Effects of Climate Change and Urbanization on Vegetation Phenology in the Bucharest Metropolitan Area

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Abstract: - Being an essential issue in global warming, the response of urban vegetation to climate change and urbanization has become an increasing concern at both the local and global levels. This study aims to investigate the effect of the urban environment on vegetation phenology for the Bucharest metropolitan area in Romania and to identify the potential climate drivers that influence key phenology in the urban environment. In this study, we comprehensively analyzed the response of urban vegetation phenology shifts due to climate variability and urbanization in the Bucharest metropolitan area from a spatiotemporal perspective during the 2002- 2022 period. Through synergy use of time series of the main climate variables, Air temperature -AT, land surface temperature (LST), and biophysical variables derived from MODIS Terra/Aqua satellite and in-situ data, this study developed a complex statistical and spatial regression analysis. Green space was measured with satellite-derived vegetation indicators Normalized Vegetation Index (NDVI), and Enhanced Vegetation Index (EVI), Net Primary Production (NPP) data, which captures the combined availability of urban parks, street trees, forest, and periurban agricultural areas. Leaf Area Index (LAI) and Photosynthetically active radiation (FPAR) indicators have been used to characterize the effects of meteorological parameters and urbanization impacts on vegetation phenology and their changes. The results show that the response of vegetation phenology to urbanization level and climate parameters variability has a distinct spatiotemporal difference across the urban/periurban gradient. The findings of this study show that the land surface temperature anomalies associated with urbanization-induced climate warming, especially during strong summer heat waves and under urban heat islands alter urban vegetation biophysical properties, directly impacting its phenology shifts. At the metropolitan scale, the urban thermal environment directly impacts vegetation phenology patterns. The quantitative findings of this study are of great importance for understanding the complex impacts of urbanization and climate changes on vegetation phenology and for developing models to predict vegetation phenological changes under future urbanization.

Key-Words: - climate changes, vegetation phenology, biophysical parameters, MODIS Terra/Aqua satellite data, Bucharest, Romania.

Received: April 26, 2023. Revised: July 15, 2023. Accepted: September 10, 2023. Published: September 27, 2023.

1 Introduction

Is well known that urban vegetation absorbs carbon dioxide - CO_2 as organic compounds through the mechanism of photosynthesis, regulating the global carbon cycle and energy exchange, [1]. Vegetation photosynthetic phenology is an ecologically sensitive indicator of seasonal and interannual changes in environmental conditions, related to the rhythm variation of its photosynthetic activity, and triggered by periodically changed environment, the temporal shift of photosynthetic phenology being responsible for the carbon balance of terrestrial ecosystems changes, [2]. In the frame of global warming and the increasing trends of extreme climate events, urban vegetation is affected by the increased levels of air temperature, atmospheric carbon dioxide (CO_2), and air pollutant concentrations, [3], [4]. Vegetation phenology acts as a control tool for urban cooling/warming effects and provides helpful information for future urban green space planning aimed at mitigating local climate warming, [5]. Urban ecosystems have remarkable human-induced characteristics, and urbanization has altered the sensible and latent heat fluxes over vegetation, causing apparent phenological shifts. Due to the highest concentration of human activity, causing the urban heat island (UHI) effect, [6], [7], [8], [9], cities can be considered ideal natural laboratories for predicting the response of vegetation phenology to regional and global warming. The response of vegetation phenology to climate changes and urbanization levels is an important issue of studies on complex interactions between urbanization and vegetation. Also, land surface vegetation and its spatiotemporal changes determine the radiation balance of the surface and affect the surface temperature and boundary-layer structure of the atmosphere. Due to anthropogenic and natural factors, urban vegetation land cover changes result in the land surface albedo changes. Recent studies highlighted that urbanization has both direct impacts on vegetation due to changes associated with the replacement of vegetated areas with build-up surfaces, and indirect impacts on vegetation related to the shifts of vegetation characteristics resulting from changes in climatic and environmental factors, [10]. The increase in urban impervious land cover surfaces can be used as a proxy for urbanization rate and assessment of its impacts on vegetation phenology as well as on induced impacts on long-term surface urban heat island intensity, [11]. On the other side, urbanization affects different climatic, especially the urban thermal environment, [12] and environmental factors that impact vegetation functions, [13]. The impact of air pollutants on urban vegetation has several aspects: with the increasing anthropogenic CO_2 emissions, the near-surface CO_2 concentrations in urban areas are enhanced, which may increase the vegetation productivity and growth through the stimulation of photosynthetic rates, while high concentrations of particulate matter -PM deposition on vegetation may have adverse effects on photosynthesis, [14]. Synergy's use of time series-derived satellite biophysical parameters and in-situ monitoring data can provide helpful information for urban vegetation phenology spatiotemporal dynamics. The rapid advance of satellite-to-earth observation technology provides a fast, systematic, cost-effective, and excellent configuration for processing large and complex spatial data. Remotely sensed phenological observations have become important for revealing the response and feedback of vegetation dynamics to global climate change, [15], [16], [17], [18], [19].

