Urban Green Space and Albedo Impacts on Surface Temperature in Bucharest Metropolitan Area

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ABSTRACT

Rapid urbanization exacerbates spatiotemporal changes of urban surface albedo, an essential biophysical variable in surface energy balance and the health risks of climate warming. Through statistical and spatial regression analysis of the time series MODIS Terra/Aqua and in-situ monitoring data of climate variables for both central city and metropolitan area, this study identified the impact of urban built in Bucharest metropolitan area on the spatiotemporal variation of land surface albedo (LSA) during 2002- 2023 period, and quantified its relationship with the urban thermal environment (land surface temperature-LST and air temperature at 2m height AT) and associated vegetation (normalized vegetation index–NDVI, leaf area index-LAI, evapotranspiration-ET) and other climate factors. During summer hot periods, this study found a strong inverse correlation between LSA and LST (r= -0.85; p<0.01) in all city sectors explaining the high negative impact on the urban thermal environment. Also, as a measure of urban surface thermal properties, land surface albedo depends on the atmospheric conditions. At the pixel scale, during the summer season (June-August) air temperature at 2m height AT is positively correlated with LST (r= 0.86%, p<0.01). For summer periods (June – August), LST shows an inverse correlation with NDVI for both central Bucharest city (r= -0.29, p< 0.01) and for the metropolitan area (r= -0.67, p<0.01). Because the urban climate system is highly sensitive to land surface albedo changes, urban/periurban vegetation land covers may have strong feedback to the anticipated climate warming. Future climate adaptation strategies must consider albedo cooling benefits and urban greening that can reduce the heat exposure of urban populations.

Keywords: - land surface albedo, urban thermal environment, biophysical parameters, time series MODIS Terra/Aqua satellite data, Bucharest, Romania.

1. INTRODUCTION

In the frame of the current multifaceted global change, urbanization, and anthropogenic climate forcing are working synergistically to expose much of the Earth's population to extremely high temperatures, that contribute to high rates of human morbidity and mortality, especially during summer seasons[1]. The increased and rapid urbanization contributes to global climate change through increasing of carbon emissions due to enhanced population, consumption, and through affecting radiative forcing due to the changes of the geometry and the composition of land surface elements. As a consequent effect, will be a serious impact on local and regional climate due to 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)[2,3] Increasing urban surface albedo through green covers improves outdoor thermal environment [4, 5], and also increasing of road and building walls albedo is mitigating Urban Heat Islands (UHIs) [6]. In the physical climate system, land surface cover determines the radiation balance of the surface and affects the surface temperature and boundary-layer structure of the atmosphere[7,8].

Land surface temperature (LST), defined also as the skin temperature of the Earth's surface LST is a crucial variable in urban climate modeling, being one of the primary elements impacting the earth's physical, chemical, and biological processes. The urban overheating during summer heat waves needs the implementation of prevention and mitigation actions.

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Understanding of changes in urban land surface albedo and urban green land cover is critical for projecting future climate changes over large metropolitan areas. UHIs, which cause a serious impact on human health, are characterized by higher ambient temperatures in the dense overpopulated 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. The scale and intensity of the UHI effect are continuing to increase in several urban areas worldwide. Previous scientific studies found the important role of high albedo materials and vegetation land cover in mitigating urban thermal stress, but local and regional atmospheric circulation and urban air quality are essential parameters in the surface energy balance. The albedo quantity, most relevant to the energy budget includes the shortwave domain (0.4 µm- 4 µm), the visible (0.4µm- 0.7µm), and near-infrared (0.7 µm- 4 µm) spectral wavelengths, where the solar downwelling radiation is more relevant. Land surface albedo is related to several biogeophysical, biogeochemical, and hydrological cycles as the absorbed radiant flux (e. g. absorbed photosynthetically active radiation), which drives the processes of evapotranspiration, plant photosynthesis, and vegetation growth [9].

