Linking urbanization with air pollution and thermal environment in Bucharest metropolis

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ABSTRACT

In frame of the global warming and urban growth, Bucharest residents and its ecosystem will be more vulnerable to increased levels of air pollution and heat stress related to urban heat island (UHI) effect and the increased frequency and duration of heat waves (HWs) during summer June-August months. The response of air quality to climate change is an increasing concern at both the local and global levels. This study examined the response of urban thermal environment to air pollution and climate variability in Bucharest, Romania, from a spatiotemporal perspective during the 2020-2023 period. Through synergy use of time series of geospatial and in-situ air pollution (particulate matter $PM_{2.5}$ and PM_{10}, O_3, NO_2, SO_2, CO), and climate data in relation with derived vegetation biophysical variables, this study developed a complex statistical and spatial regression analysis. Was quantified air pollution relationship with urban thermal environment defined by land surface temperature-LST and air temperature at 2m height AT. Green space was measured with MODIS Terra satellite-derived normalized vegetation index- NDVI, which captures the combined availability of urban parks, street trees, forest, and periurban agricultural areas. A distinct spatiotemporal difference across the urban/periurban gradient, air temperature -TA and land surface temperature -LST anomalies is associated with urbanization-induced climate warming, especially during summer UHIs and HWs. The findings of this study contribute to developing advanced models to predict air pollution impacts on urban heat under future urbanization, and also in urban planning for better mitigation and optimizing air quality in future green cities.

Keywords: air pollution, urban thermal environment, biophysical parameters, time series MODIS Terra/Aqua satellite data, Bucharest, Romania.

1. INTRODUCTION

Urban elevated land surface temperatures (LST) and air pollution are recognized as the primary challenges of rapid urbanization. Due to the conversion of natural land into impervious surfaces, the quantity of vegetation has decreased. This change in land surface properties resulted in a decline in the land surface albedo, an increase in heat storage capacity, and an increase in the Bowen ratio, representing the ratio between sensible and latent heat fluxes [1]. Numerous metropolitan areas are experiencing rapid urbanization, increase in population and anthropogenic pollution sources such as burning fossil fuels, disposing of waste by open burning on streets or at landfill sites, and increased emissions due to vehicular traffic and industrial operations. As a result, primary air pollutants, including particulate matter (PM2.5), nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon monoxide (CO), are expected to rise[2]. Urbanization has led to the concentration of vehicular traffic, that in some cities ranks as the second largest contributor to air pollution and urban heat source[3]. A consequent effect will be a serious impact on local and regional climate due to air pollutants in the lower atmosphere and alteration of the effective surface albedo (the fraction of radiative flux reflected by a surface to the atmosphere, which leads to local phenomena such as urban heat islands (UHIs). In the physical climate system, land surface determines the radiation balance of the surface and affects the surface temperature and boundary-layer structure of the atmosphere. Also, the urban overheating during summer heat waves needs the implementation of mitigation actions.

