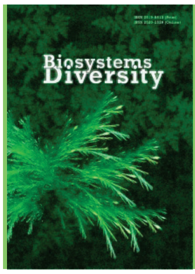

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Landscape diversity mapping allows assessment of the hemeroby of bird species in a modern industrial metropolis

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The article proposes a methodology for identifying the hemeroby of avifauna inhabiting a contemporary industrial metropolis. The Landsat 8-9 OLI/TIRS satellite image of the city of Dnipro (Ukraine) dated 14 July 2024 was employed for further analysis. The classification of land cover types was performed in SAGA-9 without training using the k-means procedure. The classification was performed on the basis of geospatial layers represented by spectral indices and road network density. For each cluster, the average value of the hemeroby level was calculated, which was rounded to a whole value and used as an indicator of hemeroby that is typical for the respective cover type. The hemeroby values were extracted from the geospatial data layer obtained using landscape metrics at the points of bird species encounters. The mean value and standard deviation of hemeroby during bird encounters were calculated based on the data obtained. These values were considered indicators of bird species hemeroby and their tolerance to hemeroby. The surface temperature within the city exhibited a range of 29.4 to 33.6 °C. The highest temperatures were recorded in the city centre and in the eastern and northern districts, with the lowest temperatures observed in the eastern region. The principal component analysis enabled the extraction of three principal components with eigenvalues exceeding one. Principal component 1 exhibited a positive correlation with the spectral indices that indicate anthropogenic surfaces and a negative correlation with indices that are sensitive to vegetation density, surface moisture and rock or soil composition. Therefore, Principal component 1 can be interpreted in a meaningful manner as an aspect of hemeroby induced by a decrease in vegetation cover due to an increase in the presence of anthropogenic objects. Principal component 2 was found to be positively correlated with surface temperature and indices that are sensitive to anthropogenic surfaces, as well as road network density. This principal component can be interpreted as an aspect of hemeroby related to thermal pollution. The most significant indicator of principal component 3 is road network density. Therefore, all of the primary extracted principal components are associated with hemeroby, and an integrated hemeroby indicator was calculated. The classification procedure, based on spectral indices and road network density, yielded 20 land cover types and one additional category representing water bodies. The hemeroby of birds exhibited considerable variation, with values ranging from 15 to 89. The birds were classified into the following categories based on the extent of their hemeroby. The ahemerobic group comprised 15 species, the oligohemerobic group 11, the mesohemerobic group 8, the beta-euhemerobic group 8, the alpha-euhemerobic group 10, the polyhemerobic group 9 and the metahemerobic group 5. The stenotopic group comprises 30 species, the mesotopic group 17 species, and the eurytopic group 19 species of birds. In the case of 34 species of bird fauna in the city of Dnipro, estimates have been obtained for the European bird fauna on the basis of the mean hemeroby score, which was calculated for the European avifauna. A statistically significant correlation was observed between the hemeroby scores and the mean hemeroby score.

Keywords: urban park; multi-storey buildings; anthropogenic transformation; environmental monitoring; avifauna; remote sensings.

Introduction

Hemeroby is regarded as an integrative measure of the impact of all human intervening factors on ecosystems (Sukopp, 1976). This concept has evolved from an understanding of hemeroby as a method of classification of individual plant species to the application of the term to plant communities as a whole (Sukopp, 1976) and to define anthropogenic soil transformation. The term ‘hemeroby’ is used to describe the tendency of plant species to adapt to urban environments (Zinnen et al., 2021), the morphological and chemical characteristics of soils (Kunakh et al., 2024) and the structure of land use types within a given landscape (Steinhardt et al., 1999). Hemeroby provides a proxy for the distance between the current state of an ecosystem and a hypothetical state of full absence of human disturbance. Thus, it is an inverse measure of closeness to nature, if anthropogenic interventions are reversed. The term “naturalness” is used to describe the distance between the current state of an ecosystem and its natural state. It can be argued that there is a potential for hemeroby and naturalness to be considered symmetrical if the trajectory of ecosystem naturalness were to decrease in line with increasing anthropogenic pressure, in a similar manner to the trajectory of ecosystem return to the natural state with decreasing pressure. However, this is not a valid assumption, and therefore the meaning of hemeroby differs from the meaning of ecosystem naturalness (Yorkina et al., 2022).

The intricate web of interactions and relationships that characterise natural ecosystems render them highly complex. The effects of human intervention in ecosystems are complex and difficult to predict, with different types of anthropogenic impact often interconnected and variable. The impact of anthropogenic disturbance on biodiversity is a significant concern on a global scale. However, the consequences extend beyond the loss of species (Matuoka et al., 2020). The consequences of anthropogenic impacts can be disproportionate to their physical dimensions, and the intensity of the impact is subject to significant variability in space and time. Consequently, the characterisation of anthropogenic ecosystem transformation through the use of individual indicators is a challenging and frequently unfeasible endeavour (Fehrenbach et al., 2015). It is unlikely that biological systems at different levels of organisation would develop specific adaptations to the impact of anthropogenic activity during the process of evolutionary development (Bell & Collins, 2008), therefore, the response to this impact is of a nonspecific nature (Häder et al., 2020). The nonspecific nature of the response forms a common pattern that can be ordered as anthropogenic pressure increases, which is reflected in the concept of hemeroby. It is for this reason that any form of land use can be described in accordance with the concept of hemeroby. (Fehrenbach et al., 2015). The deterioration of an ecosystem's primary structural and functional properties as a result of human-induced impacts is defined as ecosystem degradation (DeFries et al., 2012). The degradation process can be understood as a series of successive stages of ecosystem change, progressing from the natural state, which is characterised by high complexity, resilience and functional efficiency, to the most anthropogenically transformed state, which exhibits low complexity, minimum functional efficiency and sustainability in space and time. The response of species to anthropogenic degradation varies. Some species are capable of sustaining themselves in predominantly natural or near-natural conditions, whereas others are able to tolerate, benefit from, or even require anthropogenic impacts (Fanelli & De Lillis, 2004). An appreciation of the preferences of plant species in the context of anthropogenic environmental transformation is instrumental in gauging the extent of ecosystem degradation. It is therefore evident that an understanding of the composition of plant communities is fundamental to the assessment of the impact of human activity on ecosystems.

The process of urbanisation has been identified as a significant contributor to a range of environmental issues, including soil compaction, air and water pollution, the suppression of natural vegetation, biodiversity loss and climate transformation. The objective study of the spatial and temporal transformations of urban ecosystems induced by anthropogenic pressure can be achieved through the utilisation of remote sensing methods that identify land surface types (Furtado et al., 2024). The aforementioned land surface types can be ordered from the most preserved to the most altered areas (Steinhardt et al., 1999). The process of urbanisation and the intensity of urban land use have a significant impact on the environment (Knapp et al., 2017). The concept of hemeroby is employed for the assessment of the anthropogenic transformation of urban landscapes (Walz & Stein, 2014).

The natural history and ecology of animals is a determining factor in their specific sensitivity to environmental disturbances. The impact of disturbance on competition and predation has an effect on the dynamics of the community. The interaction between disturbance and these biological processes represents a pivotal factor in the organisation and spatial structure of natural communities (Sousa, 1984). The location of animals within functional space is an effective predictor of the intricate changes that occur in disturbed ecosystems (Mouillot et al., 2013). Birds represent the most diverse class of terrestrial vertebrates (Gross, 2019), encompassing a vast array of species that inhabit diverse habitats (Tu et al., 2020). The functional diversity of avian communities is adversely impacted by anthropogenic pressures (Matuoka et al., 2020). Bird species may be specialised, inhabiting only one or a few habitat types, or generalists, capable of existing in a vast array of habitats. The specialist/generalist gradient is a key feature of bird communities, and this pattern becomes more apparent with habitat degradation (Julliard et al., 2006). Bird species exhibit disparate responses to natural and anthropogenic disturbances (Brawn et al., 2001). The isolation of habitats and the expansion of urban areas have a deleterious effect on the functional diversity of birds, which in turn compromises the ability of ecosystems to maintain their functions and resilience (Matuoka et al., 2020).