Due to anthropogenic and natural factors, urban land cover changes result in the land surface albedo changes. Both urban microclimates and outdoor thermal environments depend not only on the regional climate at a large scale but at local scale and 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. For urban thermal environment characterization, this study uses land surface temperature (LST), which is an important parameter used to characterize the land surface changes and the spatiotemporal pattern and influencing factors of the urban thermal environment. Green space was measured with a satellite-derived vegetation index normalized vegetation index (NDVI), which captures the combined availability of gardens, street trees, parks, and forests. 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. Remotely sensed data of various spatial, spectral, angular, and temporal resolutions have been widely used to study the urban land cover changes associated with urban growth and to retrieve land surface biogeophysical parameters, such as vegetation fraction cover, built-up indices, land surface temperatures, land surface albedo, which are good indicators of urban thermal environment[10]. Synergy use of time series derived satellite biophysical parameters and in-situ monitoring data can provide useful information for urban land cover spatiotemporal dynamics. Extreme summer heatwaves events driven by a persistent high-pressure systems coupled with low soil moisture on the land surface can exacerbate the people' vulnerability to increased air temperature (AT) and land surface temperature (LST) in Bucharest metropolitan area. 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 land surface albedo and 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 to detect urban footprints on Land Surface Temperature and land surface albedo and their changes during 2000-2023 period in the metropolitan area Bucharest, capital of Romania. Also, this study 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.

2. BIOGEOPHYSICAL PARAMETERS FOR URBAN LAND SURFACE ANALYSIS

2.1. Land surface albedo

Urban land surface albedo (LSA) was identified as a primary essential climate variable (ECV) and essential tool of climate change at the local urban scale, being an important parameter in describing the radiative properties of the Earth's surface, and important for the remote sensing of atmospheric aerosol, cloud properties from space, climatic analysis, biophysically based land surface modeling of the exchange of energy, water, momentum, and carbon for various land use categories as impervious, vegetation and agriculture surfaces, as well as for surface energy balance studies.

Urban applications need proper representation of the surface albedo's spatial and spectral variation, due in part to the distribution of vegetated surface types and growing conditions, and temporal variations, due largely to changes in the amount of vegetation over phenological growth cycles.

Land surface albedo (LSA) can be calculated from the following equations [9]:

$$H_m = H'\{1 - LSA[0.25(S/S_o) + 0.6(1 - 0.25(S/S_o))]\} \tag{1}$$

with H' monthly average of daily global irradiation that strikes the surface, defined by:

$$H^{'} = H_o[A + (BS/S_o)] \tag{2}$$

H_m, S and S_o are monthly averages of measured daily global irradiation, S_o monthly averages of daily sunshine duration and monthly of the daily maximum possible duration of sunshine hours.

$$H_m = H_o[A + (BS/S_o)] \tag{3}$$

$$S_o^{'} = 2/15\cos^{-1}[(\cos 85^o - \sin L \sin \partial)/(\cos L \cos \partial)] \tag{4}$$

with L latitude of the sites in degrees, ∂ the declination angle of the sun in degrees and H_o the estimation of the monthly average of daily extraterrestrial irradiation. Then, can be defined A and B regression constants in the previous equations equations (3) - (4) for each month of the year.

In a shortened case surface albedo is defined as the ratio of reflected to incident solar radiation flux intensity (measured in W m^{-2}) on the earth's surface. The total energy reflected by the earth's surface in the short-wave domain is characterized by the short-wave (0.3±4.0 μm) broadband albedo. The shortwave broadband albedo is one of the most important physical parameters for climate models, because it governs the exchange of solar radiation between the land surface and the atmosphere. Solar radiation energy is the fundamental source of power that drives the circulation of water and energy in the atmosphere, continents, and sea. Moreover, solar radiation at the ground level affects global climate and meteorology. Therefore, accuracy in the measurement of short-wave broadband albedo directly affects the results of a climate model. However, using satellite remote sensing techniques, albedo can be determined at the pixel level over an entire area. This allows more accurate estimation of climate models. In the IPCC report, surface albedo is listed among those radiatively important components that are known at a very low confidence level[11].