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Urban heat island phenomenon, that cause a serious impact on human health, is characterized by higher ambient temperatures in the dense parts of the cities compared to their surrounding environment It is generated by the positive thermal balance in the urban built environment attributed to the excessive absorption of solar radiation by the impervious surfaces, the release of anthropogenic heat, the reduced evapotranspiration and surface permeability, and the lack of urban ventilation. Due to anthropogenic and natural factors, urban land covers changes result is the land surfaces albedo changes[4]. Both urban microclimates and outdoor thermal environment depend not only on the regional climate at a large scale, but at local scale are also linked to the features of the urban built environment (its form and fabrics). The urban thermal environment is under the influence of city spatial structure characteristics, landuse/land cover, and landscape patterns. Due to the increased urban heat island phenomenon, the urban thermal environment will be gradually deteriorated, which affects the quality of urban human health, being related to urban energy consumption, ecosystem operation, vegetation phenology, and sustainable city economy[5]. For urban thermal environment characterization, this study used MODIS Terra/Aqua derived land surface temperature LST, which is an important parameter to characterize the land surface changes and the spatiotemporal pattern and influencing factors. Green space was measured with MODIS Terra/Aqua satellite-derived vegetation index normalized vegetation index (NDVI), which captures the combined availability of gardens, street trees, parks and forest. Was assessed the variability in urban vegetation land cover cooling impacts on city thermal environment a function of sunlight and vegetation moisture content, with surface solar irradiance and the cooling variability of vegetation characteristics described by Leaf Area Index (LAI) and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) across the metropolis' selected sectors. Urban green and reflective urban surfaces can improve the urban thermal environment through reducing urban heat. Although several studies have described the spatial pattern and influencing factors of the urban thermal environment, the relationship between the air pollution impact on urban thermal environment in Bucharest has not yet been established. This study conducted a spatiotemporal analysis of urban biophysical parameters in their interaction with climate changes and extremes using time series of MODIS Terra/Aqua data during 2000-2023 period in the metropolitan area Bucharest. To address these issues this work focuses on the influences of urban growth and climate change impacts on urban thermal environment in relationship with several biogeophysical variables in Bucharest metropolitan area. Also, this paper considers potential change in urban environment due to climate change and land cover management practices. However, in frame of climate variability and the increasing rate of extreme events, the complex temporal and spatial characteristics of air pollution in urban areas pose a great challenge for its monitoring, prediction, and control. This work investigated the spatiotemporal air pollution patterns and its correlation with urban thermal environment parameters in Bucharest metropolitan area, and capital of Romania.

2. STUDY TEST SITE AND DATA USED

Bucharest (Fig. 1), the capital of Romania, situated in southeastern Europe, centered at 44.43°N and 26.10°E longitude, has approximately 1.8 million inhabitants and covers an area of 240 km^2. Bucharest city has 6 sectors with a population density ranging from 3548 to 13 915 inhabitants/km^2.The test area includes the city of Bucharest and the surrounding periurban areas with complex landcover environments (built, green, and blue structures), and ongoing urbanization. The periurban area covers approximately 543 km^2 and has approximately 0.81 million inhabitants. The periurban population density ranges from 60 to 160 inhabitants/km^2. After the communist regime in 1990, due to urban growth the metropolitan vegetation landcover decreased from 4839 ha in 1993 to 4506 ha in 2020. Local climate is of temperate continental type, with very hot summers during June-August, especially during heat waves, and cold humid winters during December-February. Urban growth and associated urban heat island phenomenon together with the increased frequency of summer heat waves is responsible for a rising trend in air temperature conditions. In addition to human health, high levels of atmospheric pollution also affect natural ecosystems and have been causing changes in ecological patterns and biodiversity processes.

Daily average time series data of air pollutants concentrations PM2.5, PM10, O_3 and NO_2 for Bucharest were provided by available Copernicus and Air pollution Network in Bucharest [6,7] . Free available data on climate were collected in this study. We used the daily time series of meteorological data, including air average temperature at 2 m height, air pressure, air relative humidity, average wind speed intensity and direction provided by MERRA-v2 [8], and Copernicus Climate Change Service (C3S) datasets [9], as well as from the National Administration of Meteorology in Romania. From the MODIS-NASA platform [10] a time series of MODIS Terra/Aqua [11] parameters (land surface temperature (LST), normalized vegetation index (NDVI) and land surface albedo (LSA) were used for the period 2020-2023. Has been used information on urban land cover changes between 2012-2018 years [12, 13]. Two study areas were selected inside

Bucharest metropolis (the city center defined as 6.5x6.5 km size, and the metropolitan area of 40.5x40.5 km). In situ monitoring spectroradiometric data and meteorological observational data were used to verify the MODIS data.

