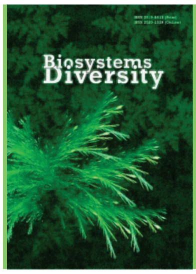

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Modeling the spatial variation of urban park ecological properties using remote sensing data

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Parks perform a wide range of ecosystem services in urban environments. The functional importance of parks depends on the composition and structure of the tree stand and the specific influence on soil and microclimatic conditions. The article reveals the dependence of soil and microclimatic properties on the structure of the crown space of a park stand. Spectral indices were also shown to be applicable for predicting the spatial variability of soil and climatic properties and indicators of crown space. Soil properties (temperature, moisture, and electrical conductivity in the 5–7 cm layer) and microclimatic parameters (light exposure, air temperature, and atmospheric humidity) were measured in the park plantation using a quasi-regular grid. The canopy structure and gap light transmission indices were extracted from the true-colour fisheye photographs. Thirty species of trees and shrubs were detected in the stand and understory. *Robinia pseudoacacia* L. was found most frequently (24.5% of all tree records). *Acer negundo* L. and *A. platanoides* L. were also frequent (12.4% and 15.5%, respectively). The first four principal components, whose eigenvalues exceeded unity, were extracted by the principal components analysis of the variability of ecological properties and vegetation indices. The principal component 1 explained 50.5% of the variation of the traits and positively correlated with the spectral vegetation indices. The principal component 1 reflected the variability of tree cover densities due to the edaphic trophicity. The principal component 2 described 13% of the variation in the feature space. This component correlated positively with the spectral indices. The principal component 2 was interpreted as a trend of vegetation cover variability induced by moisture variation. The principal component 3 described 8.6% of trait variation. It was most strongly correlated with the atmospheric humidity. An increase in atmospheric humidity was associated with an increase in the soil moisture and electrical conductivity and a decrease in the soil and atmospheric temperature. The principal component 4 described 7.5 % of the variation of traits. An increase in the values of principal component 4 was associated with an increase in the soil moisture and electrical conductivity and atmospheric moisture and was associated with a decrease in the soil and atmospheric temperature. The combinations of the trophotope and hygrotope create the optimal conditions for specific tree species, which is a condition for achieving the maximization of ecosystem services. The mineral nutrition conditions of plants and soil moisture exhibit spatial patterns that allow them to be considered in the design and management of park plantations. The ecological indices measured in the field were shown to be predicted using the vegetation indices. Multiple regression models were able to explain 11–61% of indicator variation. The regression relationships between markers of soil and microclimatic conditions and vegetation predictors are important for monitoring the condition of park plantations and evaluating the performance of park plantation management tools.

Keywords: GIS-technology; human ecology; ecological monitoring; spatial ecology; vegetation indexes; urban ecology.

Introduction

The urban population is constantly increasing. In 2021, the number of people living in cities will be 57% of the world's population. In the European Union, the number of city residents is 0.75 of the total population. Urbanization, population agglomeration, economic development, industrial development, urban construction and transport construction lead to pollution and climate change in the urban environment (Bazrkar et al., 2015; Liang et al., 2019). An urban park is a community of living organisms and in this sense is certainly an ecological system (Yorkina et al., 2022), but this ecosystem is designed to perform a spectrum of ecosystem services to meet human needs. Urban parks play an important role in improving the environment and landscape conditions, resulting in green spaces that have become an integral part of cities because of their strategic importance for quality of life. City parks are a key recreational resource that supports the well-being of city residents. Access to urban parks contributes to human longevity (Mitchell & Popham, 2008). Urban parks are places for physical exercise, social interaction, and reflection (Aldous, 2007). The experience of communicating with nature in an urban environment is a source of positive emotions and useful services that satisfy important intangible and non-consumptive human needs (Chiesura, 2004). Public gardens perform important ecosystem services in the urban environment (Mexia et al., 2018).

Cities are responsible for more than 80% of global greenhouse gas emissions. The sequestration of air pollutants is one of the main ecosystem services that urban forests provide to city dwellers (Fares et al., 2020). City trees remove carbon dioxide from the air and release oxygen. The urban forests in the United States are estimated to produce ≈61 million metric tons (67 million tons) of oxygen annually, enough to offset the annual oxygen consumption of about two-thirds of the US population (Nowak et al., 2007). Thus, urban parks influence climatic conditions both in the city itself and are a factor in changing global climatic conditions as a significant tool for the sequestration of greenhouse gases and toxic substances (Yorkina, 2016). Urban park vegetation improves air and water quality

(Badach et al., 2020; Zymaroieva et al., 2021). Green spaces greatly reduce the probability of urban flooding (Kim et al., 2016; Miller & Hutchins, 2017). Urbanization is a major factor in environmental change and is closely linked to the future of biodiversity (Alasmary et al., 2020; Umerova et al., 2022). Public parks are islands in an otherwise hostile urban landscape for fauna and flora (Zhou & Chu, 2012). The variety of species richness and abundance of living organisms (including genetic variation) and habitats found in populated areas and at their edges is urban biodiversity (Müller et al., 2013; Koshelev et al., 2021). The level of biodiversity is much higher in urban parks than in the surrounding urban environment (Matteson et al., 2013; Yorkina et al., 2019). The sustainability of ecosystem functions is due to the high biodiversity of urban parks (Kowarik et al., 2020; Pidlisnyuk et al., 2020). High biological richness improves the aesthetic perception of urban ecosystems (Lindemann-Matthies et al., 2010; Putchkov et al., 2019). The biological diversity of park areas has a positive influence on the psychological well-being of people (Dallimer et al., 2012).

Many urban dwellers around the world suffer from health problems and discomfort caused by overheated urban areas, and there is strong evidence that these problems will be exacerbated by global climate change (Lomas & Porritt, 2017). Increasing the area of urban vegetation is a measure to reduce the urban heat island effect, which is an important environmental problem facing all major urban centers (Hulley, 2012). City parks help cool down the summer temperatures locally and across the city (Rehan, 2016). The greatest range of the cooling effect and the intensity of the cooling effect are for large urban parks of more than 10 hectares. In addition to area, the natural elements and qualities of urban green spaces as well as climatic characteristics largely determine the cooling effect of urban green spaces (Aram et al., 2019). The cooling effect of green spaces, which extends beyond parks, creates conditions for reducing the city's energy consumption (Oliveira et al., 2011). Urban parks and green spaces have the potential to provide a climate that is comfortable for city residents and help reduce vulnerability to heat stress. However, in order for them to fulfill this function, parks must be designed in the context of the prevailing climate and projected future climate conditions (Brown et al., 2015).

City parks today are seen not only as recreational and leisure spaces, but also as an important part of the development of the city. The creation of sustainable urban parks has become an important approach to urban planning policy and development (Nady, 2016; Kunakh et al., 2022). Urban parks have dual benefits for people and biodiversity (Holoborodko et al., 2022). The management of parks focused on ecological restoration can increase urban sustainability as well as benefit public health and well-being (Tzoulas et al., 2007). The mechanisms for sustainability and functioning of park plantings are in the context of general ecological patterns, but park management can modify the trajectory of the park ecosystem to maximize human desired functions (Bahriny & Bell, 2020; Holoborodko et al., 2021). Thus, park management must consider the biological nature of urban parks (Palliwoda et al., 2017) and the importance of creating an environment favourable in various senses to human life (Chiesura, 2004; Seymour, 2016). Trees form the basic appearance of the park and determine the performance of ecosystem functions (Shanahan et al., 2015; Brygadyrenko, 2016). The life cycle of trees and the length of their growth and development determine the need for long-term planning of management actions and the understanding that actions taken at a given point in time will have a significant impact (Solonenko et al., 2021). Clearly, an effective management effort must be based on reliable quantitative data on the effectiveness of certain actions. Thus, understanding the dynamics of park development over a significant spatial and temporal range is the basis for effective urban park management.

Earth remote sensing methods provide an opportunity to assess the environmental properties and processes in urban parks in a wide spatial and temporal range (Chen et al., 2018; Shahtahmassebi et al., 2021). Analysis of satellite images showed that park size and greenness of vegetation were the dominant factors of park cooling efficiency (Sun et al., 2021). Remote data indicate that park area, park perimeter, water area fraction, and park shape index correlate significantly negatively with the average land surface temperature in the park (Zhu et al., 2021). The intensity of heat islands in parks varies by season, and the cooling effect of parks is greater in the summer than in the fall. Increasing the size of urban parks is an effective measure to mitigate urban heat island effects, but urban park size is nonlinearly correlated with the intensity of the cooling effect. Optimizing the shape of urban parks and forest structures in parks can increase the intensity of a park's cool island. The relationship between the intensity of the cooling effect and the characteristics of urban parks varies by season (Ren et al., 2013).