2 Materials and Methods

2.1 Study Site

The urban metropolitan region of Bucharest (Figure 1) capital of Romania is located in the South – Eastern part of the country, and South-Eastern part of Europe, being bounded by latitudes 44.33 ^{O}N and 44.66 ^{O}N and 25.90 ^{O}E and 26.20 ^{O}E longitudes. Its center is situated at 44.4355381 ^{o}N Latitude and 26.100049 ^{o}E Longitude. It has about 1.8 million inhabitants. According to the European Commission urban vegetation land cover represents 5.6% of the total territory of the urban core, [20]. In Bucharest, the green space is very low as compared with other European metropolises like Paris, London, and Brussels, where urban/periurban vegetation land cover is placed in the range (7.37 - 20.84) m^2/capita. From 1993 year till 2020 the metropolitan vegetation land cover in Bucharest has decreased, from 4839 ha in 1993 to 4506 ha, [21]. This large area covers multiple urban-to-rural transition areas and consists of different vegetation types (shrubs, grass, forest, crops, etc.). Additionally, the metropolitan area has a diverse landscape pattern in terms of the spatial distribution of various land cover types, with flat plain areas. Satellite remote sensing time series data can be used to gather data on the urban vegetation density, the size of the land area, and field conditions.

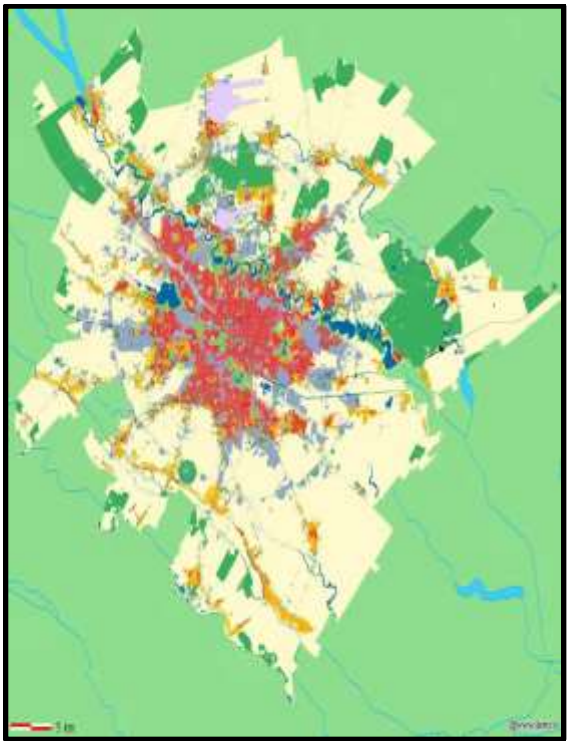

Fig. 1: Bucharest test site, capital of Romania

The study test area includes Bucharest city and the surrounding periurban areas with very complex environments (built, green, and blue structures), under a rapid urbanization process, and one of the most air-polluted cities in Europe. Its climate is temperate continental, with Western European Climate influences, Mediterranean Cyclones, and the East-European Anticyclone.