The effects of environmental disturbances have been observed to result in the degradation of habitats for certain species, yet simultaneously, or indirectly, create opportunities for others (White, 1979). Birds can be classified as either tolerant or sensitive to disturbances (Brawn et al., 2001). Synanthropic bird species demonstrate a preference for anthropogenic ecosystems (Guetté et al., 2017). The assessment of the impact of urbanisation on biodiversity is constrained by the absence of ideal indicators. The traditional classification, such as 'urbanisation tolerant', provides an opportunity to determine the ecological specificity of synanthropic bird species; however, it does not provide the necessary accuracy in assessing the level of anthropogenic transformation (Conole & Kirkpatrick, 2011). One of the earliest classifications of birds distinguished between synanthropic and non-synanthropic species. The former were defined as those that live in urban environments, as well as on farms, in rural areas, and in gardens and vegetable gardens (Nicholson, 1951). The proportion of individuals residing in anthropogenic habitats and the duration of their life cycle spent in such environments represents a criterion for the identification of synanthropic birds. Birds are classified according to their adaptations to human-modified habitats as full, accidental or partial synanthropes, with the latter category comprising species with the least dependence on humans (Johnston, 2001). Furthermore, a quantitative index of synanthropy has been developed which takes into account the preferences of birds in urban, rural and natural habitats. The synanthropy index ranges from +100 to –100, with a value of +100 reflecting the highest degree of synanthropy. The negative values indicate a preference for avoiding human contact, with a value of –100 indicating the highest degree of avoidance. The index offers an analysis of seasonal alterations in the habitat distribution of birds. The principal objective of the synanthropic index is to facilitate comparative studies of the extent to which birds have adapted to the conditions created by humans. The synanthropic index enables the expression of a complex situation in a single figure, as well as facilitating comparisons between different geographical regions or monitoring the evolution of adaptation over time (Nuorteva, 1971). The indicators of hemeroby and hemerobiotic entropy are based on the relative abundance of bird species in habitats classified according to their level of anthropogenic transformation (Battisti & Fanelli, 2016). The degree of sensitivity exhibited by bird species to habitat disturbance can be indirectly inferred through an examination of the relationship between species and vegetation types (Hasui et al., 2024). Birds may be confined to natural habitats that are least disturbed, which is why they are a reliable indicator for conservation (Kovařík et al., 2021). Additionally, birds may exhibit synanthropic characteristics, demonstrating a preference for habitats that have undergone significant human transformation and exhibit elevated levels of disturbance intensity or frequency (Hornok et al., 2013).

Two principal methodologies are employed to ascertain the hemeroby of ecosystems. The first is the phytoindication approach, which utilises indicator values of hemeroby or naturalness. The second is the landscape approach, which employs the interpretation of remote sensing data. The role of animals in assessing the level of hemeroby has yet to be sufficiently elucidated. Birds represent a significant element of the urban animal population, which represents a key target for nature conservation. Additionally, they can serve as a valuable source of information for assessing the extent of anthropogenic transformation of ecosystems. The study of bird communities offers significant advantages in the field of urban ecology. A significant gap exists in the study of bird community hemeroby in Eastern Europe, which this study aims to address. To achieve this, we had to address the following issues: 1) to classify the land surface types of the urban environment and perform their interpretation; 2) to assess the hemeroby of land surface types and construct a map of the city's hemeroby; 3) to establish the peculiarities of hemeroby of bird species of the urban fauna based on bird counts with geographical reference to the points of encounter.

Materials and methods

Satellite image. Landsat 8-9 OLI/TIRS image of Dnipro city (Ukraine) dated 14 July 2024 was used for further analysis. The image was downloaded from EarthExplorer (https://earthexplorer.usgs.gov/). Data on the surface reflectance of the Earth's surface temperature from the Landsat Collection 2 Level-2 Science Products were used for the calculations.

The temperature of the Earth's surface. The temperature of the Earth's surface was calculated on the basis of the information in band 10 using the formula:

$$T = 0.000341802 * B10 + 14.9,$$

where T is the temperature of the Earth's surface in °C, B10 is the reflection in band 10 (wavelength range 10.60–11.19 μm).

Aerosol index. The short-wave aerosol/coastal band (Band 1 which covers the wavelength range from 0.433 to 0.453 μm) was developed to detect aerosols and is useful for imaging shallow water and tracking small atmospheric particles such as dust and smoke. The aerosol index (AC-Index) was determined by the formula:

$$\text{AC-Index} = (B2–B1)/(B1+B2),$$

where AC-Index is the Aerosol Index, B2 is band 2 (blue band 0.452–0.512 μm), and B1 is band 1 (ultra-blue band 0.433 to 0.453 μm).

Normalized Difference Vegetation Index. The index is sensitive to the primary production and transpiration of vegetation cover (Ranjbar et al., 2018). The index was calculated using the following formula:

$$NDVI = (B5 - B4)/(B5 + B4),$$

where NDVI is a Normalized Difference Vegetation Index, B5 is band 5 (near-infrared band from 0.851 to 0.879 µm), B4 is band 4 (red band from 0.636 to 0.673 µm).

Vegetation Index, or Normalised Difference Tillage Index. The B6/B7 ratio is called a Mineral Composite Index (Dogan, 2009), or Hydrothermal Composite Index (Bishta & Qudsi, 2023), or Clay Minerals Index (Kamh et al., 2022). This ratio indicates the presence of clay sediments and clay-rich rocks, thereby facilitating the separation of water bodies from soils. Furthermore, it improves the determination of moisture in arable land and vegetation. Consequently, it is employed to study root yield and vegetation capacity. The Vegetation Index (VI) (Dai et al., 2018), or the Normalised Difference Tillage Index (NDTI) (Van Deventer et al., 1997) can be calculated as follows:

$$NDTI\ (VI) = (B6 - B7)/(B7 + B6),$$

where NDTI is the normalised difference tillage index, B6 is band 6 (shortwave infrared from 1.566 to 1.651 µm), B7 is band 7 (shortwave infrared from 2.107 to 2.292 µm).

Laterite Index. Laterite is a soil characterised by a high concentration of iron and aluminium. The presence of these elements in rocks can be estimated by the following method:

$$LI = B6 / B7,$$

where LI is the Laterite Index, B6 is band 6 (short-wave infrared range from 1.566 to 1.651 µm), and B7 is band 7 (short-wave infrared range from 2.107 to 2.292 µm). Also, the B6/B7 ratio is able to distinguish between rocks of different chemical and mineralogical compositions (Shokry et al., 2021), and also enhance information about hydroxyl modification (Yang et al., 2024).

Anthropogenic Cover Index. The B4/B7 ratio is sensitive to different types of anthropogenic cover, such as roads, urban land, fields, and other objects (Krenke & Puzachenko, 2008), and is also able to distinguish between rocks of different chemical and mineralogical compositions (Shokry et al., 2021). The index can be calculated as follows:

$$ACI = (B4–B7) / (B4+B7),$$

where ACI is the normalised differential index of anthropogenic cover, B4 is band 4 (red range from 0.636 to 0.673 µm), B7 is band 7 (short-wave infrared range from 2.107 to 2.292 µm).

Normalized Burn Ratio (NBR). The NBR is used to identify burned areas and assess the severity of the damage (García & Caselles, 1991). It is calculated as the ratio between NIR and SWIR values in the traditional way:

$$NBR = (B5 - B7) / (B5 + B7),$$

where NBR is Normalised Burn Ratio, B5 is band 5 (near-infrared range from 0.851 to 0.879 µm), B7 is band 7 (short-wave infrared range from 2.107 to 2.292 µm).

A high NBR value is indicative of healthy vegetation, whereas a low value is indicative of bare soil and recently burned areas. In areas that have not been subjected to combustion, the values are typically close to zero. It is evident that the index is indicative of the presence of vegetation with the potential to burn, therefore a more appropriate designation would be the Normalised Differential Vegetation Index of Burnable Cover. In order to calculate the NBR for a given site, the image that was taken immediately prior to the occurrence of thermal damage is used as a reference point. The second NBR value is then calculated using the image taken immediately after the damage has occurred. The extent and severity of the damage can be gauged by the discrepancy between the two index layers. A value of –0.25 indicates a high level of post-fire regrowth. A difference value from –0.25 to –0.1 corresponds to a low level of post-fire regrowth. An index from –0.1 to +0.1 indicates unburned areas. A difference from 0.1 A value of 0.27 indicates low severity burning, while a value between 0.27 and 0.44 indicates burning of medium and low severity. A value between 0.44 and 0.66 indicates burning of medium and high severity, and a value greater than 0.66 indicates high severity burning.

Green Normalised Difference Vegetation Index (GreenNDVI) is an indicator of photosynthetic activity of vegetation cover, most often used to assess moisture content and nitrogen concentration in plant leaves (Gitelson et al., 1996). In comparison to the NDVI index, it is more responsive to variations in chlorophyll concentration. It is employed for the assessment of vegetation that is exhibiting signs of stress or advanced age. The index can be calculated as follows:

$$GreenNDVI = (B5–B3)/(B5+B3),$$

where GreenNDVI is the Green Normalised Difference Vegetation Index, B3 is band 3 (green range from 0.533 to 0.590 µm), B5 is band 5 (near-infrared range from 0.851 to 0.879 µm).