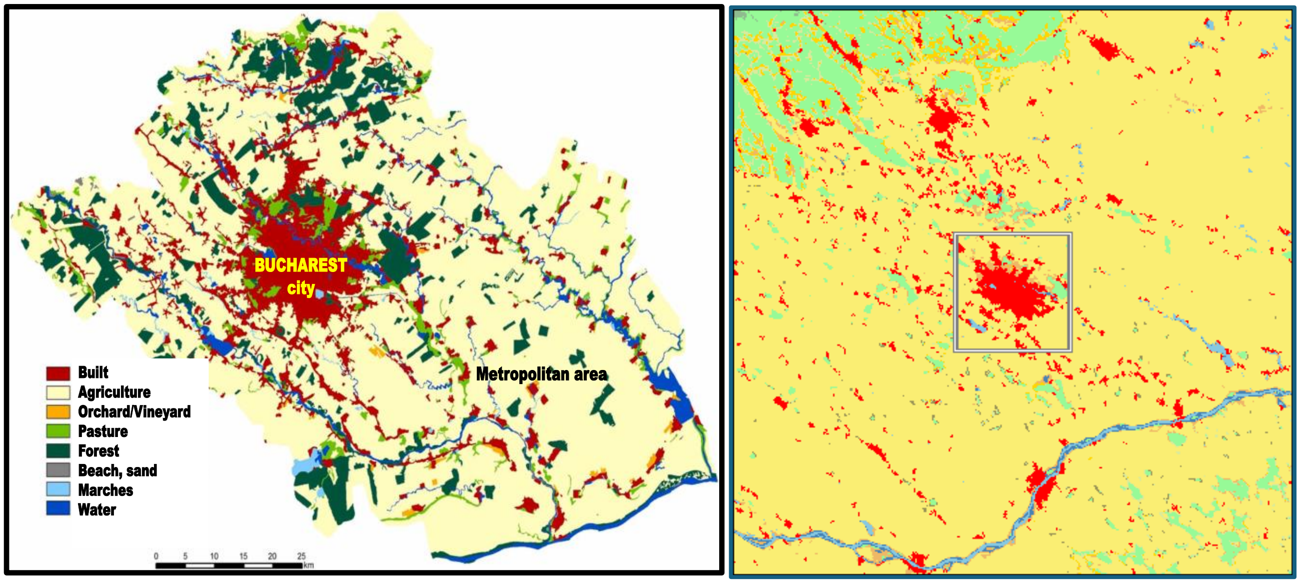

Fig. 1. Bucharest city on Bucharest metropolitan test area, and investigated test area 40.5 km x 40.5 km.

3. STATISTICAL ANALYSIS USED

For similarity between two-time series data of the averaged daily air pollutants, climate observables (air temperature at 2 m height- AT and air relative humidity- RH, wind speed-w, surface solar irradiance -SI and Planetary Boundary Layer height-PBL with land surface temperature-LST, and normalized vegetation index-NDVI and land surface albedo -LSA 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 was used Kolmogorov-Smirnov Tests of Normality. ORIGIN 10.0 software version 2021 for Microsoft windows, and ENVI 5.7 software have been used for data processing.

4. RESULTS AND DISCUSSION

4.1. Land surface temperature impact on local climate

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 urban/periurban areas. From MODIS Terra time series data is clear that LST is very well correlated with air temperature at 2 m height under clear-sky conditions. During 2020-2023 period, the rank correlation analyses at the metropolitan scale revealed that both day (LST_Day) and night (LST_Night) present strong positive correlations ($r=0.91$, $p<0.01$ and $r=0.93$, $p<0.01$, respectively). Figure 2 presents the temporal variation of LST_Day and average daily 2 m air temperature in Bucharest metropolitan area. As can be seen in Table 1, LST is positive correlated with air temperature and planetary boundary layer height. Based on time series analysis of MODIS Terra satellite data, this study shows diverse relations between LST and NDVI among the various urban/periurban biomes and seasons in 2020-2023. In the spring (March–May), LST-NDVI showed the dominance of significant positive correlation (Spearman rank correlation coefficient $r=0.89$, $p<0.01$ for the city center;

and r=0.68; p<0.01 for the metropolitan area), during the summer (June–August), most of the vegetation areas show a negative correlation (for city centre r=-0.25, p< 0.05; and for metropolitan area r=-0.65, p<0.01).