To date, there are no studies that have simultaneously studied the impact of the park stand on soil and microclimatic properties of urban greenery. Therefore, the purpose of our study was: 1) to find the relationship between soil and microclimatic indicators and the structure of the crown space of a stand in an urban park; 2) to estimate the possibility of spatial modelling of the soil and microclimatic properties, as well as the indicators of the crown of a stand using spectral vegetation indices.

Material and methods

Sampling design. The study was conducted in the recreational area of the Botanical Garden of the Oles Honchar Dnipro National University (Ukraine) June 27, 2022. Soil properties (temperature, moisture, and electrical conductivity in the 5–7 cm layer) and microclimatic parameters (light exposure, air temperature, and atmospheric humidity) were measured in the park plantation using a quasi-regular grid (Fig. 1).

The soil classification position according to WRB: Calcic Chernozem (Siltic, Tonguic) (Yakovenko & Zhukov, 2021). The highest point of the relief (176 meters above sea level) is in the western part of the park and the height of the relief decreases in the direction to the east. The southern edge of the Dovgaya gully is in the northwestern part of the park. The gully has the lowest part of the relief (153 meters) within the park. The gully's talweg is filled with construction debris and the soil cover is represented by technosol. In total, the measurements were carried out at 230 sampling points. In 2019, a 2.8 ha area of the park was reconstructed. The park reconstruction work included such processes as restoring pedestrian paths, removing shrubs and old, damaged trees, and trimming the crowns of trees. Young trees were planted in place of the removed old trees. The old outbuildings, which greatly impaired the aesthetic perception of the park, were also removed. Transport and construction machinery was involved in the reconstruction. The works were carried out during the whole warm period of the year. The distance between sampling points was 14.0 ± 0.28 m and ranged from 7.1 to 31.0 m. The coordinates of sampling points were recorded using a GPS device. Tree species were recorded at each sampling point within a radius of 5 meters. The tree species was determined and its height and trunk diameter at 1.3 meters were measured.

Measurement of soil and microclimatic properties. The soil moisture content was measured with an MG–44 (Ukraine) at a depth of 5–7 cm. The measurement step of the device is 0.1% and the error is 1%. The soil temperature in the 7–10 cm layer was measured by a digital thermometer TC–3M (Ukraine). Air temperature and atmospheric humidity at a height of 1.5 m were measured with a HUATO HE–173 temperature and humidity logger (China). The illuminance at a height of 1.5 m was measured with a RSE–174 luxmeter (Germany). An HI 76305 sensor (Hanna Instruments, Woodsocket, RI) was used to measure the electrical conductivity of the soil *in situ*. This sensor works together with a portable HI 993310 tester. The tester evaluates the total electrical conductivity of the soil, i.e. the combined conductivity of air, water and soil particles. The measurement results of the device are presented in units of soil salt concentration (g/L). The comparison of HI 76305 measurements with laboratory data allowed us to estimate the unit conversion factor as 1 dS/m = 155 mg/L (Pennisi & van Iersel, 2002; Yorkina et al., 2021). The tree height was measured with an optical altimeter SUUNTO "PM-5/1520" (Finland). The diameter of the trunk of a tree at a height of 1.3 meters was measured with a Mantax Precision Blue Caliper 650 mm Haglof (Sweden) as an average of measurements in two perpendicular directions. The length of the trunk diameter circle was measured with a Stanley Longtape Fiberglass 30 m × 12.7 mm tape measure when the diameter exceeded 650 mm, followed by the calculation of the diameter value.

Canopy structure and gap light transmission indices. The canopy structure and gap light transmission indices were extracted from the true-colour fisheye photographs using Gap Light Analyzer (GLA) software.

Hemispherical smartphone photography allowed a rapid assessment of the forest canopy and light regime. The smartphone hemispherical photography is an appropriate alternative to the hemispherical photography with traditional cameras, providing similar results with a faster and cheaper technique (Bia6nchi et al., 2017). The following indices were evaluated. The canopy openness percentage (CO) is the proportion of open sky visible from under the forest canopy. This index is calculated only from a hemispherical photograph and does not consider the influence of the surrounding topography. The LAI 4 Ring (LAI4) is the effective leaf area index integrated over the zenith angles 0 to 60° (Stenberg et al., 1994). The LAI 5 Ring (LAI5) is the effective leaf area index integrated over the zenith angle 0 to 75° (Welles & Norman, 1991). The Trans Direct (Dr) is the amount of direct solar radiation transmitted by the canopy (Mols/m^2 dl). The Trans Diffuse (Df) is the amount of diffuse solar radiation transmitted by the canopy (Mols/m^2 d1). The Trans Total is the sum of Trans Direct and Trans Diffuse (Mols/m^2 d1).

Spectral indices based on remote sensing data. This study used Sentinel-2 satellite images downloaded from Earth Explorer (https://earthexplorer.usgs.gov) USGS website (Geological Survey (U.S.), & EROS Data Center. (2000). Earth Explorer. Reston, Va.: U.S. Dept. of the Interior, U.S. Geological Survey). The images were taken on June 20, 2022 (L1C_T36UXU_A036526_20220620T084448, Cloud Cover = 0.00). The Level-2A products, which are orthorectified Bottom-Of-Atmosphere (BOA) reflectance in cartographic geometry were generated using the Sen2Cor processor (https://step.esa.int/main/snap-supported-plugins/sen-2cor). Sentinel-2 band spectra were retrieved using the extraction tool in the spatial analysis toolset in ArcGIS 10.8. The extracted values were multiplied by the scale factor (0.0001) that was used to store the data.

The Normalized Difference Vegetation Index (NDVI) is sensitive to net production and transpiration (Rouse et al., 1974):

$$NDVI = (b8 - b4) / (b8 + b4),$$

where b8 is the near infrared band (0.78–0.90 nm), b4 is the is the red band (650–680 nm).

The Normalized Difference Infrared Index (NDII) was developed to estimate the vegetation water content based on the difference of light reflectance in NIR and SWIR wavelengths (Hardisky et al., 1983) or Normalized Difference Moisture Index (NDMI) (Xiao et al., 2019). The values of NDII range from –1 to 1 and green vegetation is detected within values from 0.02 to 0.6. The higher the value, the higher is the water content. NDII is widely used for the monitoring of forest canopy and the detection of vegetation stress:

$$NDII = (b8 - b11) / (b8 + b11),$$

where b8 is the near-infrared (NIR) band (780–900 nm), b11 is the Shortwave infrared (SWIR1) band (1570–1660 nm).