Normalised Difference Snow Index. The index is calculated on the basis of the B3 and B6 bands. The green channel (B3) is particularly useful for observing the photosynthetic processes occurring in optically dense leaves, lower-level leaves, and dense crops. The data provided by this band can assist in the identification of vegetation conditions. The light in the middle infrared channel B6 is absorbed by intracellular and intercellular water, thereby increasing the rate of thermal biochemical reactions. The variability in colour within this range is indicative of changes in the water content of leaf tissue. The Normalised Difference Snow Index (NDSI) is a numerical indicator that reflects the level of snow cover in a particular area. The green and short-wave infrared (SWIR) spectral bands are employed to map snow cover. Given that snow absorbs the majority of incident radiation in SWIR, whereas clouds do not, this enables NDSI to differentiate between snow and clouds. This formula is frequently utilised for snow/ice cover mapping and glacier monitoring (Paul et al., 2016). In general, snow is characterised by high NDSI values (more than 0.4) (Bălulescu et al., 2013). Obviously, the index can also be used to assess the state of the land cover that does not have snow cover. The index can be calculated as follows:

$$NDSI = (B3 - B6)/(B3 + B6),$$

where NDSI is the Normalised Differential Snow Index, B3 is band 3 (green band from 0.533 to 0.590 µm), and B6 is band 6 (short-wave infrared band from 1.566 to 1.651 µm).

Land Surface Water Index (LSWI) (Chandrasekar et al., 2010) (or Normalized Difference Infrared Index) uses infrared, which is sensitive to the liquid water content of the crop and the background soil moisture, and can be valuable for assessing early season drought. LSWI is sensitive to the liquid water content of vegetation and soil (Chandrasekar et al., 2010). The index can be calculated as follows:

$$LSWI = (B5–B6)/(B5+B6),$$

where LSWI is the Land Surface Water Index, B5 is band 5 (near-infrared range from 0.851 to 0.879 µm), and B6 is band 6 (short-wave infrared range from 1.566 to 1.651 µm).

The variant of the formula (B6–B5)/(B5+B6) is called Normalised Difference Built-up Index (NDBI) (Zha et al., 2003), or a Shortwave Infrared Water Stress Index (SIWSI) (Fensholt & Sandholt, 2003) or Normalized Difference Infrared Index (NDII) (Hunt Jr. & Rock, 1989). NDBI is used to automate the process of mapping built-up areas (Kebede et al., 2022). NDII is an effective indicator of moisture accumulation in the root zone during moisture deficit, as well as a powerful indicator for assessing droughts (Sriwongsitanon et al., 2015).

Ferric Iron Index, Fe^{2+}. The content of ferric iron in rocks can be estimated by the index (Rowan & Mars, 2003):

$$Ferric\ iron = B7/ B5 + B3 / B4,$$

where ferric iron is the index of ferrous iron, Fe^{2+}, B3 is band 3 (green range from 0.533 to 0.590 µm), B4 is band 4 (red range from 0.636 to 0.673 µm), B5 is band 5 (near infrared range from 0.851 to 0.879 µm), B7 is band 7 (short-wave infrared range from 2.107 to 2.292 µm).

Ferric Oxides Index. The content of ferric oxides in rocks can be estimated as follows (Rowan & Mars, 2003):

$$Ferric\ Oxides = B6 / B5$$

where ferric oxides is the index of iron oxides, B5 is band 5 (near-infrared range from 0.851 to 0.879 µm), B6 is band 6 (short-wave infrared range from 1.566 to 1.651 µm).

Road network density. The data on the spatial location of roads within the city of Dnipro was obtained from OpenStreetMap (https://download.geofabrik.de/europe/ukraine.html). The density of the road network was calculated in ArcMap 10.8 using the Line Density (Spatial Analyst) tool with a 100-metre window. International roads, motorways, primary roads connecting major cities, secondary roads that are not part of the main routes but are nevertheless part of the national transport network, service roads used for access to buildings and other facilities, roads connecting city neighbourhoods, unpaved roads, streets in residential areas, pedestrian paths, and pedestrian paths in wide pedestrian streets were taken into account to calculate the road network.

Principal component analysis of spectral indices and road network density. The data obtained after calculating the spectral indices and the road network density were subjected to principal component analysis. The principal components with eigenvalues greater than 1 were selected for further analysis. The principal components were meaningfully interpreted by factor coordinates and ordered from lower to higher levels of hemeroby, which corresponds to intuitive perceptions of anthropogenic transformation of ecosystems. For example, the anthropogenic cover index, road cover density, and indices sensitive to industrial rust indicate an increase in hemeroby. And higher values of vegetation indices indicate more natural ecosystems. Hypothetically, if a principal component cannot be meaningfully interpreted as a particular aspect of hemeroby variability, it should not be used in further analysis. Factor scores were rescaled to a range of 0–100, where 0 corresponds to the lowest level of hemeroby and 100 corresponds to the highest level of hemeroby. The integral hemeroby scale was constructed by selecting the highest scores from those indicating hemeroby on the various principal components.

Classification of landscape cover types by spectral indices and road network density. The classification of land cover types was performed in SAGA-9 without training using the k-means procedure by a combined method of iterative minimum distance (Forgy, 1965) and hill climbing (Rubin, 1967). The classification was performed on the basis of geospatial layers represented by spectral indices and road network density. For each cluster, the average value of the hemeroby level was calculated, which was rounded to a whole value and used as an indicator of hemeroby that is typical for the respective cover type.

Assessment of the degree of hemeroby of bird species. The hemeroby values were extracted from the geospatial data layer obtained using landscape metrics at the points of bird species encounters. The mean value and standard deviation of hemeroby during bird encounters were calculated based on the data obtained. These values were considered indicators of bird species hemeroby and their tolerance to hemeroby. According to the hemeroby values, bird species were classified as Ahemerobic (hemeroby < 20), Oligohemerobic (20 < hemeroby < 25), Mesohemerobic (25 < hemeroby < 30), Beta-Euhemerobic (30 < hemeroby < 40), Alpha-Euhemerobic (40 < hemeroby < 50), Polyhemerobic (50 < hemeroby < 60), Metahemerobic (hemeroby > 60). According to the standard deviation of hemeroby values, bird species were divided into the following tolerance classes: Stenotopic (SD < 9), Mesotopic (9 < SD < 18), Eurytopic (SD > 18). The obtained hemeroby scores were compared with the mean hemeroby score (MHS), which was calculated for the Euaropean avifauna (Fanelli & Battisti, 2015).

Results

The surface temperature within the city exhibited a range of 29.4 to 33.6 °C, with an average temperature of 31.4 ± 0.6 °C (Fig. 1). The highest temperatures were recorded in the city centre and in the eastern and northern districts, with the lowest temperatures observed in the eastern region. The AC index exhibited a range of –0.06 to 0.71. The distribution of this indicator was markedly asymmetrical due to the presence of outliers with values exceeding 0.028. The areas exhibiting the highest values of the AC-index are situated in the city centre, north-east and south. It is notable that there are some areas within other city districts that exhibit elevated AC-index values. The areas exhibiting the lowest values of this index are situated in the eastern portion of the city. The index is particularly susceptible to the influence of artificial surfaces, such as the roofs of buildings, particularly large shopping centres and industrial facilities, stadiums, and swimming pools. Additionally, elevated AC-index levels are characteristic of industrial facilities and ports with elevated dust concentrations. Furthermore, the index is also effective in identifying beaches, including public beaches, as well as sandy soils devoid of vegetation.

The Normalized Difference Vegetation Index (NDVI) exhibited a range of –0.12 to 0.68, with an average value of 0.22 ± 0.12. All land cover types were observed to exhibit positive values for this index. The highest NDVI values were observed in forest ecosystems (0.41 ± 0.03), tree plantations among high-rise buildings (0.36 ± 0.02), sparse forests and shrubs (0.36 ± 0.02), parkland (0.34 ± 0.03), and cottage buildings with dense tree plantations (0.31 ± 0.02). The lowest level of NDVI was observed in asphalted industrial sites (0.04 ± 0.01), industrial enterprise territories (0.07 ± 0.03), unpaved industrial sites (0.04 ± 0.01), and multi-storey buildings (0.09 ± 0.04). NDTI ranged from -0.18 to 0.17, with an average of 0.08 ± 0.04. It was highly correlated with NDVI (r = 0.92, P < 0.001), so their patterns of variability were quite similar. NDTI was higher than predicted by the relationship with NDVI for paved industrial sites, wastelands and lawns. On the contrary, NDTI was lower than predicted by NDVI for unpaved industrial sites. GreenNDVI was strongly correlated with NDVI and, accordingly, followed the pattern of variability of the latter (r = 0.99, P < 0.001).

The anthropogenic cover index exhibited a range of –0.74 to 0.22 and an average value of –0.07 ± 0.05. The highest values were observed for asphalt industrial sites (0.14 ± 0.02), shores (0.03 ± 0.02), industrial enterprises (–0.04 ± 0.03), lake or riverside vegetation (–0.04 ± 0.02), and roads (–0.06 ± 0.03). The lowest value of the anthropogenic cover index was observed for unpaved industrial sites (–0.20 ± 0.08), lawns (–0.13 ± 0.03), and single-storey buildings (–0.12 ± 0.02). The NDSI exhibited a range of –0.64 to 0.21, with an average value of –0.14 ± 0.08 (Fig. 2). The index yielded positive values for water bodies (0.04 ± 0.02), while terrestrial ecosystems exhibited negative values. The highest values were observed for river bank and lakeside areas, with a mean value of –0.03 ± 0.04, while the lowest values were observed for lawns, with a mean value of –0.24 ± 0.03. Similarly, wasteland and soil industrial sites exhibited the lowest values, with a mean value of –0.24 ± 0.02 and –0.22 ± 0.03, respectively. The NDSI exhibited the highest correlation with the anthropogenic cover index (r = 0.92, P < 0.001).