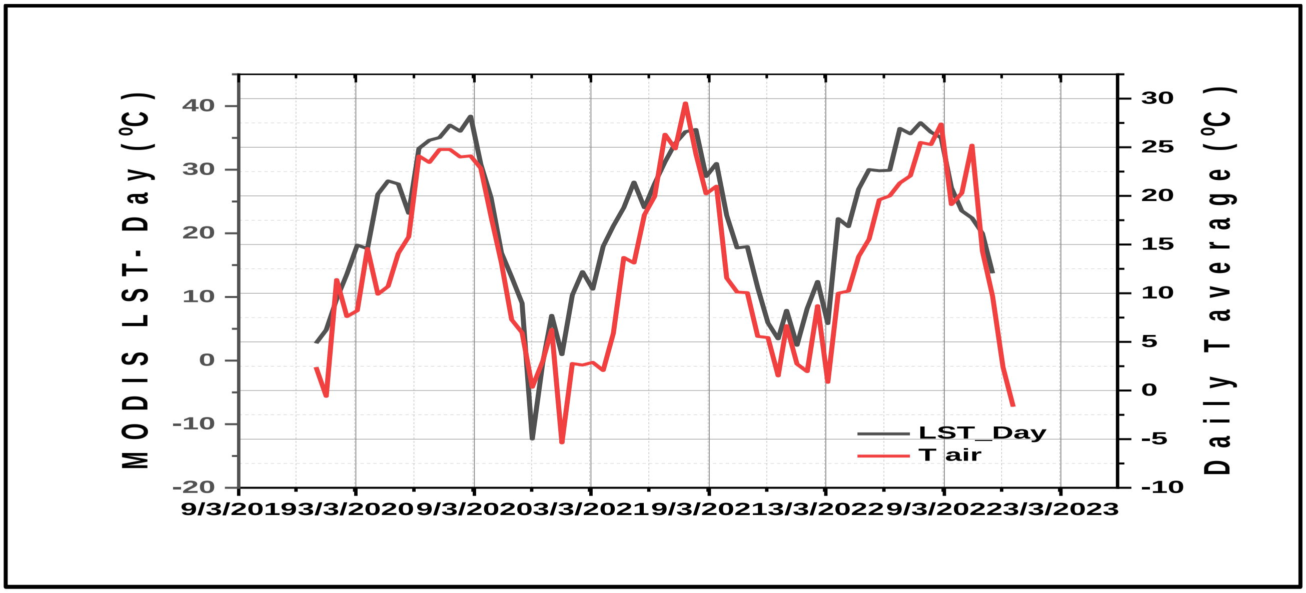

Figure 2. Temporal pattern of LST_Day and average daily 2 m air temperature in Bucharest metropolitan area during 2020-2023.

For autumn and winter seasons, LST correlations with NDVI were positive in the range of r=0.45 to r=0.67 and p<0.01 for city center and metropolitan areas, respectively. For the entire investigated period, values were negative correlated. Based on the prevalent hypothesis of an inverse summer LST–NDVI correlation, this study demonstrated the spatially and temporally dependence of drought/vegetation/stress spectral indices.

Figure 3 presents the temporal variation of land surface temperature recorded by MODIS Terra satellites during day LST-Day and during night LST-Night during 2020-2023 period in Bucharest metropolitan area.