2.2 Data Sets

Daily time series of average daily meteorological data, including air temperature at 2m height (T), air relative humidity (RH), air pressure (p), wind speed intensity (w), and direction, for the Bucharest metropolitan region were collected from the Modern-Era retrospective analysis for Research and Applications, Version 2 (MERRA-2) at, [22], and, Climate Change Service of Copernicus (C3S) data, [23]. This study focused on estimating Bucharest metropolis vegetation land cover phenology dynamics using time series MODIS Terra data for the 2002-2022 period. The analyzed period has registered several heat wave periods, of which the summers of 2003, 2007, 2010, 2012, 2017, and 2022 have been the highest. We used time series MODIS Terra products: 8-Day L3 Global 1km SIN Grid land surface temperature (LST)/emissivity MOD11A2/LST_Day_1km, 16-day MODIS 13Q1/250m_16_days_NDVI/EVI composites with a 250 m spatial resolution, and MODIS Tera Leaf Area Index (LAI) MOD15A2H MODIS/Terra Leaf Area Index/FPAR 8-Day with 500m spatial resolution, mainly for their capacity to detect anthropogenic and climate impacts on urban vegetation land cover changes. Also, we used MODIS Terra/Aqua phenology data for both cycles 1 and 2 data. Missing values were replaced by linear interpolation considering neighboring values within the LST, NDVI/EVI, LAI, and FPAR time series. Landsat ETM+ 17/07/2022 image was used for validation and training. Have been selected 6 periurban and 6 urban test areas corresponding to the six sectors of Bucharest city, a central Bucharest test area, and the entire metropolis test area. In situ-monitoring data with GER-260 spectroradiometer additional data, as well as meteorological observational data have been used. Statistical analysis through Spearman rank correlation coefficients was used. ENVI 5.7, e-cognition, and ORIGIN 11 software have been used.

2.3 Statistical Analysis

For similarity between two-time series data of the averaged daily air pollutants, climate observables (air temperature and relative humidity, wind speed, surface solar irradiance Planetary Boundary Layer heights), in Bucharest, this study used Spearman cross-correlation analysis and non-parametric test coefficients as well as linear regression analysis. For assessment of the normality of the averaged daily time-series data sets, Kolmogorov-Smirnov Tests of Normality were used. Because the daily climate variables have a non-normal distribution, Spearman rank correlation was selected to identify the linear correlation between the important variables: (1) air pollutants PM2.5, PM10 concentrations, climate variables, and ORIGIN 11.0 software version 2023 for Microsoft Windows was used for data processing.

3 Results and Discussion

Bucharest city, the capital of Romania had an intense and rapid periurban development after 1990, and the boundaries of the functional urban region have shifted outwards from the urban core. The rapid urbanization of the Bucharest metropolitan area may be responsible for the recorded higher air and land surface temperatures associated with UHIs and HW_S during summer periods due to vegetation land cover reduction and increase of impervious surfaces. According to Copernicus Urban Atlas land use land cover (LULC) in 2018 distribution (km^2) for Bucharest metropolitan region shows: artificial area was 33.6%, agricultural area 53%, natural areas 10.7%, wetland 0.2%, and water 2.4%. This study used spatiotemporal analysis of time series MODIS Terra/Aqua NDVI, EVI, LAI, FPAR, LST, NPP, and vegetation phenology indicators for analysis of urban vegetation phenology in the Bucharest metropolitan area during 2002-2022 years. The main objective of this study was to establish whether a significant correlation exists between these indices and other factors. The synergy of Heat Waves and Urban Heat Islands (UHI) effects increases the air and land surface temperature in densely populated metropolitan areas, making urban areas more predisposed to heat stress compared with rural areas.

