollutant levels from natural sources and long-range transport, serving as a control zone. The area was selected for its minimal contamination and distance from major pollution sources.

4 Results

The post-winter campaign revealed increased chlorophyll levels (Dx Chl) in Quercus Ilex L. (Q1) at the central Cagliari site (Ca) (see Fig.5).

This trend suggests a plant response to mild pollution, consistent with previous observations (Molnar et al., 2023; Petrova 2011).

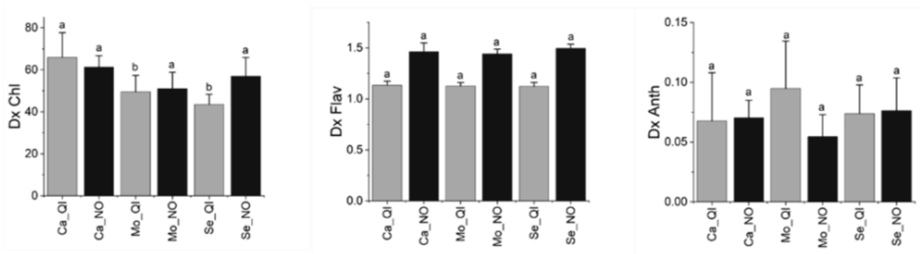

Fig.5 Dualex analysis of pigment physiological responses in Quercus Ilex L. (QI) and Nerium Oleander L. (NO) across Cagliari (Ca), Monserrato (Mo), and Seulo (Se). Values are presented as mean ± SD. Different letters denote significant differences at P <0.05

The measured levels of flavonoids (Dx Flav) (Fig.5) show consistent intraspecies behavior during the post-winter campaign, supported by the trend in the 1626 cm^{-1} Raman band (I1626, see Fig. 6). The lack of variation in both Dx Flav and I1626 suggests alternative adaptation mechanisms to urban stress.

The Dx Anth index (Fig.5) reveals very low, constant anthocyanin levels across locations, indicating no secondary metabolism response. Minimal differences in carotenoids, with an increasing trend from metropolitan areas (Ca, Mo) to the control zone (Se), were observed via the 1526 cm^{-1} Raman band (Fig.6), potentially indicating partial photosynthetic impairment in urban sites (notably for NO at Ca).

In summary, both Dualex and Raman analyses show homogeneous behavior in pigments, confirming the absence of secondary metabolism responses to pollutant levels and environmental variations. Instead, the species exhibit compensatory responses in pigments linked to photosynthesis.

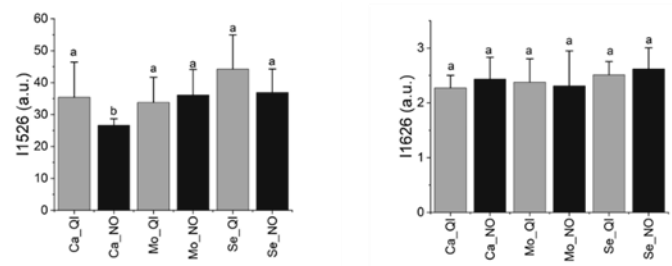

Fig.6 Raman signal intensities at 1526 cm^{-1} (I1526) ascribed to carotenoid content and at 1626 cm^{-1} (I1626) ascribed to total phenols content for *Quercus Ilex* L. (QI), *Nerium Oleander* L. (NO) in Cagliari (Ca), Monserrato (Mo), and in Seulo (Se). Each value represents the mean ± SE

NDVI measurements (Fig.7) partially align with Raman observations, showing poorer vegetation conditions—such as reduced plant vigor and canopy density—in plants located in Ca and Mo. This is attributed to the challenging environmental conditions they are exposed to.

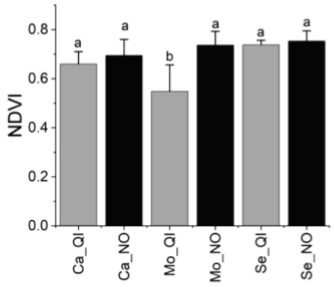

Fig.7 NDVI measurements in Cagliari (Ca), Monserrato (Mo), Seulo (Se). Each value represents the mean ± SE

Biometric data (Fig.8) show reduced leaf expansion in both QI and NO, along with decreased fresh and dry weights in NO plants from metropolitan areas. This reduction in leaf surface and weight indicates a morphological adaptation to protect plants from environmental variations and medium-high pollution levels.