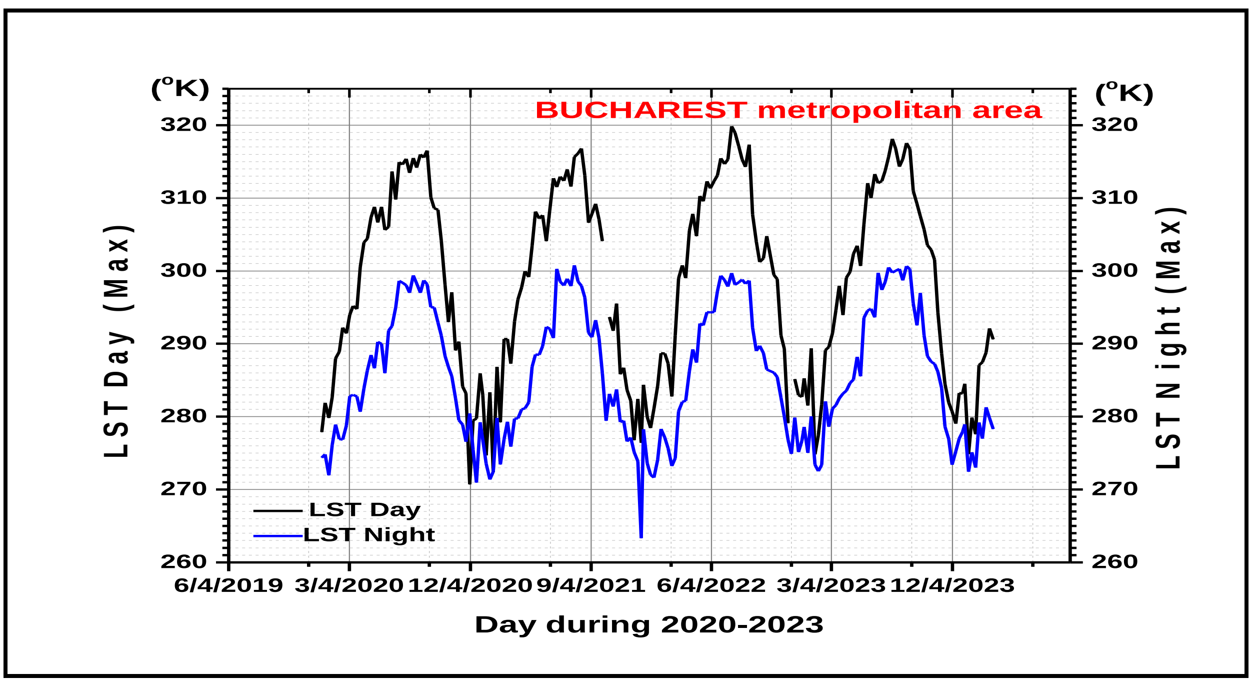

Figure 3. Temporal patterns of MODIS Land Surface Temperature Day and Night for Bucharest metropolitan area (40.5 km x 40.5 km)

during 2020-2023 period.

Table 1. Spearman correlation coefficients between LST in Bucharest area and meteorological parameters during 2020-2023.

LST (ºC)	NDVI 6.5 km x 6.5 km	NDVI 40.5 km x 40.5 km	LSA Land Surface Albedo	TA (ºC) Air Temperature at 2m height	PBL Planetary Boundary Layer height (m)
LST_Day	0.88	0.64	-0.58	0.91	0.79
LST_Night	0.86	0.64	-0.57	0.95	0.71

4.2 Air pollution and air temperature impacts on urban/periurban vegetation

Besides air pollution effects on urban/periurban vegetation, climate variability and the increased frequency of extreme climate events have a high negative impact on urban ecosystem of Bucharest [14-19]. According to the European Environment Agency , Bucharest has a low percentage of urban green and blue spaces, compared with the other European capitals, being ranked as 31 of the 37 analyzed cities. The green space of Bucharest city is represented by few parks, forests, sports areas, cemeteries, and small urban green areas, such as gardens, street alignments or green roofs, while periurban green areas included in the metropolitan area have mostly agricultural, forest and gardens. Meteorological parameters variability has a high impact on urban/periurban vegetation and vegetation feedbacks play a key role in climate regulation by cooling and humidifying processes of urban areas [20-24]. During 2020-2023 period normalized vegetation index- NDVI presented a Spearman rank positive correlation with air temperature TA at both central area of Bucharest ($r= 0.85$; $p< 0.01$) as well as at metropolitan scale ($r= 0.69$; $p< 0.01$), explaining the effect of heat island of the city center. This result is illustrated also in the Figure 4, which shows the temporal variation and seasonality of NDVI and TA during the study period.