3.1 Impact of Air Temperature and Land Surface Temperature on Urban Vegetation

During the summer season (June-August), the rank correlation analyses at the metropolitan pixel scale (40.5km x 40.5 km) revealed that TA and LST present a strong positive correlation ($r = 0.86\%$, $p<0.01$). Land Surface Temperature (LST) is a significant radiative skin parameter of the ground, that provides essential information on surface-atmosphere interactions and energy fluxes between the atmosphere and the ground in the urban/periurban areas. Gross Primary Production (GPP) and Net Primary Production (NPP) represent vegetation productivity. Figure 2 shows the annual rates of Net Primary Production at 500m spatial resolution from MODIS Terra data for the 2002-2022 period and evidences the clear decreasing trends of urban vegetation phenology during recorded summer HWs of years 2000, 2003, 2007, 2012, 2016 and 2022. During the recorded summer heat wave events in Bucharest metropolitan region, the average extracted net radiation was in the range of 896- 999 Wm^{-2}. At the microscale, surface albedo and temperature should have a large variety in the selected six urban sectors because of the large material and structural versatilities. The storage heat flux exceeds the sensible heat flux in urban areas, whereas the sensible heat flux is higher than the storage heat flux in industrial areas. In particular, negative storage heat flux appears at a number of industrial points, [24]. This tendency shows that high surface temperature in the periurban industrial areas of Bucharest is induced by mass energy consumption because most of the anthropogenic heat discharge is transferred to the atmosphere as sensible heat. Figure 3 presents the temporal distribution of NDVI and LST over the Bucharest metropolitan area during the 2002-2022 period.

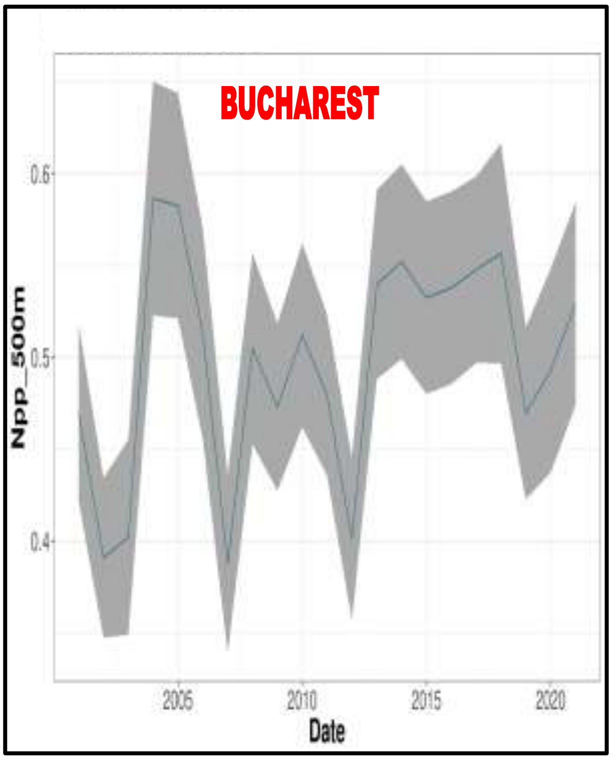

Fig. 2: Temporal pattern of Net Primary Production of Bucharest vegetation during the 2002-2022 period

Based on the spatial and seasonal (spring and summer) distributions of LST–NDVI relations over Bucharest metropolitan area (40.5km x 40.5 km), using long-term (2002–2022) MODIS Terra images, this study found that relations between LST and NDVI/EVI were highly diverse among the various urban/periurban biomes and seasons throughout the entire study period. So, during the spring season March–May), LST-NDVI presents the dominance of significant positive correlation (Spearman rank correlation coefficient $r=0.71$; $p<0.01$ for metropolis area), while during the summer season (June–August), most of the vegetation test areas turned to negative correlation (for metropolis areal $r= -0.68$, $p<0.01$). For the autumn and winter seasons, LST shows positive correlations with NDVI/EVI ($r= 0.62$ and $p<0.01$ for the metropolis area). This study demonstrates that the drought/vegetation/stress spectral indices, based on the prevalent hypothesis of an inverse summer LST–NDVI correlation are spatially and temporally dependent.