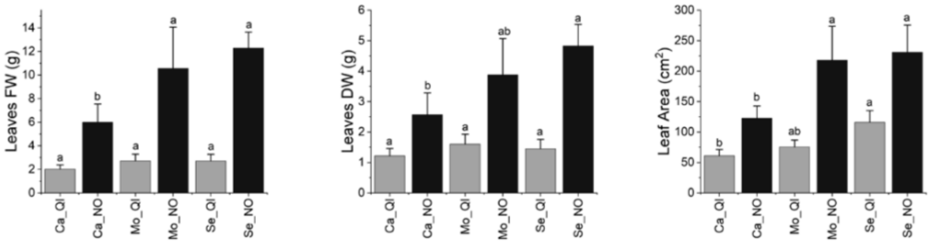

Fig.8 Fresh weight (FW), dry weight (DW), and Leaf Area of leaves in Cagliari (Ca), Monserrato (Mo), and Seulo (Se). Each value is represented as the mean ± SE

In general, these findings indicate that both plant species studied exhibit a notable degree of tolerance to the elevated pollution levels characteristic of urban environments.

4.1 Focus on the optical techniques proposed

Portable optical instruments, such as chlorophyll meters, spectrometers, and multispectral cameras, are increasingly used to monitor urban vegetation health. These lightweight, user-friendly tools provide immediate feedback on plant conditions, improving urban green space management.

GreenSeeker NDVI Sensor: An affordable device offering instant readings of plant greenness and vigor, with higher readings indicating better vitality.

Dualex: A portable tool measuring chlorophyll and flavonoid content in leaves, key indicators of plant health and stress resilience, using transmitted and fluorescent light.

Raman Spectroscopy: Provides detailed molecular composition analysis, offering a non-destructive "fingerprint" of plant health and stress levels.

These instruments enhance understanding and maintenance of urban greenery, supporting effective management and ecological functions.

5 Discussions and conclusions

The application of photonic methodology presents some limitations, such as the need for instrument calibration and validation of results against traditional methods. Although the portability of these tools is an advantage, it is essential to adopt standardized procedures to ensure consistent results. Additionally, extreme environmental conditions, such as high temperatures and humidity, can affect the accuracy of measurements. To overcome these limitations, it is useful to develop more robust calibration protocols and integrate photonic data with other sources, such as satellite data and air quality information, for a more comprehensive understanding of urban green health.

This research project adopts a multidisciplinary approach to develop an urban green monitoring protocol using portable optical instruments, incorporating additional environmental data such as soil information, atmospheric parameters, and pollution levels. The preliminary phases combined traditional and innovative tools, including the collection of plant biometric data and the use of portable devices, correlated with pollution data provided by ARPAS stations. This approach enables real-time, non-invasive analysis of how green spaces respond to a dynamic urban environment, providing policymakers with timely information for informed decisions.

As cities grow and the demand for sustainability increases, the use of these tools becomes crucial for integrating greenery into urban planning, offering benefits such as improved air quality and climate change mitigation. Understanding ecological dynamics is essential for urban development, and the use of portable tools represents a significant advancement in assessing the state of urban greenery, allowing for a more precise response to environmental conditions.

The results of this research have a direct impact on urban green space planning, thanks to the ability to conduct non-destructive analyses that preserve the integrity of vegetation. These tools enable repeated measurements over time, monitoring the physiological state of plants in response to pollution and climate variations. Portability facilitates on-site analysis, eliminating the risk of sample alteration during transport and providing real-time data. Furthermore, these instruments do not require complex infrastructure, making them suitable for widespread use in urban contexts.

The advantages of photonic instruments include greater data granularity, detecting variations at the individual plant level, and faster measurement and processing speeds compared to traditional methods. The multi-throughput capability allows for multiple insights from a single measurement, offering a comprehensive view of plant physiology. These tools are also easy to use, requiring minimal training, which promotes broader and more comprehensive monitoring.

The detailed data collected enables the identification of urban areas requiring targeted interventions, improving the planning and management of green spaces. The integration of these technologies supports strategic decisions on the placement and maintenance of greenery, ensuring its effectiveness as an environmental mitigator and enhancing the quality of life for citizens.

In summary, this study initiates an innovative approach to urban green monitoring, combining established and new technologies to provide real-time data. These tools enable more informed and effective management of green spaces, contributing to urban sustainability and resilience. Urban greenery is crucial not only for aesthetics and quality of life but also for addressing environmental challenges, promoting healthier and more adaptable cities for the future.

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Image Sources

Fig.1: Google Earth;

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He has been a research director at the Institute of Applied Physics of the CNR since 2021 where he carries out research and management activities in the field of optical spectroscopies for the development of biomedical diagnosis methods and agrifood applications. His research interests include: 1) biophotonic technologies, including advanced microscopy techniques (Confocal Fluorescence, Raman, AFM) for biomolecule characterization; 2) Raman spectroscopy and Surface-Enhanced Raman spectroscopy for monitoring altered human and plant health states; 3) Functional nanomaterials (gold and silver nanoparticles, graphene, biopolymers) that can be activated with laser radiation for applications in cell imaging and detection. He has been scientific Coordinator of several European and national projects on development of novel strategies based on optical sensing and co-authored more than 150 publications in international journals, scientific books and international proceedings.