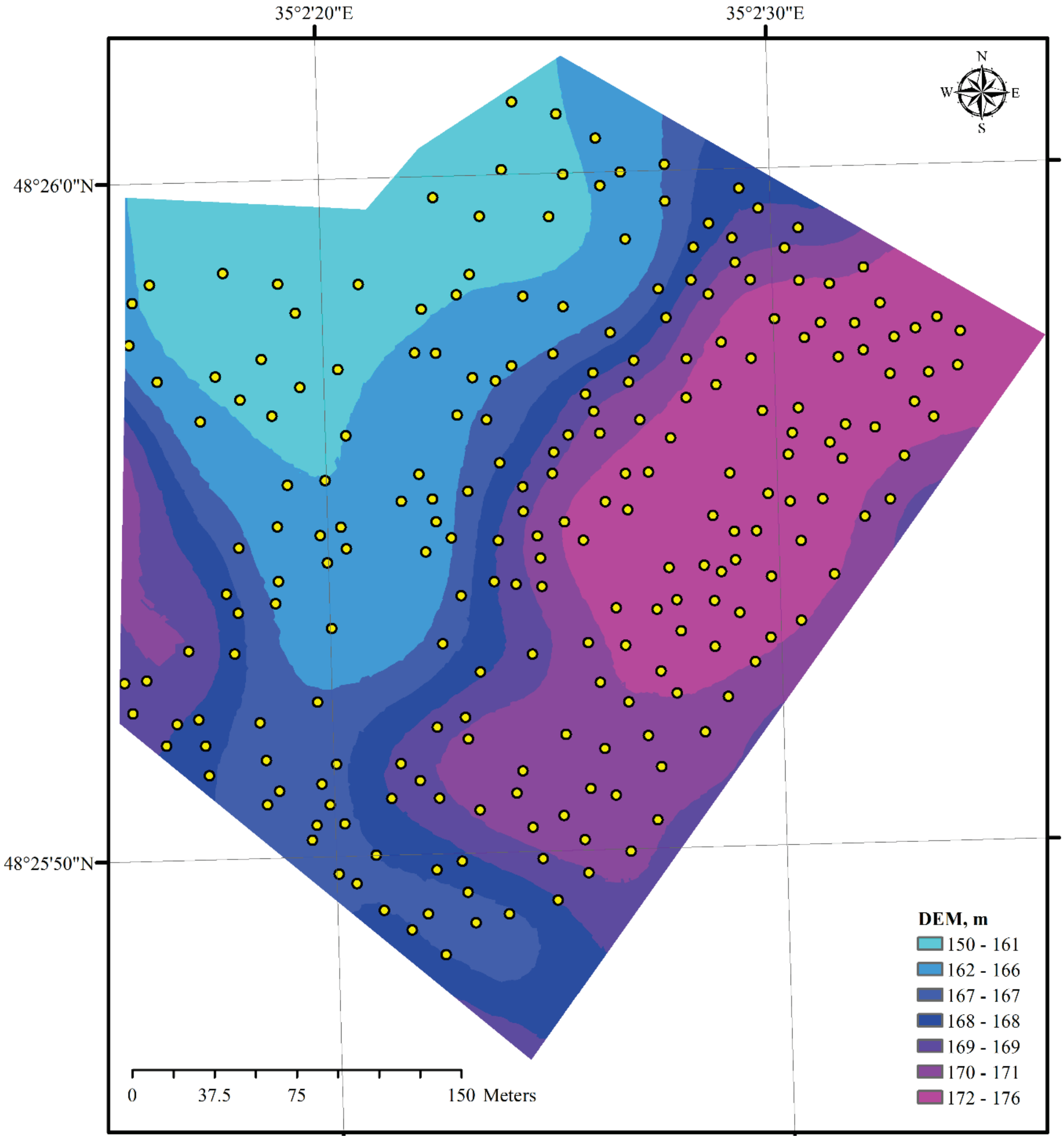


Fig. 1. Digital elevation model of the relief and the locations of sampling points

The Red-Edge NDVI-1 (RE NDVI–1) was estimated by the formula (Xie et al., 2018):

$$RE\ NDVI\text{–}1 = (b6 – b4) / (b6 + b4),$$

where b6 is the red edge band (730–750 nm), b4 is the is the red band (650–680 nm).

The Red-Edge NDVI-2 (RE NDVI–2) was estimated by the formula (Xie et al., 2018):

$$RE\ NDVI\text{–}2 = (b7 – b4) / (b7 + b4),$$

where b7 is the red edge band (770–790 nm), b4 is the is the red band (650–680 nm).

The Green NDVI (GNDVI) is very sensitive to chlorophyll concentrations (Gitelson et al., 1996). GNDVI ranges from –1 to 1:

$$GNDNI = (b7 – b3) / (b7 + b3),$$

where b7 is the red edge band (770–790 nm), b3 is the green band (540–580 nm).

Land Surface Water Index (LSWI) (or Normalized Difference Infrared Index) (Jurgens, 1997). The LSWI uses the SWIR band, which is sensitive to the crop liquid water and background soil moisture, it can be a valuable input for the assessment of early season drought. The LSWI is sensitive to liquid water content in vegetation and soil (Chandrasekar et al., 2010):

$$LSWI = (b8a – b12) / (b8a + b12),$$

where b8a is the near-infrared (NIR) band (0.86–0.88 nm), b12 is the shortwave infrared (SWIR2) band (2.10–2.28 nm).

Leaf Area Index (LAI) is applicable for estimating green LAI over multiple agricultural sites (Delegido et al., 2011):

$$LAI = (b5 – b4) / (b5 + b4),$$

where b4 is the is the red band (650–680 nm), b5 is the red edge band (700–710 nm).

MERIS Terrestrial Chlorophyll Index (MTCI) is a suitable index for the estimation of chlorophyll content (Dash & Curran, 2004) First developed for the Medium Resolution Imaging Spectrometer (MERIS):

$$MTCI = (b6 – b5) / (b5 – b4),$$

where b4 is the is the red band (650–680 nm), b5 is the red edge band (700–710 nm), b6 is the red edge band (730–750 nm).

Statistical calculations. The descriptive statistics and regression model parameters were calculated in the software Statistics. The parameters of the variogram were estimated in the ArcGIS 10.8. software. The spatial dependence level (SDL) was derived from the semivariogram geostatistics (Cambardella et al., 1994):

$$SDL = 100\% * C0 / (C0 + C1),$$

where C0 is the variogram nugget effect, C1 is the partial sill. A ratio of <25% indicated strong spatial dependence, between 25 and 75% indicated moderate spatial dependence, and >75% indicated weak spatial dependence.

Results

Thirty species of tree plants and shrubs were detected in the stand and understory. *Robinia pseudoacacia* L. was found most frequently (24.5% of all tree records). *Acer negundo* L. and *A. platanoides* L. were also frequent (12.4% and 15.5%, respectively).

Soil temperatures ranged from 17.8–27.0 °C and showed a spatial dependence with a radius of 220 m (Table 1). The high soil temperature was in plots without tree vegetation or with a thinned stand (Fig. 2). The lowest soil temperature was in plots with dense stands on the gully slope. Soil moisture ranged from 4.6% to 49.9% and showed a weak spatial dependence. Soil temperature and moisture were strongly negatively correlated (r = –0.40, P < 0.001), so the spatial pattern of soil moisture repeats that of soil temperature. Soil electrical conductivity ranged from 0.07 to 1.50 dSm/m and exhibited a moderate spatial dependence. The electrical conductivity of the soil increased with the soil moisture (r = 0.52, P < 0.001), but the electrical conductivity pattern is characterized by a much smaller radius, indicating the different causes generating variability in the two indicators.

Illuminance ranged from 69 to 9710 Lx and showed a moderate spatial dependence with a radius of 110 m. The most illuminated areas are non-forested areas and the area in the park reconstruction zone. Air temperature ranged from 22.4 to 31.3 °C and had a strong level of spatial dependence with a radius of 97 m. The illumination and air temperature correlated strongly positively (r = 0.52, P < 0.001), which explains the similar spatial pattern of these indicators. The peculiarity of spatial variation in air temperature consists in the presence of a "cold island" in the southeastern part of the park. Atmospheric humidity varied from 37.1% to 56.5% and had a strong level of spatial dependence with a radius of 89 m. The atmospheric humidity decreased with increasing air temperature (r = –0.58, P < 0.001). A zone of increased atmospheric humidity was observed in the southern and central parts of the park, and a zone of decreased atmospheric humidity was observed in the northwestern part.

Table 1

Descriptive and geostatistics of environmental properties and spectral indices (N = 230)

Variable	Descriptive statistics			Geostatistics			
	Mean ± SE	Min	Max	Nugget	Partial sill	SDL*, %	Range, m
Ecological properties**							
ST	20.8 ± 0.08	17.8	27.0	0.34	0.73	31.8	220
SW	16.3 ± 0.49	4.6	49.9	0.74	0.22	77.1	96
EC	0.27 ± 0.02	0.07	1.50	0.64	0.34	65.3	48
L	2129 ± 142	128	9710	0.43	0.72	37.4	110
AT	26.4 ± 0.13	22.4	31.3	0.11	1.04	9.6	97
AH	47.3 ± 0.29	37.1	56.5	0.047	0.94	4.8	89
CO	28.2 ± 1.09	9.2	100.0	0.32	1.00	24.2	152
LAI4	1.9 ± 0.06	0.0	4.1	0.49	0.67	42.2	132
LAI5	1.7 ± 0.05	0.0	3.3	0.41	0.77	34.7	140
Dr	4.5 ± 0.21	0.2	14.6	0.62	0.53	53.9	152
Df	4.3 ± 0.18	1.1	14.6	0.35	0.75	31.8	150
TT	8.92 ± 0.38	1.43	29.28	0.48	0.79	37.8	154
Spectral indexes							
NDVI	0.57 ± 0.003	0.22	0.68	0.20	0.83	19.4	138
NDII	0.30 ± 0.003	0.11	0.41	0.01	0.99	1.0	126
RE NDVI–1	0.47 ± 0.003	0.22	0.57	0.02	0.88	2.2	73
RE NDVI–2	0.55 ± 0.004	0.29	0.65	0.02	0.97	1.5	66
GNDVI	0.48 ± 0.003	0.31	0.58	0.00	0.89	0.0	76
LSWI	0.49 ± 0.003	0.29	0.59	0.00	0.89	0.0	89
LAI	0.09 ± 0.001	0.03	0.17	0.01	0.79	1.0	33
MTCI	8.04 ± 0.104	3.17	12.00	0.14	0.88	13.7	55

Notes: * – SDL is the spatial dependence level; ** – ST is the soil temperature, °C; SM is the soil moisture, %; EC is the soil electrical conductivity, dSm/m; L is the lighting, Lx; AT is the air temperature, °C; AH is the air humidity, %; CO is the canopy openness, %; LAI4 is the effective leaf area index integrated over the zenith angles 0 to 60°; LAI5 is the effective leaf area index integrated over the zenith angles 0 to 75°; Dr is the amount of direct solar radiation transmitted by the canopy, $Mols/m^2\ d^1$; Df is the amount of diffuse solar radiation transmitted by the canopy, $Mols/m^2\ d^1$; TT is the sum of Dr and Df, $Mols/m^2\ d^1$.