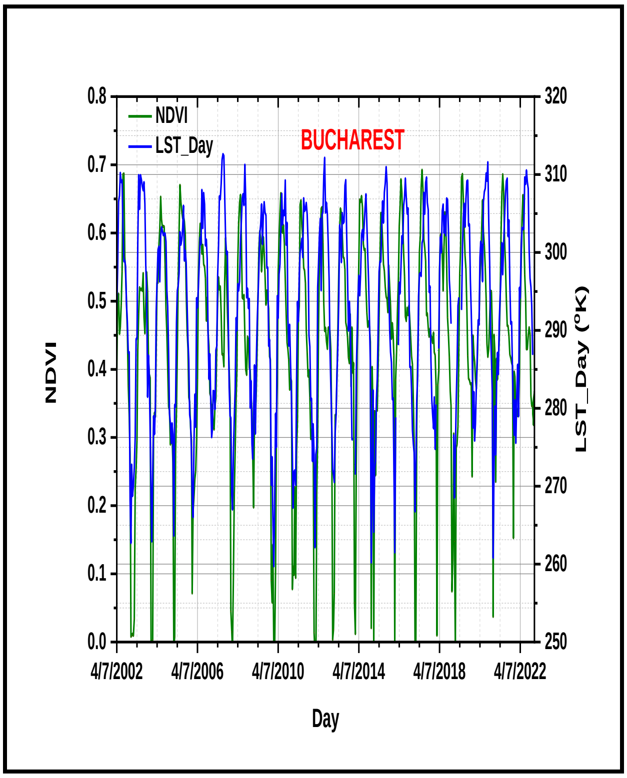

Fig. 3: Temporal patterns of daily average MODIS LST (°K) and NDVI during 2002-2022 for the Bucharest metropolitan area.

Figure 4 presents the temporal distribution of FPAR and LAI over the Bucharest metropolitan area during the 2002-2022 period. Statistical analysis shows positive significant correlations between land surface temperature both day and night with FPAR (Spearman rank correlation coefficient LSTDay-FPAR r=0.87; p<0.01, and LST_{Night}-FPAR r=0.85; p<0.01, for metropolis areal). Also, LST exhibits lower positive correlations with LAI for both day and night monitoring data (Spearman rank correlation coefficient LST_{Day}-LAI r=0.20; p<0.01, and LST_{Night}-LAI r=0.25; p<0.01, for metropolis areal). Spearman rank correlation coefficients between LST and evapotranspiration- ET present moderate positive values (LST_{Day}-ET r=0.32; p<0.01, and LST_{Night}-ET r=0.39; p<0.01, for metropolis areal).

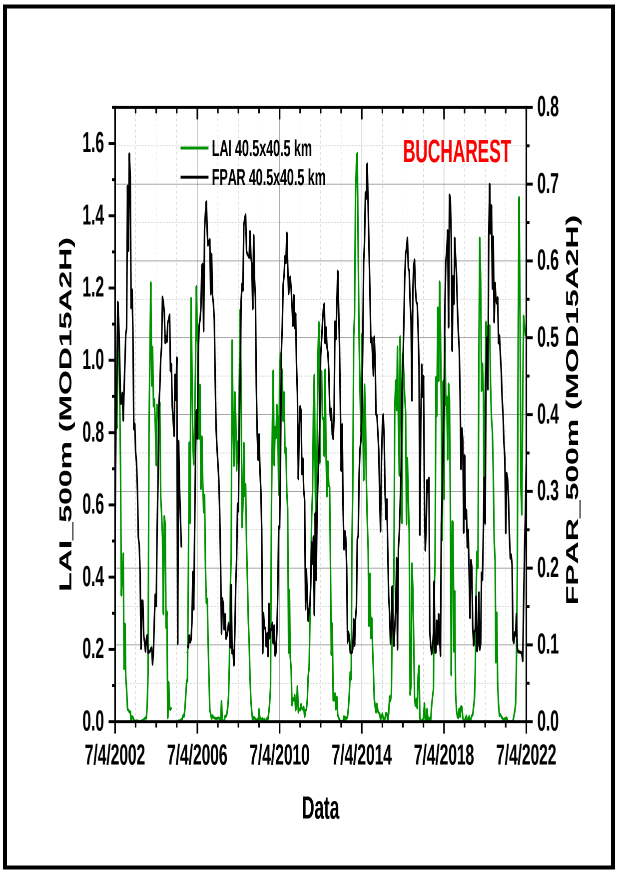

Fig. 4: Temporal patterns of daily average MODIS LAI and FPAR during 2002-2022 for the Bucharest metropolitan area.