The LSWI ranged from –0.51 to 0.39, with an average value of 0.08 ± 0.08. The highest values were observed in forest ecosystems (0.22 ± 0.02), tree plantations in high-rise buildings (0.16 ± 0.02), and in sparse forests and shrubs (0.16 ± 0.02). The LSWI exhibited negative values at soil industrial sites (–0.10 ± 0.02), lawns, and in high-rise buildings (–0.03 ± 0.03). The LSWI values for wasteland sites, water bodies, roads and industrial enterprises were not found to be statistically significantly different from zero. In all other cover types, the LSWI was found to be greater than zero. The strongest positive correlation between LSWI and NBR was r = 0.95 (P < 0.001), while the strongest negative correlation was r = –0.99 (P < 0.001) between LSWI and the ferric oxides index. The latter correlation is inconsequential, given that the indices differ only in the manner by which information is calculated in the same spectral channels. LSWI is a differential index, whereas the ferric oxides index is a reflection ratio in different channels. The Fe^{2+} index ranged from 1.27 to 5.69 and averaged 1.75 ± 0.13. The highest index value was found for a soil industrial site (2.24 ± 0.26), water bodies (1.97 ± 0.02), high-rise buildings (1.95 ± 0.08), and industrial enterprises (1.89 ± 0.05), and the lowest values were found for forest ecosystems (1.55 ± 0.03), sparse forests and shrubs (1.60 ± 0.02), and for tree plantations among high-rise buildings (1.60 ± 0.08). The highest modulus correlation of this index was with NBR (r = –0.96, P < 0.001) and NDVI (r = –0.94, P < 0.001). The ferric oxides index ranged from 0.44 to 3.06 and averaged 0.86 ± 0.12. The highest values were for industrial soil (1.23 ± 0.06), lawns (1.08 ± 0.05), high-rise buildings (1.06 ± 0.05), and industrial enterprises (0.99 ± 0.04). The lowest ferric oxides index was for forest ecosystems (0.64 ± 0.03), tree plantations among high-rise buildings (0.72 ± 0.03), and in sparse forests and shrubs (0.72 ± 0.03). The Laterite Index ranged from 0.63 to 1.53 and averaged 1.19 ± 0.10. The highest values were for asphalt industrial sites (1.37 ± 0.04), forest ecosystems (1.33 ± 0.03), and tree plantations among high-rise buildings (1.32 ± 0.08). The Laterite Index had the lowest value for a dirt industrial site (0.96 ± 0.14), water bodies (1.01 ± 0.01), and high-rise buildings (1.06 ± 0.04). The index had the highest correlation with NDTI (r = 0.99, P < 0.001). The NBR index ranged from -0.65 to 0.5 and averaged 0.16 ± 0.10. The highest values were for forest ecosystems (0.35 ± 0.02), tree plantations among high-rise buildings (0.29 ± 0.04), sparse forests and shrubs (0.29 ± 0.02), and urban parks (0.28 ± 0.03). The lowest NBR value was for a soil-based industrial site (-0.13 ± 0.02), high-rise buildings (0.01 ± 0.04), water bodies (0.03 ±

0.02), and industrial enterprises (0.04 ± 0.02). The density of the road network varied from 0 to 95 km/km^2 and averaged 8.2 ± 9.9 km/km^2 (Fig. 3). This indicator was highly correlated with surface temperature ($r = 0.32$, $P < 0.001$).

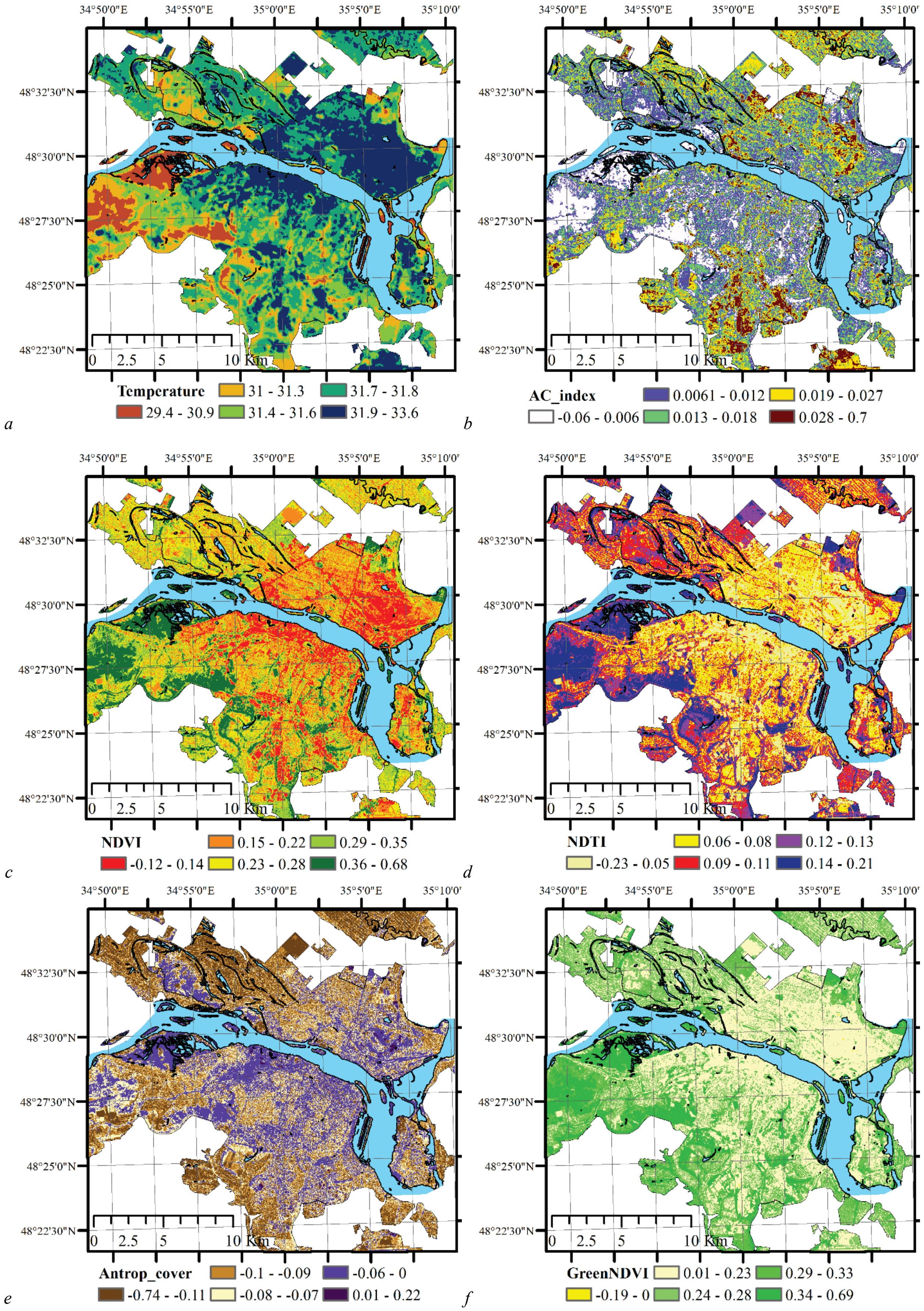

Fig. 1. Spatial variability of the Earth's surface temperature (*a*), Aerosol Index (*b*), Normalized Difference Vegetation Index (*c*), Normalised Difference Tillage Index (*d*), Anthropogenic Cover Index (*e*), and Green Normalised Difference Vegetation Index (*f*)

The principal component analysis enabled the extraction of three principal components with eigenvalues exceeding one (Table 1). Principal component 1 exhibited a positive correlation with the spectral indices that indicate anthropogenic surfaces (ACI, AC-Index, Fe^{2+}, FO, NDSI) and a negative correlation with indices that are sensitive to vegetation density (GNDVI, NBR, NDVI), surface moisture (LSWI) and rock or soil composition (LI). Therefore, Principal component 1 can be interpreted in a meaningful manner as an aspect of hemeroby induced by a decrease in vegetation cover due to an increase in the presence of anthropogenic objects. Principal component 2 was found to be positively correlated with surface temperature and indices that are sensitive to anthropogenic surfaces (AC-Index, FO), as well as road network density. This principal component can be interpreted as an aspect of hemeroby related to thermal pollution. The most significant indicator of principal component 3 is road network density. Therefore, all of the primary extracted principal components are associated with hemeroby, and an integrated hemeroby indicator was calculated.

The classification procedure, based on spectral indices and road network density, yielded 20 land cover types and one additional category representing water bodies (Table 2). The mean value of the hemeroby index was calculated for each land cover type. The statistical analysis revealed a significant difference in hemeroby between the various land cover types ($F = 530.1$, $P < 0.001$). A comparison of the landscape cover types with high-resolution satellite images enabled their decoding and meaningful interpretation.