Canopy openness ranged from 9.2% to 100.0% and exhibited a strong spatial variability with a radius of 152 m. The lowest canopy openness was found for the tree stand in the central and northern part of the park (Fig. 3). In the eastern and southern parts of the park, the canopy openness was very high. A completely open space, devoid of tree cover, was in the gully talweg in the northeastern part of the park. The LAI4 and LAI5 were strongly positively correlated (r = 0.96, P < 0.001) and exhibited a similar spatial pattern. The LAI was greatest in the central and northern part of the park. The direct solar radiation ranged from 0.2 to 14.6 $Mols/m^2$ d1 and exhibited a moderate spatial dependence with a radius of 152 m. The direct solar radiation was lowest in the central and northern part of the park, and highest in the northwestern and eastern part of the park. The diffuse solar radiation ranged from 1.1 to 14.6 $Mols/m^2$ d1 and exhibited a moderate spatial dependence with a radius of 150 m. The direct and diffuse radiation were strongly positively correlated (r = 0.85, P < 0.001). The peculiarity of diffuse radiation is that it is higher in areas of the park that are closer to the border with non-forested areas.

A strong level of spatial dependence with a radius of 33–138 m was found for all vegetation indices. The maximum values of NDVI index were characteristic of gully slopes (Fig. 4). The lowest values of this index were found for treeless areas. All vegetation indices except MTCI had a high level of mutual correlation (r = 0.37–0.99, P < 0.001). The MTCI index had a positive correlation with the NDVI, NDII, Red-Edge NDVI-2, GNDVI, and LSWI indices (r = 0.15–0.30, P < 0.001) and a negative correlation with the LAI index (r = –0.47, P < 0.001).

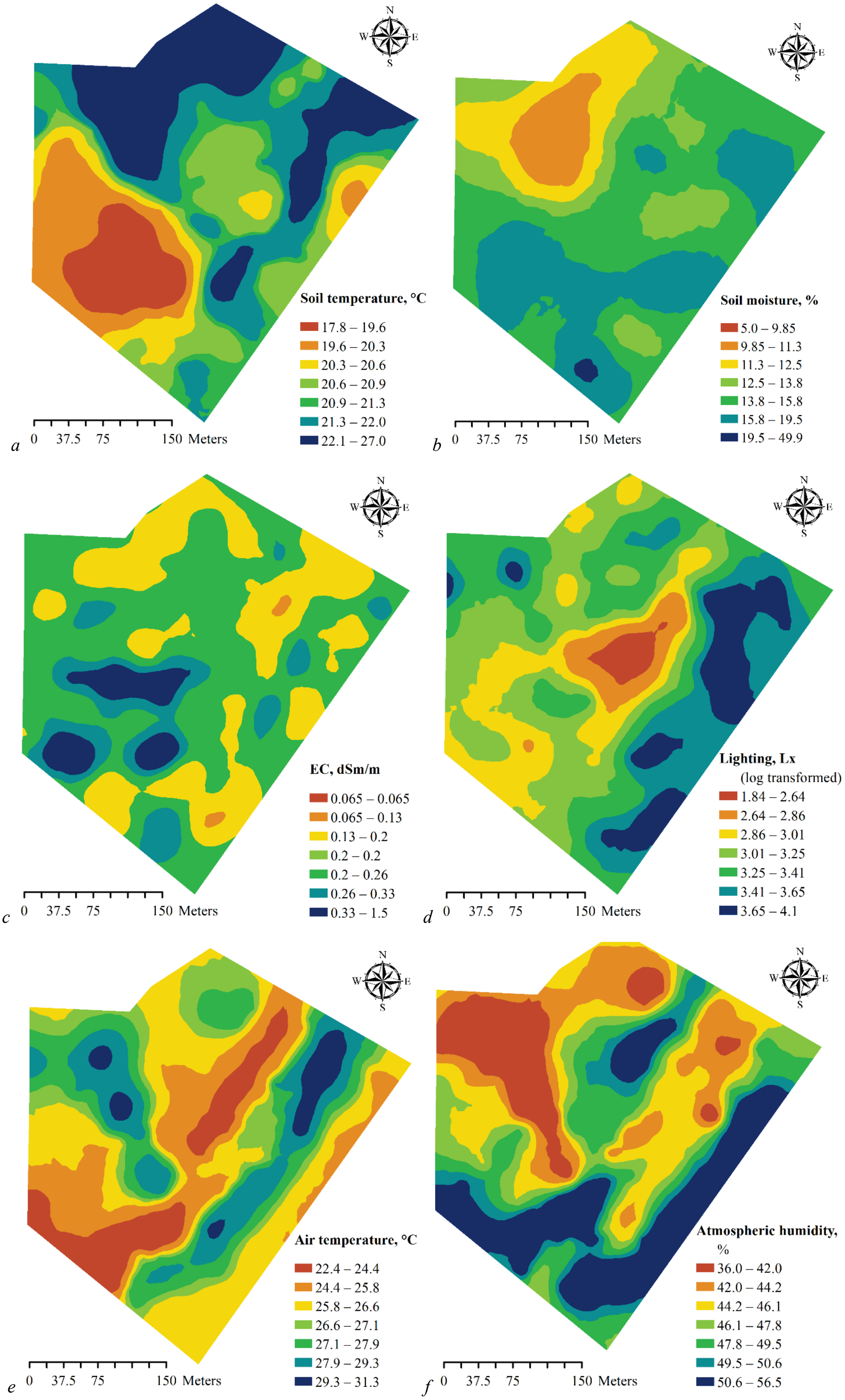


Fig. 2. Spatial variation of soil and microclimatic parameters: *a* is the soil temperature (°C); *b* is the soil moisture (%); *c* is the soil electrical conductivity (dSm/m); *d* is the lighting (Lx); *e* is the air temperature (°C); *f* is the air humidity (%)

The first four principal components, whose eigenvalues exceeded unity, were extracted by the principal components analysis of the variability of ecological properties and vegetation indices (Table 2). The first four components were able to explain 79.6% of the variation of the trait space. The principal component 1 explained 50.5% of the variation of the traits and positively correlated with the spectral vegetation indices. This component reflected the trend of increasing vegetation indices, with increasing soil moisture, electric conductivity, atmospheric moisture and leaf area index, but decreasing soil temperature, lightness, atmospheric temperature, canopy openness percentage and solar radiation transmitted by the canopy. Obviously, the principal component 1 reflected the variability of tree cover densities due to the edaphic trophicity. The principal component 1 exhibited a strong spatial variability with a radius of 129 m. The maximum value of the principal component 1 was reached on the slopes of the gully and in the eastern part of the park.

The principal component 2 described 13% of the variation in the feature space. This component correlated positively with the spectral indices, except for NDVI and MTCI. The principal component 2 correlated strongly positively with the soil moisture and electrical conductivity, canopy openness percentage, and solar radiation transmitted by the canopy and correlated negatively with the soil temperature and leaf area index. This component had a moderate level of spatial dependence with a radius of 141. The maximum of the principal component 2 was found for the gully slope of the server exposure. The principal component 2 can be interpreted as a trend of vegetation cover variability induced by moisture variation.

The principal component 3 described 8.6% of trait variation. It was most strongly correlated with the atmospheric humidity. An increase in atmospheric humidity was associated with an increase in the soil moisture and electrical conductivity and a decrease in the soil and atmospheric temperature. An increase in atmospheric humidity was associated with an increase in LAI and a decrease in other indices except NDII. This principal component had no correlation with stand canopy characteristics. The principal component 3 had a strong spatial dependence with a radius of 67 meters. Plots with high and low values of principal component 3 formed a mosaic structure with oval-shaped patches measuring several tens of meters. The principal component 3 can be interpreted as a marker of atmospheric humidity.