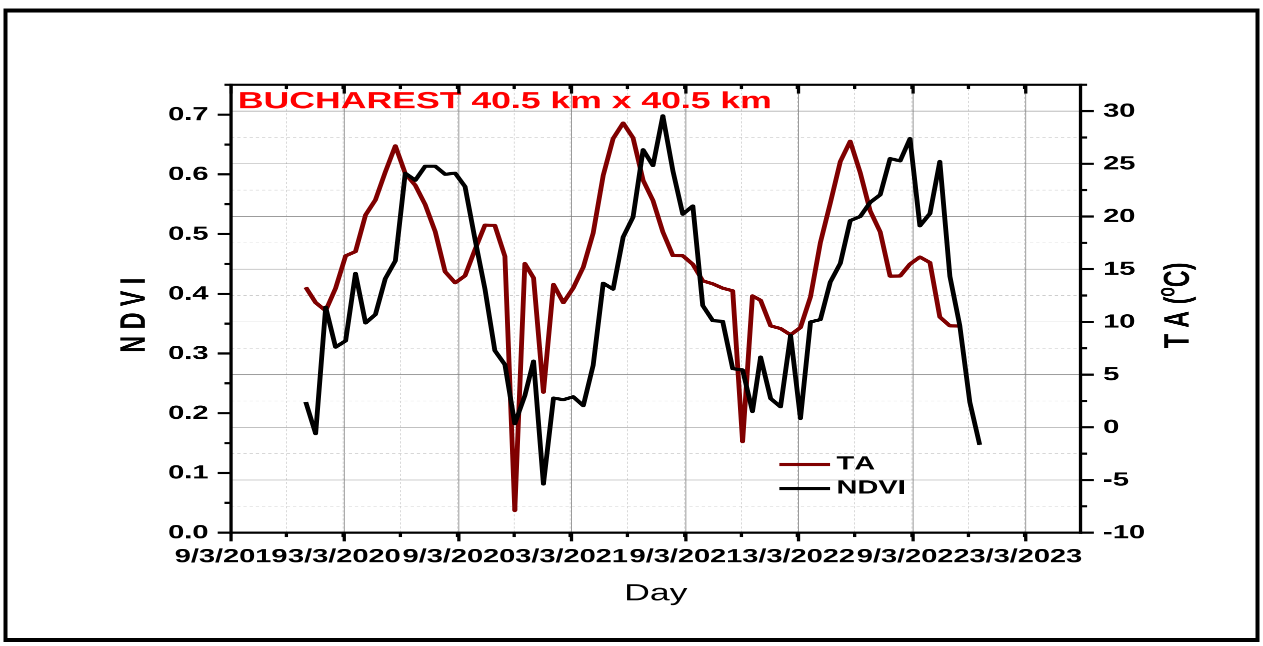

Figure 4. Temporal variation and seasonality of NDVI and TA during 2020-2023 study period.

A similar finding is presented by the temporal pattern and seasonality variability of land surface albedo LSA function of land surface temperature LST from MODIS Terra time series data in Figure 5. This study found also Spearman rank positive correlation between NDVI, TA, planetary boundary layer height PBL with LST_Day and LST_Night in

Bucharest metropolitan area (Table 2.) and city center defined by 40.5 km x 40.5 km and respectively 6.5 km x 6.5 km surfaces, supporting the effect of heat island in the city center of Bucharest. An inverse correlation was found between NDVI with air relative humidity RH and land surface albedo LSA.

Table 2. Spearman correlation coefficients between NDVI in Bucharest central city/metropolitan area and climate parameters

NDVI	TA (ºC)	RH (%)	PBL (m)	LST (ºC)	LSA
NDVI central Bucharest 6.5 km x 6.5 km	r= 0.85 $p<0.01$	r= -0.67 $p<0.01$	r= 0.70 $p<0.01$	r= 0.86 $p<0.01$	r= -0.55 $p<0.01$
NDVI metropolitan Bucharest 40.5 km x 40.5 km	r= 0.69 $p<0.01$	r= -0.42 $p<0.01$	r= 0.63 $p<0.01$	r= 0.63 $p<0.01$	r= -0.31 $p<0.01$