In the physical climate system, albedo determines the radiation balance of the surface and affects the surface temperature and boundary-layer structure of the atmosphere. In urban systems, albedo controls the microclimate conditions, been recognized that accurate surface albedo information is important for weather forecasting, climate projection, and ecosystem modeling.

Land surface albedo is essential information used as an input parameter for numerical Regional Climate Models and Atmospheric General Circulation Models. Surface albedo dynamics are closely related to ecosystem dynamics. Therefore, the impacts of climate change and variations in urban ecosystem processes could affect surface albedo characteristics. Since the physical climate system is very sensitive to surface albedo, urban ecosystems could significantly feedback to the projected climate scenarios through albedo changes. As such, the impacts of climate change on surface albedo and ecosystem feedback have been recommended for further investigation. This is of particular significance for those ecosystems whose structure is highly responsive to climate change and variations. Earth's radiation budget changes, such as in albedo values, can be compared directly with the effects of greenhouse gases and aerosols through the concept of radiative forcing[12]. Land cover change-induced surface albedo change perturbs the radiation budget by modifying the absorption of shortwave radiation forcing which can then be compared with the radiative forcings by greenhouse gases, aerosols, and solar output changes to assess the importance of surface albedo change concerning these other climatic influences.

2.2. Vegetation Index NDVI

Urban/periurban vegetation land cover dynamics were studied by means of vegetation indices (VIs) developed based on combinations of two or more spectral bands, using radiance, surface reflectance (ρ), or apparent reflectance (measured at the top of the atmosphere) values in the red (R), and the near-infrared (NIR) spectral bands. This study used Normalized Difference Vegetation Index NDVI expressed as:

$$NDVI = (\rho_{NIR} - \rho_R)/(\rho_{NIR} + \rho_R) \tag{5}$$

For *Green Vegetative Cover* of urban/periurban green, the most commonly used index is the NDVI and it has been used in mixture modeling to compute green fractional vegetation cover (*fc*) the following relationship:

$$f_C = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{6}$$

where NDVIsoil is the NDVI value of bare soils and $NDVI_{veg}$ is the NDVI value of a pure vegetation pixel. In order to use equation (6) to compute fractional green cover, have been used two parameters, $NDVI_{soil}$ and $NDVI_{veg}$, which can be empirically determined (0.1 and 0.8) [10, 13]. The fractional cover computed using equation (6) is only an estimate of the green component. Vegetation can be distinguished using remote sensing data from most other (mainly inorganic) materials by its notable absorption in the red and blue segments of the visible spectrum, its higher green reflectance, and especially, its very strong reflectance in the near-IR. Different types of vegetation show often distinctive variability from one another owing to such parameters as leaf shape and size, overall plant shape, water content, and associated background (e.g., soil types and spacing of the plants (density of vegetative cover within the scene).

2.3. Land Surface Temperature LST

Land surface temperature measured in the direction of the satellite airborne sensor (satellite) represents the average surface temperature in a given unit area at a certain time of day, instead of measuring the temperature of the air, like weather stations do. It depends on the land surface albedo, the vegetation land cover, and the soil moisture. Therefore, LST is an essential indicator of surface energy and moisture conditions. LST retrieved from multisensor satellite data provides a means to understand efficiently land surface processes via periodicity, high-spatial resolution, and global coverage. Satellite-retrieved LST was widely applied to urban environments to investigate soil moisture, surface energy fluxes, vegetation dynamics, and environmental and ecological changes. In urban climate studies, satellite-based LST can comprehensively describe the complex spatiotemporal temperature distribution in highly heterogeneous urban environments [14,15].