3.2 Urban Vegetation Phenology Evolution

Time series satellite remote sensing data provide a useful tool for spatiotemporal observations of the land surface, making it essential for urban vegetation phenology study across large geographic areas. From MODIS Terra available MOD17A3HGF products, during analyzed 2002-2022 period urban vegetation phenology showed different temporal patterns per cycles 1 (spring) and 2 (autumn), the changes been triggered by climate changes being influenced by alterations in meteorological conditions at micro- and mesoscale as a result of urbanization and the intensification of anthropogenic activities in Bucharest metropolitan region (as can be seen in Figure 5 and Figure 6). Like other studies, [25], [26], [27], the figures in this article found different yearly changes (advanced or delayed) in the average start of the vegetation in spring and autumn seasons date of selected years during the period 2002-2022. Although differences were also observed for the end and length of the growing season, these patterns showed great interannual variability of urban vegetation phenology corresponding to different stages (Greenup, Maturity, MidGreendown, MidGreenup, and Peak). The analysis of more specific vegetation classes enables a better understanding of the phenological response of vegetation to urbanization intensity. Also, the sensitivity of vegetation productivity to air temperature, precipitation rate, soil moisture, and solar surface irradiance are the key metrics for understanding the variations in vegetation productivity under changing climate and predicting future changes in ecosystem functions, [28], [29].

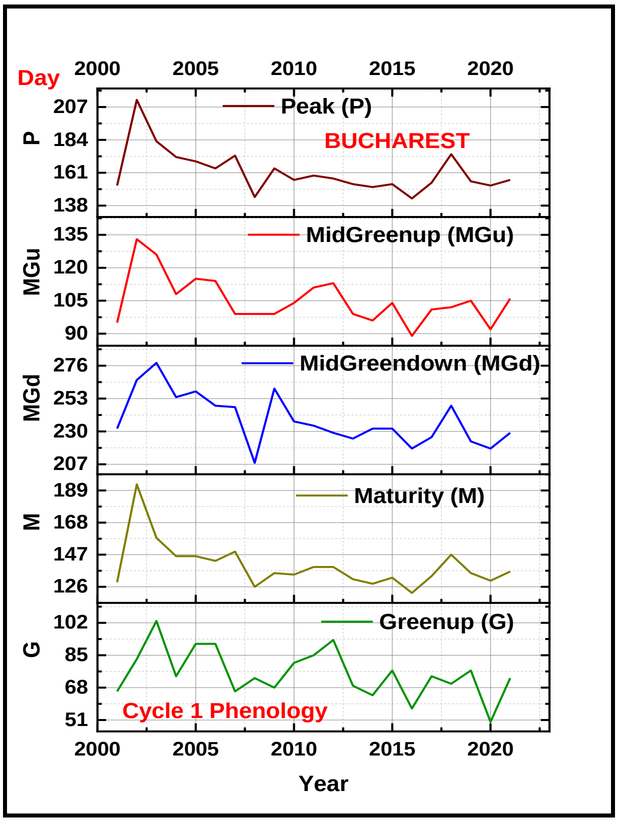

Fig. 5:Temporal pattern of the vegetation phenology during cycle 1 in Bucharest metropolitan region.

Is considered that solar-induced chlorophyll fluorescence is a great proxy for vegetation productivity in urban and all terrestrial ecosystems. Among several factors that directly and indirectly affect vegetation productivity the most important are: meteorological and hydrological conditions; increasing carbon dioxide (CO_2) concentrations drive enhanced vegetation productivity) and also lead to rising temperatures; soil nutrient availability determines potential vegetation productivity, [30], [31], [32].