The principal component 4 described 7.5 % variation of traits. It is most sensitive to the opposite dynamics of variation of the vegetation indices MTCI and LAI. An increase in the values of principal component 4 was associated with an increase in the soil moisture and electrical conductivity and atmospheric moisture and was associated with a decrease in the soil and atmospheric temperature. This principal component had no correlation with stand canopy characteristics.

The ecological indices measured in the field can be predicted using the vegetation indices (Table 3). Multiple regression models were able to explain 11–61% of indicator variation. The statistically significant predictors of soil temperature were NDVI, NDII (negative regression coefficients), and GNDVI (positive coefficient). Only the LSWI index was a statistically reliable predictor of soil moisture. The NDII index was the only significant predictor of the soil electrical conductivity.

Table 2
Principal component analysis of variation
in the ecological properties and spectral indices of park plantations

Variable	PC1 $\lambda_1 = 10.1$, 50.5%	PC2 $\lambda_2 = 2.6$, 13.0%	PC3 $\lambda_2 = 1.7$, 8.6%	PC4 $\lambda_2 = 1.5$, 7.5%
Ecological properties*				
ST	–0.63	–0.34	0.31	–0.26
SW	0.35	0.51	–0.23	0.19
EC	0.30	0.60	–0.24	0.21
L	–0.70	–	–	–
AT	–0.59	–	0.45	–0.42
AH	0.24	–	–0.85	0.15
CO	–0.88	0.35	–	–
LAI4	0.76	–0.49	–	–
LAI5	0.77	–0.51	–	–
Dr	–0.79	0.45	–	–
Df	–0.87	0.37	–	–
TT	–0.86	0.44	–	–
Spectral indexes				
NDVI	0.76	–	0.21	–
NDII	0.76	0.42	–	–
RE NDVI–1	0.89	0.32	0.16	–0.19
RE NDVI–2	0.89	0.31	0.20	–0.14
GNDVI	0.85	0.36	0.23	–0.14
LSWI	0.88	0.31	0.24	–
LAI	0.50	0.28	–0.22	–0.70
MTCI	0.16	–	0.55	0.73
Variogram statistics**				
Nugget	0.16	0.38	0.0081	0.33
Partial sill	0.90	0.72	0.89	0.73
SDL, %	15.09	34.55	0.90	31.13
Range, m	129	141	67	88

Notes: * – ST is the soil temperature, °C; SM is the soil moisture, %; EC is the soil electrical conductivity, dSm/m; L is the lighting, Lx; AT is the air temperature, °C; AH is the air humidity, %; CO is the canopy openness, %; LAI4 is the effective leaf area index integrated over the zenith angles 0 to 60°; LAI5 is the effective leaf area index integrated over the zenith angles 0 to 75°; Dr is the amount of direct solar radiation transmitted by the canopy, Mols/m^2 d^1; Df is the amount of diffuse solar radiation transmitted by the canopy, Mols/m^2 d^1; TT is the sum of Dr and Df, Mols/m^2 d^1; ** SDL is the spatial dependence level.

Illuminance can be predicted using GNDVI (positive regression coefficient) and NDVI and RE NDVI-2 (negative regression coefficients). Atmospheric temperature increases with LAI and decreases with NDVI and NDII. Atmospheric humidity can be predicted with NDII and MTCI. A variety of predictors were included in regression models to describe variation in stand crown characteristics. They have always included NDVI, RE NDVI-2, and GNDVI.

Table 3
Regression analysis of the influence of spectral indices on the ecological properties of the park plantation
(beta-regression coefficients ± SE are presented, which are significant at P < 0.05)

Response variable*	R_{adj}^2	Predictors (spectral indexes)							
		NDVI	NDII	RE NDVI–1	RE NDVI–2	GNDVI	LSWI	LAI	MTCI
ST	0.46	–0.48 ± 0.09	–0.69 ± 0.11	–	–	0.55 ± 0.25	–	–	–
SW	0.19	–	–	–	–	–	0.73 ± 0.24	–	–
EC	0.16	–	0.54 ± 0.15	–	–	–	–	–	–
L	0.43	–0.52 ± 0.09	–	–	–1.48 ± 0.41	0.88 ± 0.25	–	–	–
AT	0.22	–0.27 ± 0.11	–0.43 ± 0.14	–	–	–	–	0.22 ± 0.11	–
AH	0.11	–	0.31 ± 0.15	–	–	–	–	–	–0.32 ± 0.09
CO	0.61	–0.41 ± 0.07	–	–0.82 ± 0.30	–1.36 ± 0.34	1.60 ± 0.21	–	0.23 ± 0.08	–
LAI4	0.37	0.23 ± 0.09	–0.35 ± 0.12	–	1.25 ± 0.43	–1.36 ± 0.27	0.47 ± 0.21	–	–
LAI5	0.35	0.24 ± 0.10	–0.28 ± 0.13	–	1.33 ± 0.44	–1.37 ± 0.27	0.44 ± 0.21	–	–
Dr	0.42	–0.36 ± 0.09	–	–	–1.82 ± 0.42	1.58 ± 0.26	–	–	–
Df	0.58	–0.36 ± 0.08	–	–0.66 ± 0.31	–1.42 ± 0.35	1.67 ± 0.22	–	0.24 ± 0.08	–
TT	0.52	–0.37 ± 0.08	–	–	–1.71 ± 0.38	1.68 ± 0.23	–	–	–

Notes: * – ST is the soil temperature, °C; SM is the soil moisture, %; EC is the soil electrical conductivity, dSm/m; L is the lighting, Lx; AT is the air temperature, °C; AH is the air humidity, %; CO is the canopy openness, %; LAI4 is the effective leaf area index integrated over the zenith angles 0 to 60°; LAI5 is the effective leaf area index integrated over the zenith angles 0 to 75°; Dr is the amount of direct solar radiation transmitted by the canopy, Mols / m^2 d^1; Df is the amount of diffuse solar radiation transmitted by the canopy, Mols / m^2 d^1; TT is the sum of Dr and Df, Mols / m^2 d^1.