LST brings information on the urban landscape characteristics (land cover types, biogeophysical components, spatial configuration, spatial intensity of human activity), being important parameters for understanding the landscape pattern ecological processes in urban landscape ecology. From time series LST satellite data provided by different sensors will be available information on urban heat island UHI, especially during summer HWs events in urban densely populated areas. Also, LST describes the impact of urbanization (landscape composition and size, patterns, and their thermal properties such as heat capacity, heat conductivity, reflection, biogeophysical characteristics, etc.) on the thermal environment at different spatial-temporal scales, including single-site, neighborhood, city, and regional scales. Derived from remote-sensing satellite data excluding the influence of the atmosphere and accounting for surface emissivity, LST is directly related to surface radiation and its thermodynamic properties. Different land cover (vegetation, impervious, water, unused land, and grassland) characteristics influence solar-radiation absorption and re-radiation and influence directly LST and thermal transmission [16, 17, 18].

3. TEST AREA AND DATA USED

Bucharest is a large metropolitan area, the capital of Romania described by a star-shaped pattern (Fig.1), placed in the South – Eastern part of Romania, and the South-Eastern part of Europe being bounded by latitudes 44.33 °N and 44.66 °N and longitudes 25.90 °E and 26.20 °E. Its central region has the main coordinates: latitude 44°25′N, longitude 26°06′E. The urban metropolitan area of Bucharest includes the city of Bucharest (228 km^2) and the surrounding areas belonging to Ilfov County (329 km^2), covering a total surface 557 km^2. The city is crossed by the Colentina and

Dambovița rivers. The Colentina River is a plain river with meanders and marsh areas. It forms a succession of lakes in the northern part of Bucharest. The Dambovița River crosses Bucharest from NE to SW through its center. At the local scale its climate is continental, with four seasons (spring – March, April, May, summer – June, July, August, autumn – September, October, November, winter – December, January, February). During last years July and August months have been the warmest months of the year, with average maximum air temperatures higher than 30°C. August month recorded the lowest number of rainy days in the year and the smallest amount of rainfall in the summer.

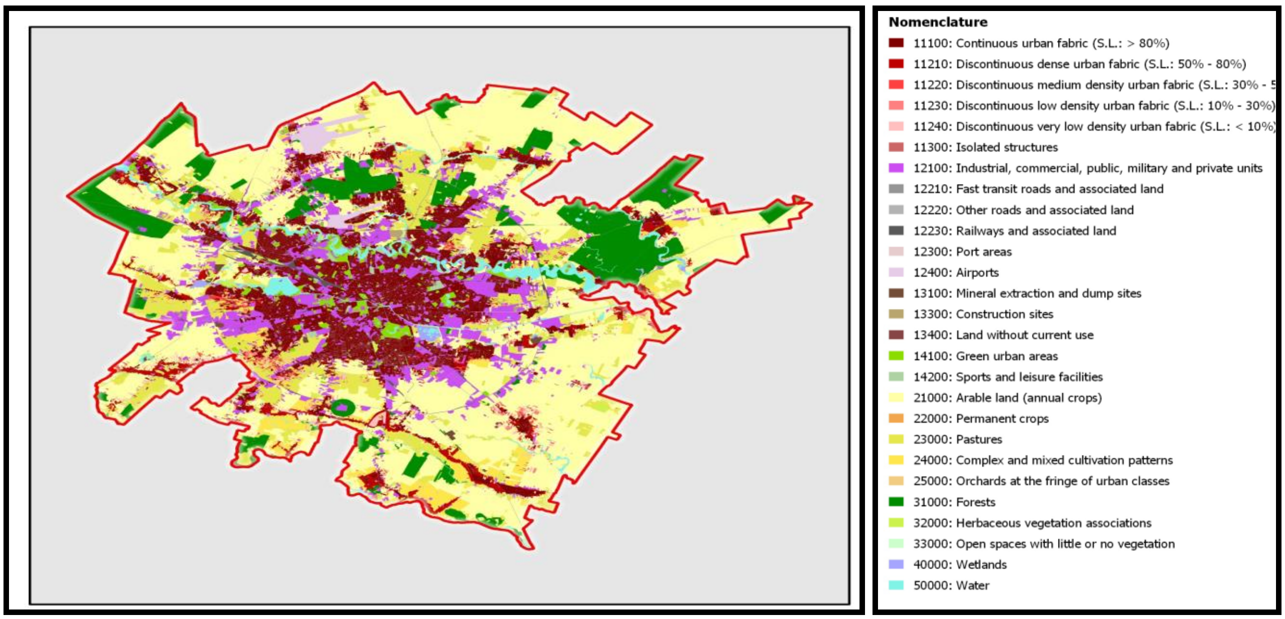

Figure 1. The study test site Bucharest metropolitan area on Copernicus Urban Atlas change 2012- 2018