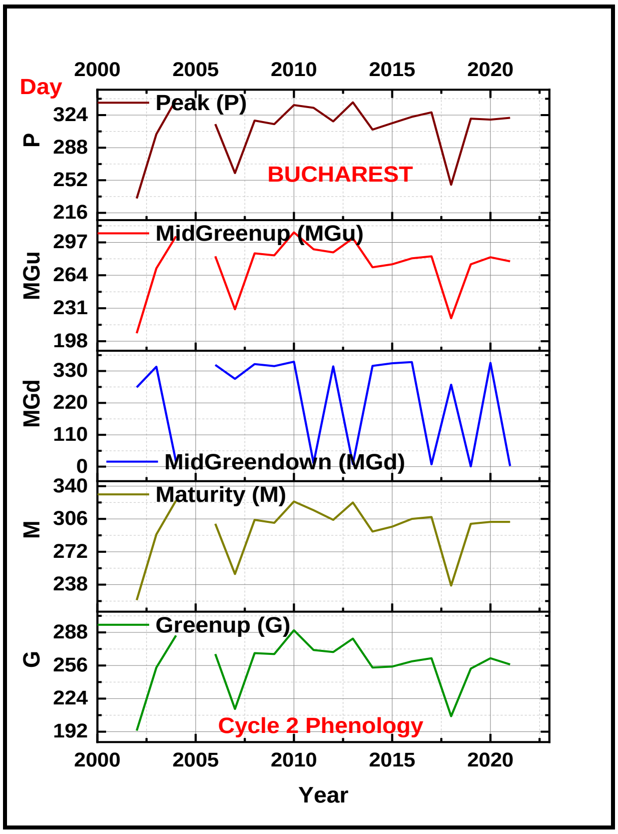

Fig. 6: Temporal pattern of the vegetation phenology during cycle 2 in Bucharest metropolitan region.

4 Conclusion

Climate warming, air pollution, and heatwaves (HWs)-related drought events could become a major driver of large-scale urban vegetation dieback. The main contributions of this study consist in: (1) the investigation of the effect of the urban environment on vegetation phenology for the Bucharest metropolitan region in Romania, and (2) identifying the main potential drivers that influence key phenology in the urban environment. Also, urban temperate deciduous and broadleaf forests placed in Baneasa, Cernica-Branesti, and Snagov areas have been affected by the rise of summer HWs temperatures through significant disturbances. In the next decades is expected as climate change to trigger significant changes in urban vegetation phenology, air and land surface temperature, and soil moisture, altering the urban ecosystems. The novelty of this research was the use of the time series MODIS Terra/Aqua remotely sensed observations to assess the importance of phenology and environmental factors on vegetation productivity indicating that phenology was the dominant driver during the investigated period, despite the differences in the importance of land surface temperature. The results of this study support the hypothesis that urbanization produces significant differences in plant phenology in Bucharest metropolis, and points to contrasting responses by different functional vegetation types. Although differences were also observed for both the end date and length of the growing season between vegetation types, these patterns showed great inter-annual variability. The analysis of different time series remotely sensed data and meteorological/hydrological data provide the trends of spatial patterns of increased land surface temperature-LST, decreased soil moisture, and lengthened phenology.

Acknowledgments:
This work was supported by the Romanian Ministry of Research, Innovation and Digitalization: through Program 1- Contract no. 18PFE/30.12.2021; National Research Development and Innovation Plan 2022-2027, project no. PN 23 05; Grant CNCS-UEFISCDI, project number PN-III-P4-PCE-2021-0585; Romanian Ministry of European Investment and Projects & Romanian Ministry of Research, Innovation and Digitalization, Contract no.8/1.2.1 PTI ap.2/17.02.2023

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Maria Zoran: Conceptualization; Methodology, Supervision, Writing - review & editing.
- Roxana Savastru: Methodology, Validation, Review.
- Dan Savastru: Methodology, Validation, Review. Marina Tautan: Methodology, Validation.
- Daniel Tenciu: Software.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This work was supported by the Romanian Ministry of Research, Innovation and Digitalization: through Program 1- Contract no. 18PFE/30.12.2021; National Research Development and Innovation Plan 2022-2027, project no. PN 23 05; Grant CNCS-UEFISCDI, project number PN-III-P4-PCE-2021-0585; Romanian Ministry of European Investment and Projects & Romanian Ministry of Research, Innovation and Digitalization, Contract no.8/1.2.1 PTI ap.2/17.02.2023

Conflict of Interest

The authors have no conflict of interest to declare.