The hemeroby of birds exhibited considerable variation, with values ranging from 15 to 89 (Table 3). The birds were classified into the following categories based on the extent of their hemeroby. The ahemerobic group comprised 15 species, the oligohemerobic group 11, the mesohemerobic group 8, the beta-euhemerobic group 8, the alpha-euhemerobic group 10, the polyhemerobic group 9 and the metahemerobic group 5. The stenotopic group comprises 30 species, the mesotopic group 17 species, and the eurytopic group 19 species of birds. In the case of 34 species of bird fauna in the city of Dnipro, estimates have been obtained for the European bird fauna on the basis of the MHS. A statistically significant correlation was observed between the hemeroby scores and the MHS ($r = 0.56$, $P < 0.001$, Fig. 4).

Table 1

Principal component analysis of the variation in spectral indices and road network density (correlation coefficients are shown, which are statistically significant at the $P < 0.05$)

Variable	PC 1, λ = 7.8	PC 2, λ = 2.9	PC 3, λ = 1.2
Anthropogenic cover index (ACI)	0.45	–0.79	–
Aerosol index (AC-Index)	0.32	0.63	–
Ferric iron index (Fe^{2+})	0.97	–	–
Ferric oxides index (FO)	0.85	0.45	–0.17
Green normalized difference vegetation index (GNDVI)	–0.97	–	–
Laterite index (LI)	–0.95	–	–0.13
Land surface water index (LSWI)	–0.85	–0.45	0.16
Normalized differential snow index (NDSI)	0.68	–0.70	0.14
Normalized burn ratio (NBR)	–0.96	–0.25	–
Normalized difference vegetation index (NDVI)	–0.99	–	–
The temperature of the Earth's surface	–	0.86	–
Normalized difference tillage index (NDTI)	–0.95	–	–
Road network density	–	0.37	0.91

The values of *Corvus monedula*, *Delichon urbica*, and *Streptopelia decaocto* deviate from the 99% confidence interval for the regression of MHS on hemeroby scores, indicating a lower level of hemeroby of these birds in Dnipro than is estimated for the European fauna. The species *Columba palumbus*, *Fringilla coelebs*, *Garrulus glandarius*, *Phylloscopus collybita*, and *Cuculus canorus* deviate to a lesser extent, indicating that these species within Dnipro city are able to exist under more hemerobic conditions than is generally observed within Europe. The hemeroby estimates for the remaining bird species are in excellent agreement with one another.

Table 2

Landscape cover types and their hemeroby derived from the geospatial layers represented by spectral indices and road network density (for each cluster, the average value of the hemeroby level was calculated, which was rounded to a whole value and used as an indicator of hemeroby that is typical for the respective cover type)

Cluster	Landscape cover type after interpretation	Total area, % of the area	Hemeroby*	Mean ± standard deviation	Minimum	Maximum
1	Park planting	5.2	23	23.1 ± 6.6	16.4	37.7
2	Cottage development with dense tree plantations	7.4	28	21.2 ± 4.5	17.5	29.0
3	Tree plantations in high-rise buildings	0.3	69	85.4 ± 11.0	73.3	90.0
4	Wasteland	3.6	63	63.2 ± 5.3	53.8	76.5
5	Water body	11.9	30	30.2 ± 1.7	21.8	36.1
6	Forest	8.3	15	15.1 ± 5.0	7.1	20.6
7	Sparse forests and shrubs	5.9	25	25.2 ± 4.6	20.1	29.6
8	Rural plantations	7.9	54	53.8 ± 5.6	41.5	66.7
9	Shoreline vegetation	2.5	27	27.1 ± 4.2	21.4	30.5
10	Rural development	8.5	48	47.8 ± 4.3	38.5	59.1
11	Main road	3.0	100	96.2 ± 10.1	90.7	100.0
12	Industrial enterprises	3.9	95	95.6 ± 4.3	70.0	100.0
13	Asphalt pavement	4.0	92	92.8 ± 8.5	69.7	98.3
14	Ground industrial site	0.2	87	87.6 ± 10.8	72.9	100.0
15	Multi-storey building	2.8	85	69.3 ± 5.5	59.9	87.4
16	Lawns	2.0	74	74.1 ± 5.7	66.8	87.6
17	Planting along roads	10.2	57	57.5 ± 5.0	46.7	76.1
18	Old multi-storey buildings	5.3	56	55.9 ± 5.0	46.9	68.9
19	Asphalted industrial site	0.1	94	94.4 ± 2.7	76.5	100.0
20	Shoreline areas	1.2	17	17.4 ± 6.9	10.2	21.5
21	One-story buildings	5.9	60	59.6 ± 4.7	50.4	71.0

Note: * – hemeroby is estimated as a result of rounding the average hemeroby value for the corresponding landscape cover type to a whole number.

Table 3
The degree of hemeroby and tolerance to hemeroby in birds of Dnipro city

Species	Hemeroby	SD	Degree of hemeroby	Tolerance
Gallinula chloropus (Linnaeus, 1758)	15.0	–	ahemerobic	stenotopic
Nycticorax nycticorax (Linnaeus, 1758)	15.0	–	ahemerobic	stenotopic
Alcedo atthis (Linnaeus, 1758)	15.0	–	ahemerobic	stenotopic
Acrocephalus arundinaceus (Linnaeus, 1758)	15.0	–	ahemerobic	stenotopic
Turdus merula (Linnaeus, 1758)	15.0	–	ahemerobic	stenotopic
Hippolais icterina (Vieillot, 1817)	15.0	–	ahemerobic	stenotopic
Sylvia borin (Martin Lichtenstein, 1823)	15.0	–	ahemerobic	stenotopic
Erithacus rubecula (Linnaeus, 1758)	15.9	3.0	ahemerobic	stenotopic
Dendrocopos medius (Linnaeus 1758)	16.5	3.0	ahemerobic	stenotopic
Sylvia atricapilla (Linnaeus, 1758)	17.2	4.9	ahemerobic	stenotopic
Turdus philomelos (C.L.Brehm, 1831)	17.3	4.1	ahemerobic	stenotopic
Circus cyaneus (Linnaeus, 1766)	18.0	4.2	ahemerobic	stenotopic
Corvus corax (Linnaeus, 1758)	18.4	5.3	ahemerobic	stenotopic
Luscinia luscinia (Linnaeus, 1758)	18.4	4.5	ahemerobic	stenotopic
Sylvia communis (Latham, 1787)	19.8	5.3	ahemerobic	stenotopic
Anthus trivialis (Linnaeus, 1758)	20.0	2.4	oligohemerobic	stenotopic
Picus canus (Gmelin, 1788)	20.0	6.9	oligohemerobic	stenotopic
Remiz pendulinus (Linnaeus, 1758)	20.3	7.1	oligohemerobic	stenotopic
Dendrocopos major (Linnaeus, 1758)	20.5	6.2	oligohemerobic	stenotopic
Parus caeruleus (Linnaeus, 1758)	20.8	4.4	oligohemerobic	stenotopic
Corvus monedula (Linnaeus, 1758)	21.0	1.0	oligohemerobic	stenotopic
Phylloscopus collybita (Vieillot, 1817)	22.8	9.1	oligohemerobic	mesotopic
Jynx torquilla (Linnaeus, 1758)	23.0	2.3	oligohemerobic	stenotopic
Sylvia curruca (Linnaeus, 1758)	23.0	2.8	oligohemerobic	stenotopic
Oriolus oriolus (Linnaeus, 1758)	24.1	7.8	oligohemerobic	stenotopic
Sterna hirundo (Linnaeus, 1758)	24.3	7.1	oligohemerobic	stenotopic
Phylloscopus sibilatrix (Bechstein, 1793)	25.2	2.0	mesohemerobic	stenotopic
Emberiza citrinella (Linnaeus, 1758)	25.8	10.6	mesohemerobic	mesotopic
Charadrius dubius (Scopoli, 1786)	26.5	6.4	mesohemerobic	stenotopic
Carduelis carduelis (Linnaeus, 1758)	26.8	10.8	mesohemerobic	mesotopic
Upupa epops (Linnaeus, 1758)	28.0	10.4	mesohemerobic	mesotopic
Phasianus colchicus (Linnaeus, 1758)	28.2	17.1	mesohemerobic	mesotopic
Podiceps cristatus (Linnaeus, 1758)	28.3	14.4	mesohemerobic	mesotopic
Dendrocopos minor (Linnaeus, 1758)	29.5	1.0	mesohemerobic	stenotopic
Cuculus canorus (Linnaeus, 1758)	30.1	7.5	beta-euhemerobic	stenotopic
Asio otus (Linnaeus, 1758)	31.2	15.8	beta-euhemerobic	mesotopic
Muscicapa striata (Pallas, 1764)	34.5	11.2	beta-euhemerobic	mesotopic
Ardea cinerea (Linnaeus, 1758)	36.7	13.3	beta-euhemerobic	mesotopic
Garrulus glandarius (Linnaeus, 1758)	37.2	15.0	beta-euhemerobic	mesotopic
Ficedula albicollis (Temminck, 1815)	37.5	11.8	beta-euhemerobic	mesotopic
Delichon urbica (Linnaeus, 1758)	38.2	14.6	beta-euhemerobic	mesotopic
Phoenicurus phoenicurus (Linnaeus, 1758)	38.5	24.7	beta-euhemerobic	eurytopic
Fringilla coelebs (Linnaeus, 1758)	41.8	19.5	alpha-euhemerobic	eurytopic
Parus major (Linnaeus, 1758)	41.8	19.1	alpha-euhemerobic	eurytopic
Larus ridibundus (Linnaeus, 1766)	43.9	7.2	alpha-euhemerobic	stenotopic
Turdus pilaris (Linnaeus, 1758)	44.4	18.2	alpha-euhemerobic	eurytopic
Columba palumbus (Linnaeus, 1758)	44.5	16.4	alpha-euhemerobic	mesotopic
Sturnus vulgaris (Linnaeus, 1758)	45.2	18.9	alpha-euhemerobic	eurytopic
Lanius collurio (Linnaeus, 1758)	47.0	14.1	alpha-euhemerobic	mesotopic
Falco tinnunculus (Linnaeus, 1758)	48.3	11.7	alpha-euhemerobic	mesotopic
Dendrocopos syriacus (Hemprich et Ehrenberg, 1833)	49.3	21.6	alpha-euhemerobic	eurytopic
Chloris chloris (Linnaeus, 1758)	50.0	20.8	alpha-euhemerobic	eurytopic
Pica pica (Linnaeus, 1758)	51.6	21.5	polyhemerobic	eurytopic
Motacilla alba (Linnaeus, 1758)	52.6	22.6	polyhemerobic	eurytopic
Anas platyrhynchos (Linnaeus, 1758)	53.1	26.3	polyhemerobic	eurytopic
Corvus cornix (Linnaeus, 1758)	53.8	25.7	polyhemerobic	eurytopic
Fulica atra (Linnaeus, 1758)	56.0	19.7	polyhemerobic	eurytopic
Streptopelia decaocto (Frivaldszky, 1838)	56.1	24.6	polyhemerobic	eurytopic
Larus cachinnans (Pallas, 1811)	57.0	15.4	polyhemerobic	mesotopic
Phalacrocorax carbo (Linnaeus, 1758)	57.9	21.9	polyhemerobic	eurytopic
Phoenicurus ochruros (S.G.Gmelin, 1774)	62.7	24.8	polyhemerobic	eurytopic
Passer montanus (Linnaeus, 1758)	70.7	28.0	metahemerobic	eurytopic
Hirundo rustica (Linnaeus, 1758)	71.7	18.9	metahemerobic	eurytopic
Columba livia (Gmelin, 1789)	81.4	22.2	metahemerobic	eurytopic
Passer domesticus (Linnaeus, 1758)	85.7	18.5	metahemerobic	eurytopic
Apus apus (Linnaeus, 1758)	88.5	12.4	metahemerobic	mesotopic