The time series analysis of derived biogeophysical parameters for the Bucharest metropolitan area is based on time series MODIS Terra/Aqua acquired during 2000-2023 period. During analyzed period have been registered several heat waves periods, of which summer 2003, 2007 and 2010, 2012, 2017, 2022, and 2023 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, MCD43A/VIS and NIR surface albedo, mainly for their capacity to detect anthropogenic and climate impacts on urban thermal environment and land cover changes[19, 20, 21, 22]. 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 a central Bucharest test area defined by 6.5 km x 6.5 km surface, and an entire metropolis test area, defined by 40.5 km x 40.5 km surface. In situ-monitoring spectroradiometrical additional data as well as meteorological observational data have been used. For similarity between two-time series data of the averaged daily air temperature (TA), and derived satellite biogeophysical parameters (LST, VIS, and NIR surface albedo, NDVI) 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. ORIGIN 10.0 software version 2021 for Microsoft Windows was used for data processing. For satellite data, ENVI 5.7 software was used.

4. RESULTS AND DISCUSSION

We conducted a systematic analysis for assessing of urban land cover– air and land surface temperature interactions, and identifying urban footprints on Land Surface Temperature and land surface albedo and their changes during 2000-2023 period in Bucharest metropolitan area.

4.1. Land use/ land cover, and changes

In 2018, according to Copernicus Urban Atlas land use land cover (LULC) distribution (km^2) in Bucharest metropolitan region was following: artificial area 33.6%, agricultural area 53%, natural areas 10.7%, wetland 0.2% and water 2.4% The registered changes of LULC during 2012-2018 period for Bucharest metropolitan area were defined as urban expansion through uptake of agricultural areas (71.9%), uptake of natural areas (1.3%), uptake of wetlands/water (1.3%), loss of artificial area (12.3%) and other changes (13.5%)[23]. Is well recognized that urban land cover artificial properties will change the urban surface energy and water balance different from the natural surfaces. Also, the city morphology and urban forms and topography of Bucharest can impact climate at the microscale by creating urban canyons due to changes of wind speed and direction, building walls creating warmer spots, which results in urban thermal discomfort. During 2000 -2023 period Bucharest city expanded in all directions with a strong urban growth inside of the town but also in periurban areas as an increase of overcrowded urban area for all 6 sectors belonging to Bucharest metropolitan area. The results provided a characteristic spatial pattern, gradients and landscape metrics, which support an understanding of Bucharest's spatial growth and future modeling of urban development in Romania

4.2. Land Surface Albedo (LSA)

Fig. 2 presents temporal variations of daily average MODIS/Terra Broadband BRDF albedo MCD43A in band-1 during 2002-2023 for the Bucharest metropolitan area. This study found a strong inverse relationship between LSA and LST ($r= -0.85$; $p<0.01$) during summertime in the city areas with a negative impact on the urban thermal environment.