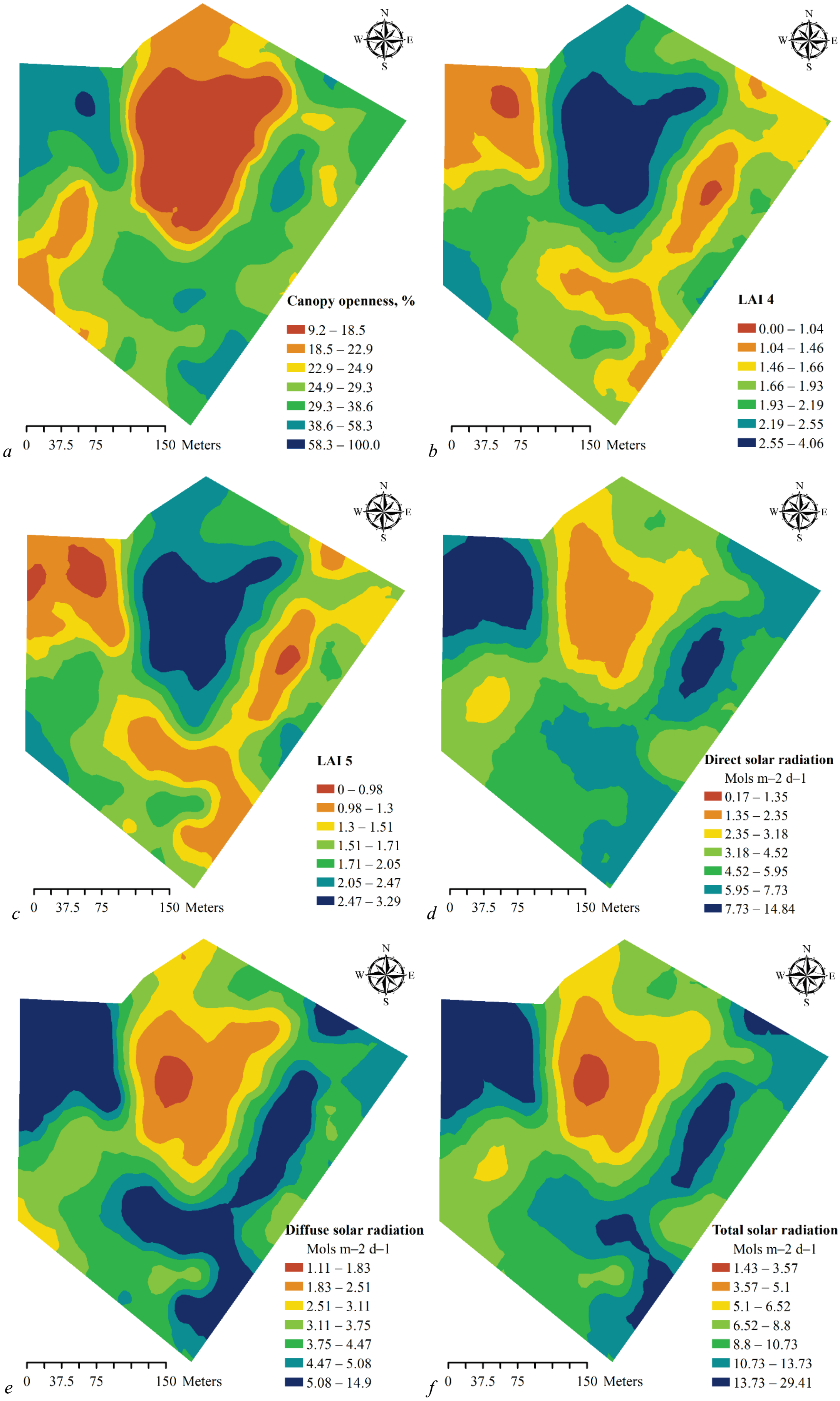
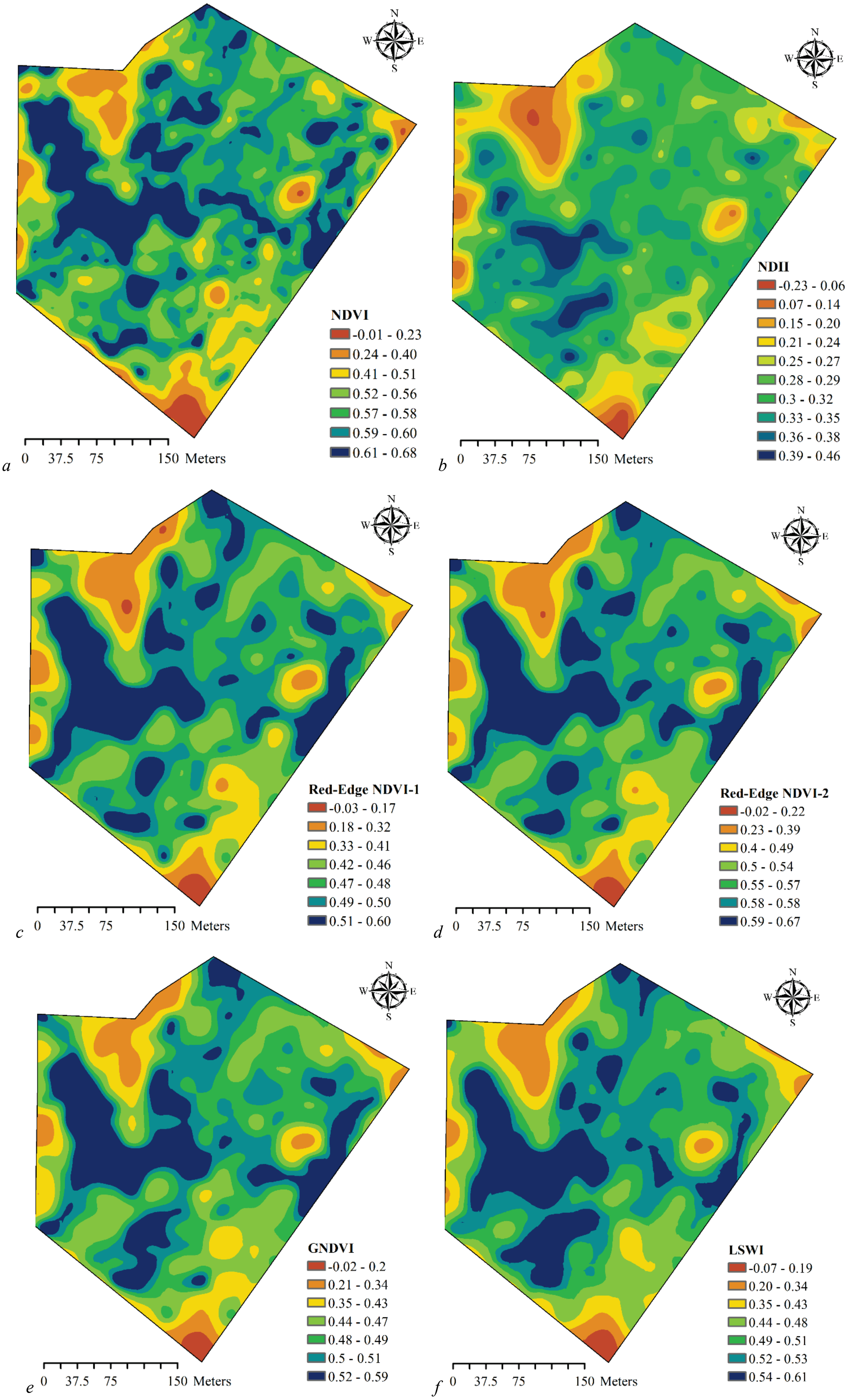


Fig. 3. Spatial variation of tree stand canopy indicators: *a* is the canopy openness, %; *b* is the effective leaf area index integrated over the zenith angles 0 to 60°; *c* is the effective leaf area index integrated over the zenith angles 0 to 75°; *d* is the amount of direct solar radiation transmitted by the canopy, Mols/m2 d^1; *e* is the amount of diffuse solar radiation transmitted by the canopy, Mols/m^2 d^1; *f* is the sum of Dr and Df, Mols/m^2 d^1


N
W
E
S
NDVI
-0.01 - 0.23
0.24 - 0.40
0.41 - 0.51
0.52 - 0.56
0.57 - 0.58
0.59 - 0.60
0.61 - 0.68
a
0 37.5 75 150 Meters
NDII
-0.23 - 0.06
0.07 - 0.14
0.15 - 0.20
0.21 - 0.24
0.25 - 0.27
0.28 - 0.29
0.3 - 0.32
0.33 - 0.35
0.36 - 0.38
0.39 - 0.46
b
0 37.5 75 150 Meters
Red-Edge NDVI-1
-0.03 - 0.17
0.18 - 0.32
0.33 - 0.41
0.42 - 0.46
0.47 - 0.48
0.49 - 0.50
0.51 - 0.60
c
0 37.5 75 150 Meters
Red-Edge NDVI-2
-0.02 - 0.22
0.23 - 0.39
0.4 - 0.49
0.5 - 0.54
0.55 - 0.57
0.58 - 0.58
0.59 - 0.67
d
0 37.5 75 150 Meters
GNDVI
-0.02 - 0.2
0.21 - 0.34
0.35 - 0.43
0.44 - 0.47
0.48 - 0.49
0.5 - 0.51
0.52 - 0.59
e
0 37.5 75 150 Meters
LSWI
-0.07 - 0.19
0.20 - 0.34
0.35 - 0.43
0.44 - 0.48
0.49 - 0.51
0.52 - 0.53
0.54 - 0.61
f
0 37.5 75 150 Meters

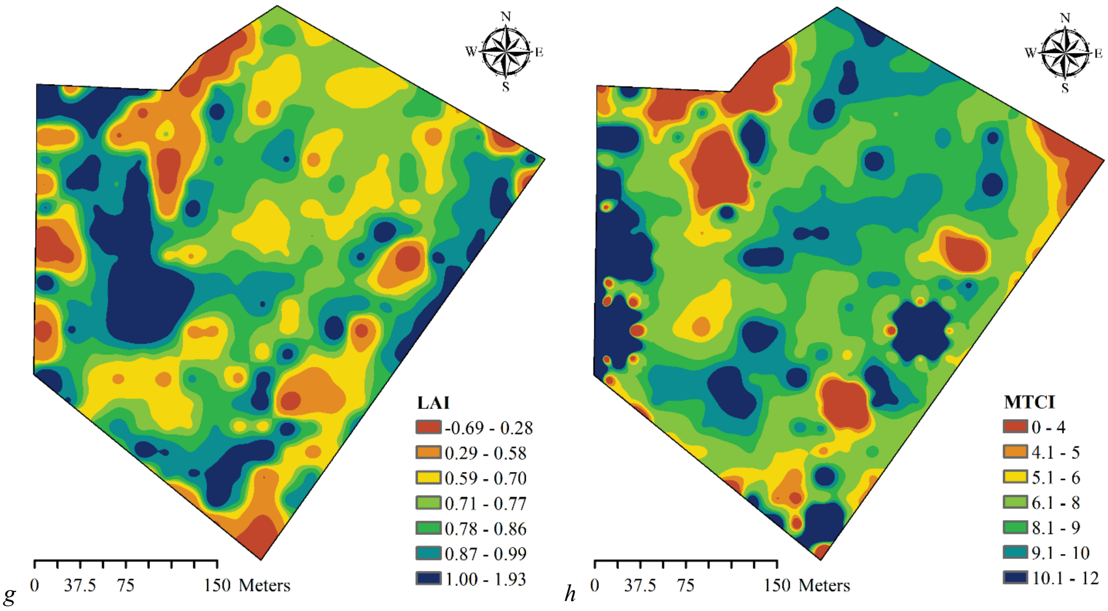


Fig. 4. Spatial variation of spectral vegetation indices: *a* is the Normalized Difference Vegetation Index (NDVI), *b* is the Normalized Difference Infrared Index (NDII), *c* is the Red-Edge NDVI-1 (RE NDVI–1), *d* is the Red-Edge NDVI-2 (RE NDVI–2), *e* is the Green NDVI (GNDVI), *f* is the Land Surface Water Index (LSWI), *g* is the Leaf Area Index (LAI), *h* is the MERIS Terrestrial Chlorophyll Index (MTCI)