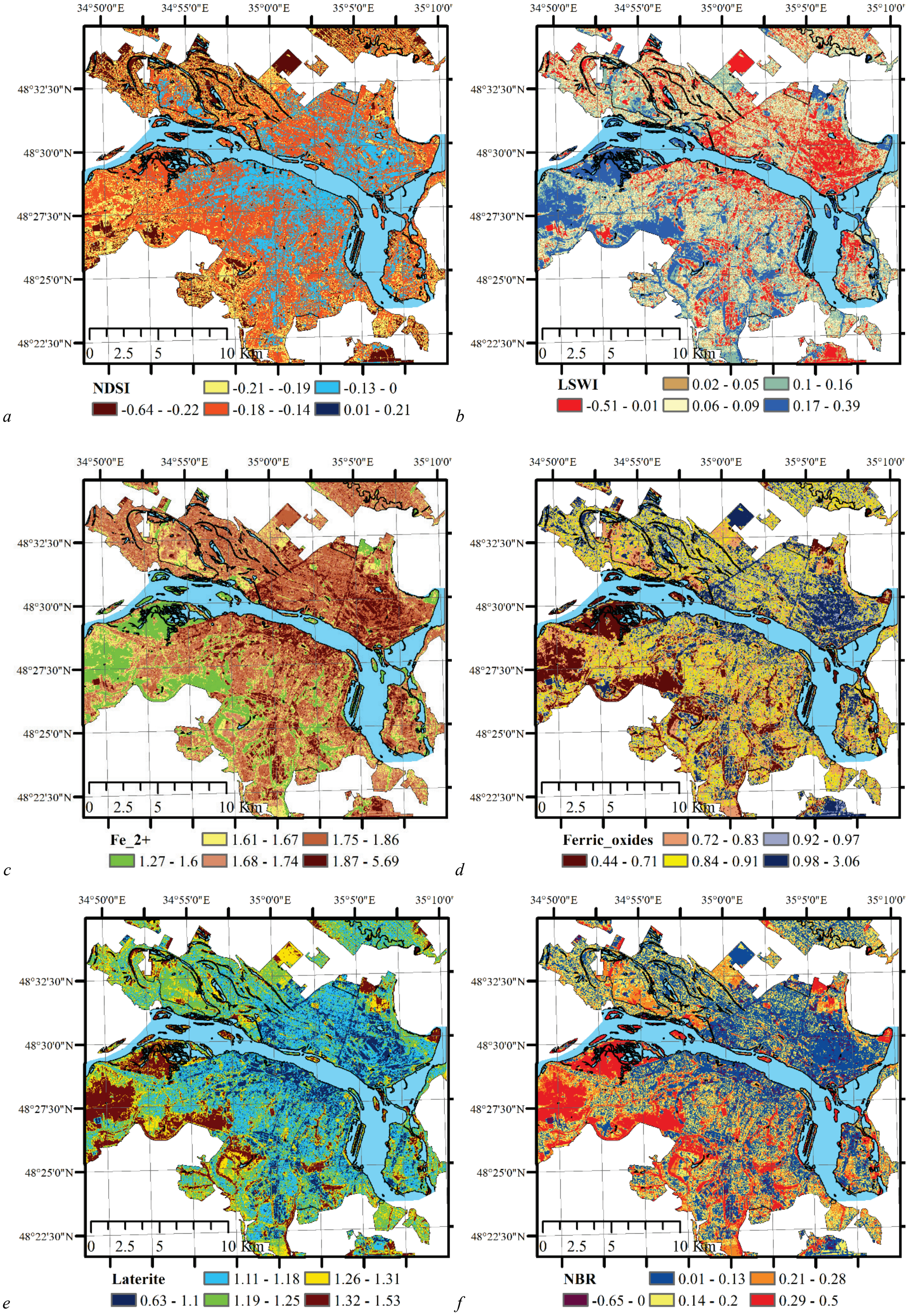

Fig. 2. Spatial variability of the Normalised Difference Snow Index (*a*), Land Surface Water Index (*b*), Ferric Iron Index (*c*), Ferric Oxides Index (*d*), Laterite Index (*e*), and Normalized Burn Ratio (*f*)

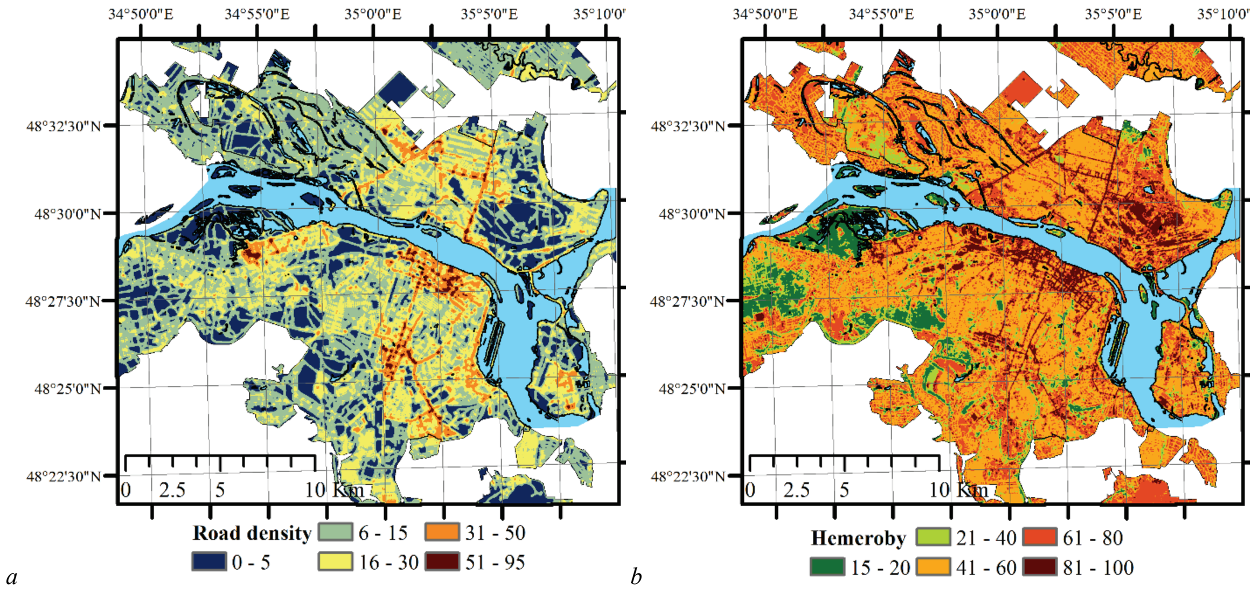

Fig. 3. Road network density (*a*) and hemeroby (*b*): international roads, motorways, primary roads connecting major cities, secondary roads that are not part of the main routes but are nevertheless part of the national transport network, service roads used for access to buildings and other facilities, roads connecting city neighbourhoods, unpaved roads, streets in residential areas, pedestrian paths, and pedestrian paths in wide pedestrian streets were taken into account to calculate the road network