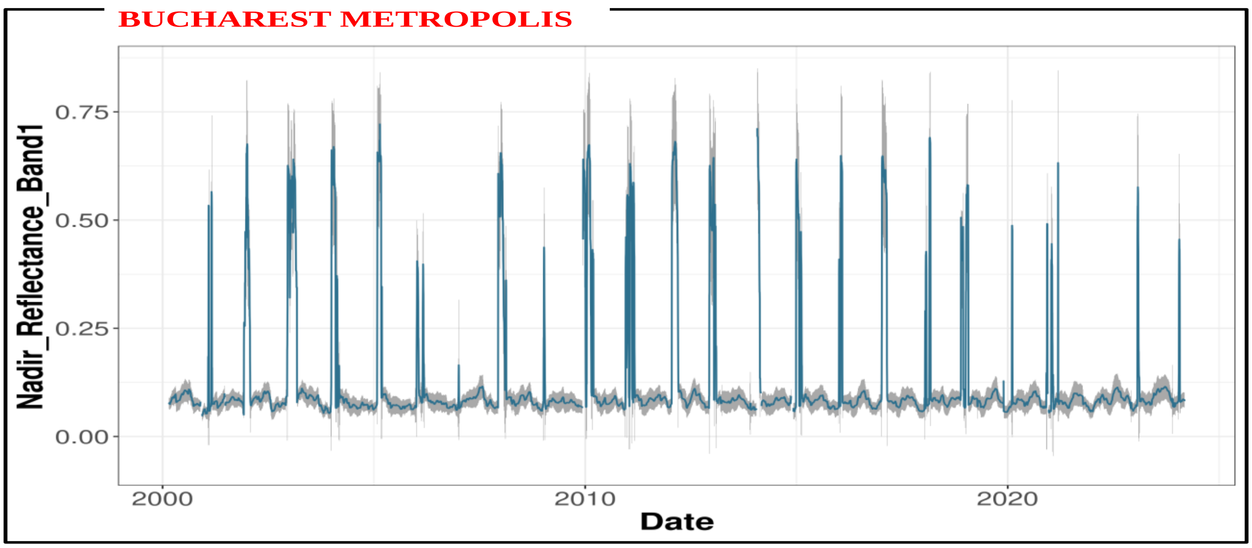

Fig.2. Temporal variations of daily average MODIS/Terra Broadband BRDF albedo MCD43A in band-1 during 2002-2023

Broadband albedo, which measures urban surface properties depends also on the atmospheric condition [24]. Assigning albedo values to different urban/periurban land cover types is useful for adopting the level of interventions and their impacts on the urban form that underwent specific evolutions between the 2000 to 2023 time window. Analysis of time-series MODIS Terra/Aqua data in this study suggest: (a) during the winter-to-summer and summer-to-winter transitional periods, TA plays an important role in determining the LSA by controlling snow absence and presence; (b) in the winter season, the amount of precipitation (snow) greatly affects the LSA of this ecosystem; (c) in the spring-summer-autumn seasons, ecosystem water conditions can significantly alter the LSA of the urban ecosystem through their impact on urban/periurban vegetation land cover growth and ecosystem conditions. Also, urban surface albedo changes of Bucharest metropolitan area highly dependent to local and regional climate variations.

4.3. Land Surface Temperature (LST)

Figure 3 presents temporal pattern of Land Surface Temperature MOD11A2/LST_Day_1km in relation with land surface albedo -LSA during 2020- 2023 period for Bucharest metropolitan area of 40.5km x 40.5km, centered at latitude

44.4355381 ºN and longitude 26.100049 ºE. A clear inverse correlation is shown in this figure between the daily LST and LSA, which supports the idea that increasing urban LSA through urban greening will decrease the LST and increase health comfort in metropolitan areas.