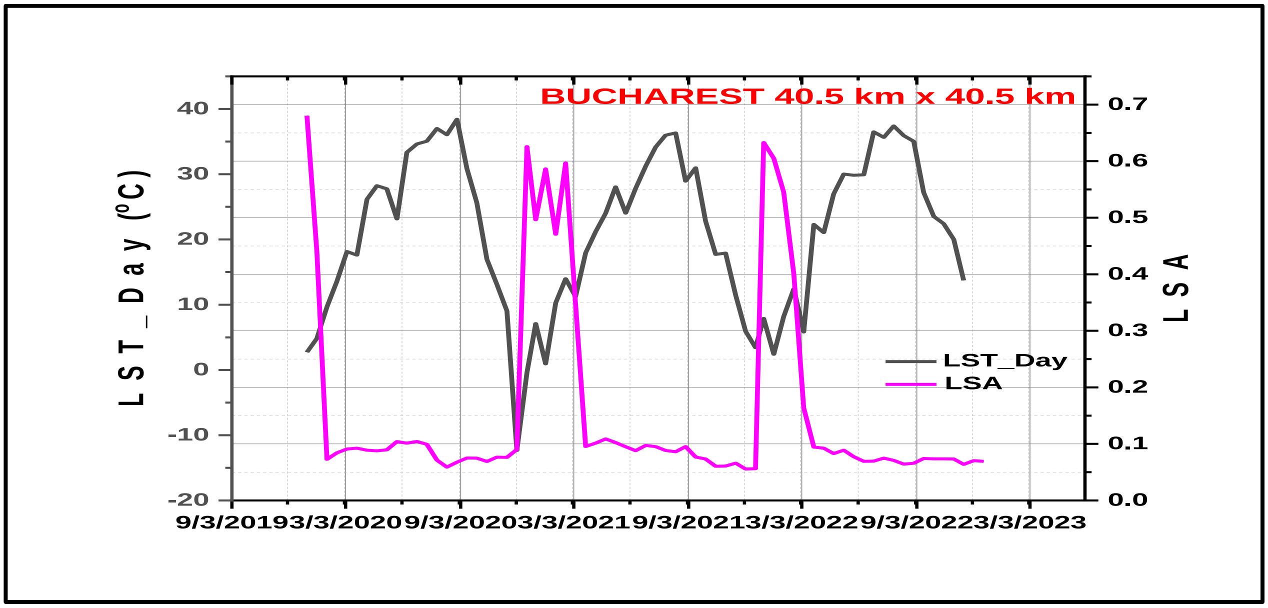

Figure 5. Temporal variation of LST_Day and LSA in Bucharest metropolitan area during 2020-2023.

Urban vegetation land cover change is a direct measure of quantitative increases or decreases in sources of urban pollution and the dimension of extreme climate events and changes that determine environment quality. Spatiotemporal monitoring of urban vegetation land cover changes in relation with air pollution and climate changes is a very important task for establishing the links between policy decisions, regulatory actions and subsequent land use activities [25].
Urban air pollution due to particulate matter (PM) is quite complex, originating from both anthropogenic sources, such as power generation and traffic, and natural sources, such as dust and biomass combustion [26-28]. The effects of vegetation cleaning on atmospheric pollutants, and the impacts on urban thermal environment explored in the study area were well correlated with the results provided by nonparametric statistical indicators based on ranking, Spearman's correlation coefficients. The high rate of the urbanization process in Bucharest, capital of Romania which was recorded during the last decades is responsible of the increased conversion rate of vegetated land cover to built-up areas, with negative impacts on the urban thermal environment, urban biodiversity conservation and human health.

5. CONCLUSION

Using time series MODIS Terra/Aqua derived biophysical parameters and in-situ monitoring data this study identified and assessed the relevance of key atmospheric pollutants and vegetation indices in synergy with climate variables for urban thermal environment assessment in Bucharest metropolitan area in Romania, in order to provide a conceptual foundation of the relevant processes to improve the quantitative representation of vegetation effects in air quality models. The findings of this study have significant implications for mitigating urban air pollution and urban heat during hot summers due to synergy of urban heat islands and heat waves events in Bucharest metropolitan area, guiding local and regional green space planning, and fostering sustainable urban development.

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