Discussion

The classification of urban surface types based on remote sensing data represents a challenging undertaking (Yakovenko et al., 2023). It is evident that the classification should be accompanied by a meaningful interpretation of the identified classes. That is to say, the classification results should be deciphered (Zhukov et al., 2022). The difficulty arises from the considerable variability and diversity of the spectral characteristics of urban surfaces, which are the result of the interaction between ecosystems of varying degrees of anthropogenic influence within urban environments, ranging from relatively natural ecosystems to those that are entirely anthropogenic (Torresani et al., 2024). The utilisation of spectral indices offers a substantial advantage in addressing the classification issue, subsequently facilitating the interpretation of the classification solution. Spectral indices are dimensionless indicators that are typically assigned a specific ecological interpretation. It is frequently the case that significant environmental phenomena possess distinctive spectral characteristics, which give rise to the formation of specific spectral images. For instance, the NDVI index is a well-established indicator of vegetation presence on Earth's surface (Spadoni et al., 2020). The GreenNDVI index exhibits analogous properties to those of the NDVI. The correlation coefficient of 0.99 between the two variables suggests that one of them is formally redundant. From a formal perspective, the rationale for utilising GreenNDVI can be seen as an additional indicator that provides insight into the functional state of plants. It can be postulated that at a specific level of vegetation cover, as indicated by NDVI, GreenNDVI is capable of discerning differences between plant communities at varying degrees of anthropogenic impact with greater sensitivity.

The indices are referred to by their traditional names, which do not always fully indicate their significance for characterising urban land cover. To illustrate, the 'aerosol index' (AC-Index) within a city is susceptible to the influence of blue surfaces that can reflect violet hues, or electromagnetic fluctuations in the vicinity of the violet spectrum, which is correlated with it. It should be noted that the AC-Index is sensitive to aerosols present in the atmosphere or suspended particles in water. In urban areas, these include the roofs of large shopping centres or industrial facilities painted with modern materials, industrial sites devoid of vegetation, and public sandy beaches that also lack vegetation. Once formed, natural sandy beaches are rapidly colonised by vegetation, although this process is often incomplete. The impact of human activity on public beaches inevitably results in the absence or fragmentation of vegetation cover. Consequently, the AC-Index has been demonstrated to be a highly sensitive indicator of the active, modern anthropogenic transformation of the urban environment. It is important to note that the AC-Index is not sensitive to older urban developments, rural areas or parkland.

The same index is referred to by different names in different publications. The Vegetation Index (VI) (Dai et al., 2018), or the Normalised Differential Tillage Index (Van Deventer et al., 1997) denote the same spectral index. In terms of its properties for characterising land cover, it can be identified with greater precision as a vegetation index, as it is highly correlated with NDVI. However, this index provides additional information compared to NDVI on the surface character of areas where vegetation cover is not very dense. This attribute of the VI (NDTI) renders it a valuable tool for a more detailed classification of urban cover. The LI index differs from the VI (NDTI) only in its calculation procedure, and thus they are highly correlated. The LI index is frequently employed to examine the prevalence of rocks of disparate compositions that lack dense vegetative cover, a phenomenon most prevalent in desert and mountainous regions (Kalinowski & Oliver, 2004).

This assignment of LI once again focuses on the use of VI (NDTI) as an indicator of the condition of surfaces in urban areas with sparse vegetation cover, where no plants are present. Indeed, these surfaces transcend the distinctive characteristics of an urban environment, functioning as man-made deserts. In such circumstances, conventional vegetation indices are rendered ineffective.

The designation "index of anthropogenic cover" is derived from a publication in which the index's intrinsic quality is not explicitly corroborated. However, the nomenclature is attributed on the basis of formal criteria (Krenke & Puzachenko, 2008). This index demonstrates a significant positive correlation with both NDSI and Fe^{2+}. NDSI is referred to as the 'snow index' due to its capacity to indicate the presence of snow cover when its value exceeds 0.4. It is evident that during the summer months, the NDSI values were below 0.4, and thus conveyed a distinct signal from that of snow cover. The two indices, therefore, provided somewhat disparate information. It is evident that the spectral antithesis of 'white' snow cover is 'black' industrial objects. The hypothesis that the anthropogenic cover index and the NDSI (if it is less than 0.4) serve as markers of industrial facilities is corroborated by their correlation with the Fe2+ index. Furthermore, this index is frequently employed to distinguish between rocks of disparate chemical compositions. In urban settings, man-made surfaces devoid of vegetative cover exhibit the corresponding spectral characteristics. Consequently, the singularity of the complex of indices pertaining to anthropogenic cover, NDSI, and Fe^{2+}, and their correlation, signifies that this complex serves as an indicator of anthropogenic surfaces with minimal or no vegetative cover.

The NBR index is a commonly employed methodology for the identification of areas that have been subjected to combustion and the assessment of the extent of associated damage (García & Caselles, 1991). Given that this index is based on vegetation, we have proposed a name that emphasises this feature: Normalised Differential Index of Vegetation Cover Suitable for Burning. It is evident that following a fire, the quantity of organic material suitable for combustion is markedly diminished or entirely absent. It is evident that this index is significantly correlated with the NDVI index. Furthermore, it is also highly correlated with LSWI. This index is the inverse of the Normalised Difference Built-up Index (NDBI) (Zha et al., 2003). In light of the aforementioned relationship, it is possible to view NBR as an indicator that is sensitive to urban development in urban environments. It is evident that the expansion of urbanisation may result in a reduction in vegetation cover density, which is also reflected in alterations to the NBR. It is also important to note that this interpretation of the NBR index renders its traditional designation somewhat contingent.

The Ferric Oxide Index is a tool used to indicate the chemical properties of rocks (Ponomarenko et al., 2021). In urban environments, the iron oxides that form the spectral features of surfaces are most likely represented by the rust of industrial enterprises. This index has a positive correlation with the Fe^{2+} index and a negative correlation with all vegetation indices. This highlights that the Ferric Oxide Index is an indicator of traditional, predominantly metallurgical industrial enterprises.

The interpretation of the spectral indices can be elucidated with the assistance of supplementary indicators that distinctly delineate the extent of anthropogenic transformation of the urban environment (Zimaroeva et al., 2016). Such factors include the density of the road network and surface temperature. The presence of urban roads represents a significant source of additional pollution, both from exhaust gases and from the use of chemicals employed to prevent icing during the winter months. Additionally, urban roads act as focal points for population concentration, and the transportation and other infrastructure that accompany them contribute to the fragmentation of the ecological space within the urban environment. The surface temperature serves to identify the sources of thermal pollution, which may include industrial enterprises or residential buildings. Furthermore, the presence of asphalt significantly alters the heat balance and contributes to thermal pollution. The analysis of spectral indicators, in conjunction with an examination of road density and surface temperature, has revealed that the primary drivers of observed variability are a range of factors related to anthropogenic environmental transformation. It is evident that the natural factors that contribute to landscape diversity and variability, such as relief, soil cover diversity, trophicity, and ecosystem humidity, are less pronounced in urban environments. The three principal components that have been identified are, in essence, distinct aspects of hemeroby.

The primary consequence of hemeroby is the substitution of vegetation as a result of the expansion of industrial production (Kunakh et al., 2024). A substantial portion of the city is devoted to the activities of the metallurgical, chemical, and machine-building industries, as well as the railroad infrastructure that connects them. Since the late 19th and early 20th centuries, these enterprises have constituted the focal points of urban development, with residential buildings subsequently constructed in their vicinity. As a consequence of the physical destruction and significant environmental pollution, the density of vegetation within and around the enterprises has been significantly reduced. It can therefore be posited that the presence and specificity of principal component 1 can be explained by the industrial nature of a significant number of enterprises in the city. The contrast between the industrial core of the city and the surrounding areas is created by the presence of pockets of natural vegetation, which are located on the periphery of the city or in relief depressions within the city itself. In most cases, this is forest vegetation that exists within the remnants of natural forests or artificial park plantations. It can therefore be argued that the juxtaposition of forest vegetation and industrial enterprises represents an important aspect of the city's hemeroby. It should be noted that the variability of road density and temperature pollution are not contingent on this aspect of hemeroby.