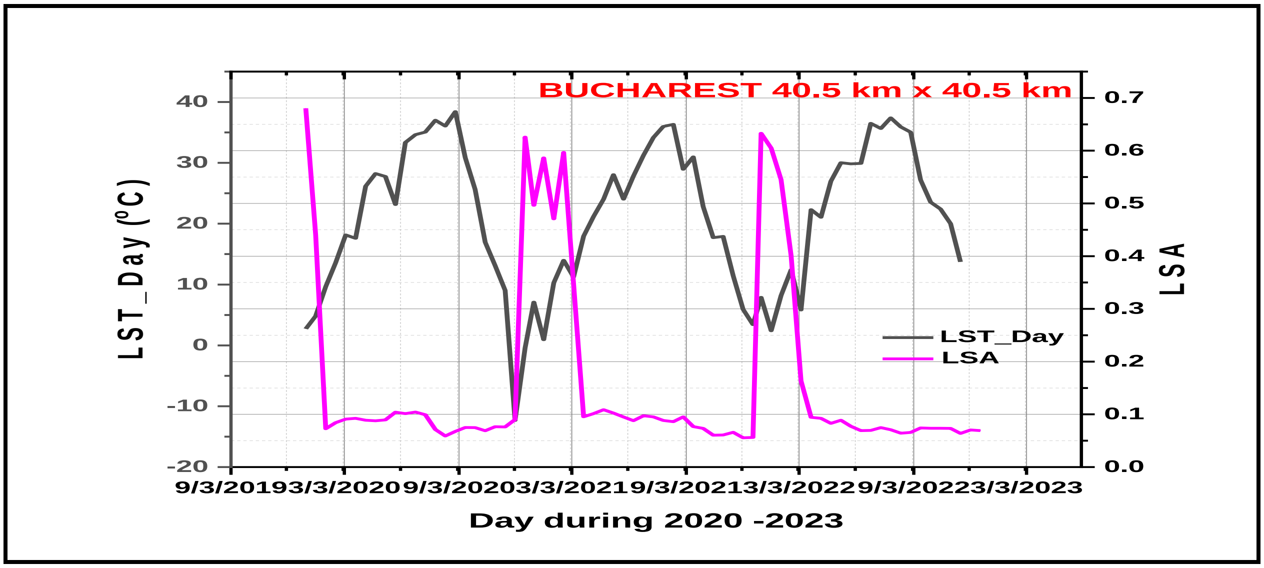

Fig. 3. Temporal variations of daily average LST MODIS Terra data and LSA for Bucharest metropolitan area (40.5 km x 40.5 km) between 2020-2023.

Also, as was expected, the central built area of Bucharest with high impervious surfaces LST presents greater temperatures and reflects more heat, while extended metropolitan area exhibits lower temperatures due to much more vegetated spaces. The significant differences of LST_Day between city central, median, and peripheral zones of Bucharest metropolitan area have been recorded especially during years with intense heat waves (2003, 2007, and 2010, 2012, 2016, 2022, and 2023). Monthly average values of the temperature differences between urban and rural areas range between 1ºC and 8ºC. Like other studies [25], this paper reveals a strong positive correlation at the pixel-scale, during summer season (June-August) air temperature at 2m height TA and LST presents (r= 0.86%, p<0.01).

4.4. NDVI/EVI

The results of this study show that the disturbances of urban forests and urban green alter land cover biophysical properties, directly impacting local climate and land surface temperature. At the metropolitan scale, urban vegetation loss has high impacts on land surface albedo increase, evapotranspiration (ET) decrease, and reduced values of LAI. In good accordance with previous papers for worldwide cities, the relationships between LST and NDVI/EVI were highly diverse among the various urban/periurban biomes and seasons throughout the entire study period [26].

Therefore, during the spring season (March-May), LST-NDVI showed the dominance of significant positive correlation (Spearman rank correlation coefficient r=0.91 , p<0.01 for city central area; and r=0.72; p<0.01 for metropolis areal), while during the summer season (June–August), most of the vegetation test areas turned to negative correlation as follow with NDVI for both central Bucharest city (r= -0.29, p< 0.01) and for metropolitan area (r= -0.67, p<0.01). Because urban climate system is highly sensitive to land surface albedo changes, urban/periurban vegetation land covers may have strong feedback to the anticipated climate warming. For autumn and winter seasons, LST correlations with NDVI/EVI were positive in the range of r= 0.47 to r= 0.69 and p<0.01 for central city, and respectively metropolitan areas. 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. The contributions of periurban vegetation land cover (cropland and forest) varied distinctly between daytime and nighttime owing to differences in their thermal inertias [27]. Temporal variations of monthly average MODIS NDVI and LST_Day during 2002-2023 are presented in Fig.4. Vegetation had a clear cooling effect as the normalized vegetation difference index (NDVI) increased during summer periods. Urban footprint analysis further revealed changes in green land cover that are highly dependent on land management scenarios.