Discussion

Environmental drivers of park plantation. The ecological parameters measured in the field and the vegetation indices obtained by analysis of remote sensed data are closely correlated with each other and form four patterns of variability, which was revealed by the principal component analysis. The principal component 1 indicates the variability of the phytomass of plant communities indicated by the spectral vegetation indices. All spectral indices make unidirectional contributions to this principal component. The most important factor that determines the phytomass of a tree stand is the trophicity of the edaphotope (Belgard, 1950; Zhukov & Shatalin, 2016). The edaphotope trophicity is an integrated indicator that reflects the availability of nutrients needed to form phytomass, to the amount of which tree plants are most sensitive, as their organisms require significantly more substances than shrubs or herbaceous plants (Belgard, 1971). The zone of high phytomass and, accordingly, high trophicity of edaphotope, corresponds to the middle part of the gully slope, where in natural conditions the most favourable mineral nutrition regime for forest development is formed. The park plantation was created artificially in the place of natural forest and, as can be seen, the patterns of spatial variation of the productivity potential of the park plantation exactly repeat the patterns of the natural ecosystem. It should be noted that the ordinate of trophicity is leading in the classification of natural forests of the steppe zone of Ukraine (Belgard, 1971). The results indicate that the trophicity is also a key factor in the organization of the artificial forest. This aspect is taken into account in the typology of artificial forests, but in a very rough approximation (Belgard, 1971). In the typology of artificial forests, the surrogate of trophicity is the granulometric composition of soils, which only in a very broad approximation can characterize the trophicity of edaphotope. It is obvious that the role of trophicity in the organization of the artificial forest is no less than in the organization of the natural forest. Also, this proximity of the artificial forest's response to the trophicity gradient indicates the process of its naturalization: it is the approximation of the artificial forest plantation by its organization and function to the natural regimes.

The trophotope influences the phytomass of the forest community (Sytnyk, 2019; Suthari et al., 2020), which in turn determines the ecological properties and regimes that are formed in the forest (Šír et al., 2009; Rahmonov et al., 2021). The influence of the forest on ecological regimes and microclimatic conditions is termed the concept of pertinence (Visotsky, 1960; Zhukov et al., 2017). An increase in the phytomass of the forest community contributes to an increase in the air and soil moisture and a decrease in the air and soil temperature. In the context of a park plantation, these transformations are important for the park plantation's ecosystem functions and to increase the park's attractiveness to visitors (Ćwik et al., 2018). The decrease in temperature and the increase in air humidity is an extremely attractive environmental change in an urban setting (Cheung et al., 2021). The increase of phytomass in the gradient of edaphotope conditions is accompanied by the structural restructuring of the stand. The canopy openness decreases and the amount of solar radiation that reaches the soil surface decreases. This explains the increase in soil moisture and the decrease in soil temperature.

The principal component 2 reflects changes in the stand structure in the moisture gradient. Along with trophicity, the moisture gradient is the most important ordinate in the typology of natural forests of the steppe zone of Ukraine (Shvidenko et al., 2017). An increase in soil moisture is associated with a decrease in its temperature. It is important to note that NDVI vegetation index is insensitive to the moisture conditions gradient, which makes it a sensitive indicator of the variability of the trophicity gradient in particular. In turn, the vegetation indices NDII, RE NDVI-1, RE NDVI-2, GNDVI, LSWI, which were developed for the indication of vegetation moisture (Hardisky et al., 1983; Gitelson et al., 1996; Jurgens, 1997; Xie et al., 2018), showed their high correlation with the hygrotope. It should be noted that NDII index is the most sensitive to humidity, as it correlates with only two principal components. All other vegetation indices, which are sensitive to moisture, correlate with four principal components, suggesting their low specificity.

The vegetation index MTCI has the highest correlation with the principal component 3. This index is sensitive to the chlorophyll content in phytomass (Dash & Curran, 2004). An important feature of principal component 3 is its absence of correlation with the indicators of crown condition of tree plants. Obviously, the species peculiarities of the stand are the reason for the formation of the trend described by the principal component 3. This component correlates positively with the presence of *Gleditsia triacanthos* and *Robinia pseudoacacia* in the stand. Both species belong to the order Fabales and are alien in the flora of Ukraine (Baranovski et al., 2016). The chlorophyll pigments of the *Gleditsia triacanthos* plants showed stable content around 20.66 ± 3.49 mg/g (Kebbas et al., 2018). Across the 823-plant species Chl a+b ranged from 1.20 to 22.58 mg/g (Li et al., 2018). Among the trees growing in Dnipro city, *Robinia pseudoacacia* has a relatively high chlorophyll content (Ivanko & Kulik, 2021). Thus, the principal component 4 reflects the spatial heterogeneity of *Gleditsia triacanthos* and *Robinia pseudoacacia* plantations within the park. These tree plant species are associated with the conditions of higher soil and air temperatures and low soil and atmospheric moisture and low soil conductivity. There is evidence that after the planting of forests of *Robinia pseudoacacia* a decrease in soil moisture occurs (Liang et al., 2018).

The principal component 4 is also marked with MTCI (positive correlation) and LAI (negative correlation). With the increase in the ordinal number of the principal component, its meaningful interpretation becomes more difficult. Obviously, this principal component can only be evaluated descriptively based on the variables that correlate with it.

Assessment of ecological properties with vegetation indices. An important result is the ability to estimate the value of environmental traits using spectral vegetation indices. The predictive power of regression models for soil and microclimatic properties is low, so it is of analytical rather than practical importance. The forest canopy characteristics can be predictted quite well with the vegetation indices, so their practical application cannot be excluded.