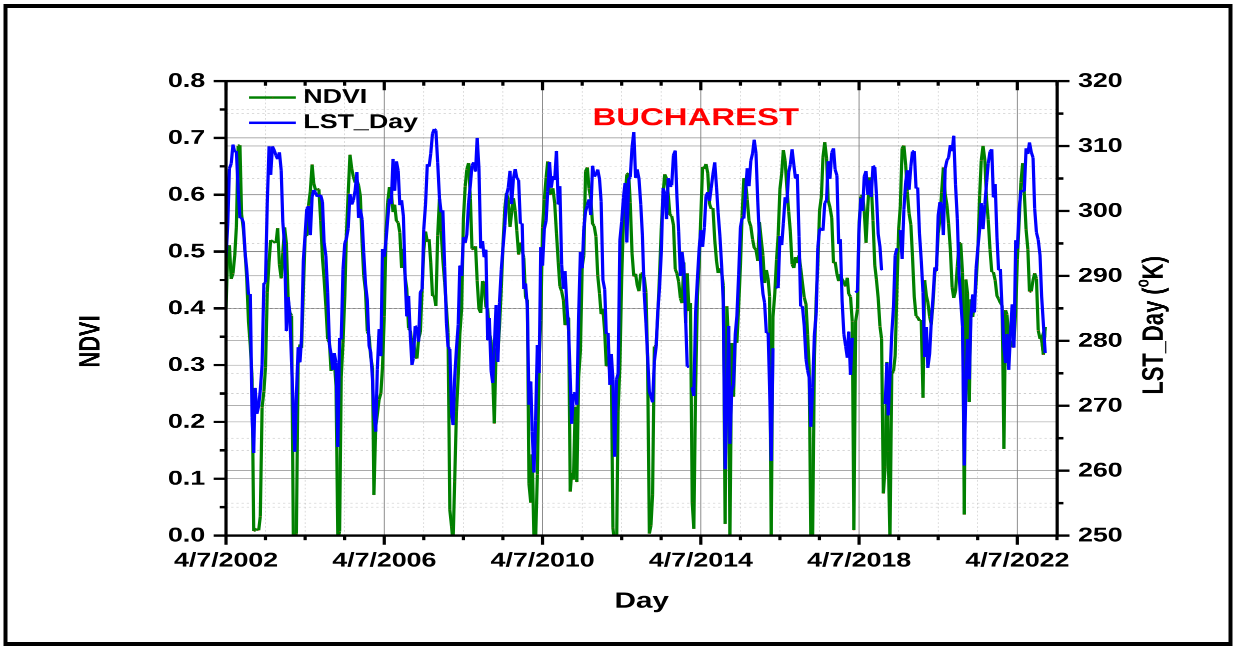

Fig.4. Temporal variations of monthly average MODIS NDVI and LST_Day during 2002-2023.

5. Conclusion

This study found also that during last ten years was recorded a decrease in urban albedo in Bucharest, which may explain the warming effect associated with positive surface radiative forcing. These findings may enhance our understanding of urbanization's impacts on the urban thermal environment and albedo-related biophysical processes and can provide useful information to quantify urban surface radiation energy and design effective prevention and mitigation strategies to reduce urban warming. As in the next years due to global climate warming heat waves are expected to become more severe and frequent in the South- Eastern parts of Europe and Romanian urban areas, with unknown consequences for urban ecosystems, quantification of urban thermal environment, and associated heat stress in frame of Urban Heat Island phenomenon with negative impacts on air quality and people's health, is an imperative research need. The results of this study may provide urban decision-makers with insights for urban planning and scientific management to optimize the urban functional structure and improve the urban thermal environment in the Bucharest metropolitan area. Also, the need of implementation of urban heat prevention and mitigation technologies must consider the decrease of the heat gains and enhance the heat losses in cities, through involving the use of advanced materials for building urban surfaces, the increase in urban green, and the urban heat cooling through implementing of urban surface albedo decreasing solutions.

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