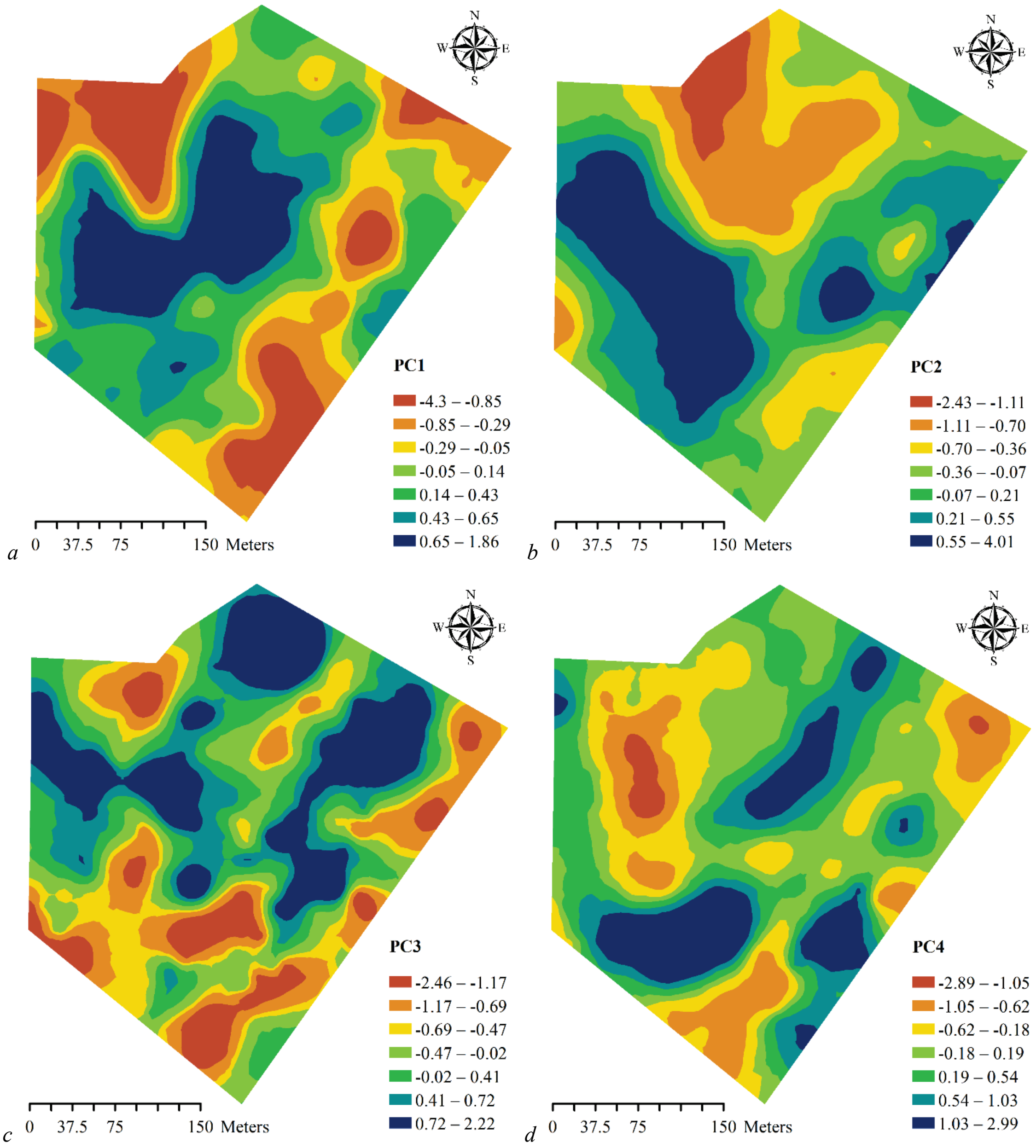


Fig. 5. Spatial variation of the principal components derived from the analysis of variation in ecological properties and spectral vegetation indices: *a* is the spatial variation of the PC1 scores, *b* is the spatial variation of the PC2 scores, *c* is the spatial variation of the PC3 scores, *d* is the spatial variation of the PC4 scores

The structure of regression models generally confirms the existing understanding of the qualitative significance of vegetation indices (Zimaroeva et al., 2016; Ponomarenko et al., 2021). Thus, the lower the soil temperature, the higher the phytomass of tree vegetation, which is well described by the NDVI and NDII indices. The GNDVI index most likely labels herbaceous phytomass, which explains its positive sign in the regression model. The LSWI index, which was created specifically to indicate the surface moisture of plant organisms, is the only predictor of soil moisture. However, NDVI was shown to correlate closely with the soil moisture (Zhang et al., 2011). It is important to note that, in general, electrical conductivity and soil moisture are closely correlated, but their predictors are different indices (Zhukov et al., 2021). The NDII index is the only predictor of soil electrical conductivity. This index was also created to indicate the green vegetation moisture. Obviously, the predictive ability of the NDII index is due to the relationship between soil moisture and electrical conductivity. The electrical conductivity should also be considered, as it indicates the mineralization of the soil solution and is thus one of the indicators of the trophicity of the edaphotope (Mazur et al., 2022). The influence of edapotope trophicity on the phytomass and plant community structure may be the cause of relationship between the soil electrical conductivity and the NDII index.

The light regime is higher in herbaceous communities than in communities with woody vegetation (Blank & Carmel, 2012), which explains the negative regression coefficients of NDVI and RE NDVI-2 for predicting light. The regression coefficient for the GNDVI predictor has a negative sign. This can be explained by the fact that this vegetation index GNDVI is sensitive precisely to the variation of herbaceous vegetation if the effect of forest vegetation was considered.

The predictive power of the models for microclimatic indicators is very low. It is obvious that the microclimatic conditions are highly variable in the urban park (Li et al., 2022), as this plant community has an island character and a significant zone of contact with the surrounding urbanized space (Motazedian et al., 2020; Amani-Beni et al., 2021). The forest community and the park as its variety is characterized by the stability of microclimate regime (De Frenne et al., 2021), while the urban development and communications are characterized by high variability of microclimatic regime (Kousis et al., 2021; Kulish, 2022). It is natural that the park plantation has a stabilizing effect on the urban environment and the urban environment has a destabilizing effect on the park environment. This is the difference between the park environment and the natural forest environment. Nevertheless, the regression models indicate the importance of park plantation structure on the microclimatic regime. An increase in vegetation contributes to a decrease in the temperature and an increase in the humidity of the park atmosphere. Obviously, the degree of this influence is site-specific, so a global regression model cannot reliably describe the nature of the dependence of microclimatic indicators on vegetation indices.

Canopy openness and penetrating solar radiation can best be predicted using the vegetation indices. The contribution of the traditional vegetation index NDVI to the regression model is much smaller than that of RE NDVI-2 and GNDVI. The vegetation indices are sensitive to the amount and functional state of chlorophyll in plants, so the mechanism of indication of canopy openness of tree vegetation can be assumed to be in the sensitivity of predictors to the composition of functional groups of vegetation, which differ in their spectral characteristics. The functional groups and life forms of plants differ in chlorophyll content. According to the degree of decrease in chlorophyll *a*, chlorophyll *b* and total chlorophyll content, plants can be ordered as follows: trees (evergreens > deciduous trees) > shrubs > grasses. In terms of the ratio of chlorophyll *a* to chlorophyll *b*, the plants can be ordered as follows: trees (conifers < broad-leaved) < shrubs < grasses (Li et al., 2018). Thus, the vegetation spectral indices are sensitive to the different amounts of chlorophyll in the plants, and the change in canopy structure and light regime leads to the changes in the functional structure of the vegetation cover. Obviously, the sensitivity of the complex of vegetation indices to the functional structure of vegetation is the mechanism of their predictive ability to assess the condition of the canopy of a park plantation.

Prospects for practical implementation. A park plantation can significantly change the microclimatic regime and have a stabilizing effect on the surrounding urban environment. Such a transformational trend is consistent with the concept of pertinence and includes changes in a number of ecosystem services performed by park plantations. Tree species composition and placement patterns are the key drivers of ecosystem services. However, the park as an ecosystem is subject to development and this development is determined by environmental conditions. The drivers of the natural forest ecosystem in the conditions of the steppe zone of Ukraine are the trophotope and hygrotope. These drivers retain their relevance for the park plantation as well. The combinations of the trophotope and hygrotope create the optimal conditions for specific tree species, which is a condition for achieving the maximization of ecosystem services. The mineral nutrition conditions of plants and soil moisture exhibit spatial patterns that allow them to be considered in the design and management of park plantations. It should be noted that the consideration of relief heterogeneity also facilitates the achievement of the maximum aesthetic attractiveness of the park plantation.

The regression relationships between markers of soil and microclimatic conditions and vegetation predictors are important for monitoring the condition of park plantations and evaluating the performance of park plantation management tools. Artificial forest plantations have a significant duration of stages of their development, which is due to the longevity of tree life. Many management decisions, which are taken at any particular moment of time, will have consequences during a significant time interval in the future. To evaluate the effectiveness of management alternatives, it is necessary to "go back in time". This can be achieved through retrospective analysis of satellite images of the territory of interest. The regression models make it possible to interpret the satellite images and get a wide range of ecologically relevant information about the state of park plantations in different time periods.

In the perspective of further research, it is advisable to solve the following problems. An important and interesting problem is relief heterogeneity of park plantations and figuring out the role of relief in the organization of park plantations. It is necessary to assess the role of species composition and species diversity in the formation of microclimate in the park plantation and variability of soil properties. The influence of forest vegetation canopy structure on the species diversity and functional condition of the herbaceous layer of the park plantation should be identified. And, of course, it is important to assess the financial impact of the ecosystem services provided by the park plantation.

Conclusion

The variation of microclimatic and soil properties depends on the features of the park stand. An increase in the phytomass of the tree stand results in a decrease in soil and air temperature and an increase in soil and atmospheric moisture in the summertime. The stand features depend on its species composition. The key drivers of park stand structure and function are the trophotope and hygrotope. The state of the park stand can be assessed using remote sensing data. The spectral vegetation indices can be applied as the predictors for the evaluation of soil and microclimatic properties. The spectral differences in the functional groups of plants are the cause of the predictive power of the vegetation indices. The state of crown space can also be effectively predicted with the help of vegetation indices.

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