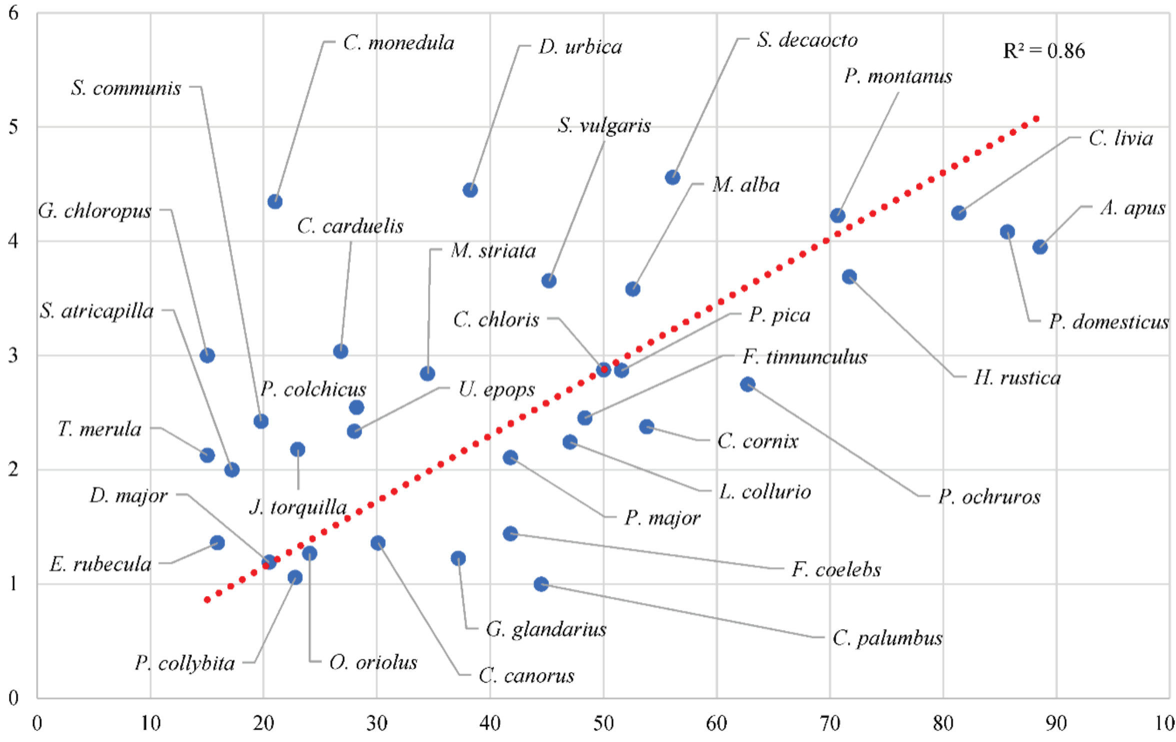

Fig. 4. Correlation between the hemeroby score of birds in Dnipro city estimated by the landscape metric (abscissa axis) and the mean hemeroby score (ordinate axis)

The phenomenon of temperature pollution represents a significant aspect of the urban environment, encompassing a diverse range of factors that contribute to its overall character. The correlation between temperature and the Ferric Oxides Index indicates that old industrial enterprises are a significant source of heat pollution. A substantial quantity of heat is released into the environment as a result of metallurgical and chemical production. This suggests that temperature fields may also serve as markers of the spread of toxic substances released into the environment from metallurgical and chemical plants. The correlation between surface temperature and the AC-Index indicates that the construction of new industrial enterprises and shopping centres also contributes to thermal pollution. It seems probable that such facilities are surrounded by dense asphalt pavement, which is a factor in heat pollution. Principal component 2 underscores the distinctive characteristics of vegetation indices and their supplementary informational value in comparison to the conventional NDVI index. The NDVI index is a distinctive indicator of principal component 1, exhibiting no correlation with principal components 2 and 3. The correlation between principal component 2 and LSWI suggests that heat pollution has a detrimental impact on surface moisture levels within the city. Additionally, there is a negative correlation between surface temperature and the index of anthropogenic cover. This suggests that not all forms of anthropogenic cover are sources of heat pollution, and that some anthropogenic surfaces can provide favourable thermal conditions. These are typically buildings with dense vegetation. Such complexes are either formed through proper design in modern times or as a result of the development of vegetation in older sections of the city. Alternatively, it could be areas comprising single-storey rural-type buildings.

Principal component 3 indicates that the density of the road network is a significant factor influencing hemeroby. The presence of roads in an urban environment inevitably results in the emission of pollutants, whether from the operation of internal combustion engines or the use of road antifreeze. The concentration of urban dwellers in the vicinity of roadways exerts further pressure on the surrounding ecosystems. Highways and pedestrian streets act as disturbance factors for birds, as well as dividing areas of greater and lesser suitability for bird habitat, thus increasing the fragmentation of the urban environment. It is important to note that the zone of influence of roads extends well beyond the geometric boundaries of these anthropogenic structures. The density of the road network is correlated with other factors of anthropogenic impact, including traffic intensity and the presence of heavier machinery, which is a source of elevated levels of environmental pollution.

The three principal components of the variability of spectral indices, surface temperature, and road density are statistically independent, yet collectively they provide insight into specific aspects of hemeroby. This reinforces the notion that hemeroby is a complex phenomenon, particularly in urban settings. The construction of an integral indicator of hemeroby was based on the selection of the maximum normalised value of hemeroby for each of the three aspects of hemeroby. This approach assumes that the impact of all three hemeroby factors on ecosystems is equal, which may not be accurate. Furthermore, this approach is a significant simplification. It would undoubtedly be beneficial for future research to develop criteria for preliminary weighting of hemeroby in the process of creating an integral indicator. Conversely, no formal reservations have been identified that would indicate a significant advantage of a particular hemeroby factor. Nevertheless, even if this is feasible, the advantage in question may be confined to a specific locality. The following procedure of averaging within the selected classes of surface types serves to eliminate fluctuations that may arise when the influence of a particular hemeroby factor increases significantly in comparison to the others. The resulting hemeroby map was employed as the fundamental geospatial layer for the calculation of the hemeroby index of urban birds.

The capacity of animal and plant species to adapt to anthropogenic disturbance varies. Some species are exclusively adapted to thrive in pristine habitats. Such adaptive capabilities ensure that they are able to tolerate a minimum level of natural disturbance in terms of both intensity and frequency (Sousa, 1984). Synanthropic species are capable of thriving and proliferating significantly in highly transformed habitats, where they can withstand a considerable level of anthropogenic and/or natural disturbance (Shochat et al., 2010). The species' optimum location in the environmental transformation gradient indicates a hemeroby pattern. A variety of disturbance levels are tolerated by different species. The existence of specialized sensitive species is contingent upon the level of disturbance. Tolerant species are capable of sustaining themselves in habitats characterised by varying levels of disturbance, a phenomenon that is referred to as hemerobiotic diversity (Battisti & Fanelli, 2016). The resulting estimates suggest a range of hemeroby levels in the city, spanning from 15 to 100 on a 100-point scale. The data on hemeroby can typically be expressed in one of two ways: as numerical results in discrete numbers or as ordinal classes. The use of precise numerical data as an indicator may, however, result in a pseudo-objective accuracy (Fehrenbach et al., 2015).

The verification of the obtained estimates of bird species hemeroby can be conducted on the basis of information pertaining to their ecology or through a process of comparison at analogous scales. The estimates obtained in this study are generally consistent with those for central Europe (Giuliano Fanelli & Battisti, 2015). However, discrepancies in estimates were noted for a number of species. One such species is *G. chloropus*. Representatives of this species can be found in a variety of aquatic habitats, including lakes, ponds, and slow-flowing rivers, as well as wetlands with dense riparian vegetation. The hemeroby level of the moorhen in the city of Dnipro is 15.0, as indicated by our data. This finding is consistent with the observation that the species is rarely found in urban environments. This species is typically found in natural or semi-natural, medium-sized, overgrown water bodies. In the urban ecosystem of Dnipro, such conditions are only preserved in limited areas on the outskirts of the city and beyond, where the impact of urbanisation is minimal. In the remaining water bodies within the city, bottom clearance and mowing of higher aquatic vegetation are conducted, which explains why *G. chloropus* is rarely observed in urban water bodies. However, data from Europe, in particular from central Italy, indicate a considerably higher level of hemeroby for this species (60.0). This value suggests that there may be an increased focus on the maintenance and restoration of urbanised wetlands in European regions, even in the context of a highly disturbed environment. This is due to the fact that the conditions within the urban area are conducive to nesting and feeding for the species in question.

A number of species were classified as ahemerobic, although in European cities they are characterised by a significantly greater tendency towards hemeroby (*Turdus merula*, *Erithacus rubecula*, *Sylvia atricapilla*, *Sylvia communis*). A common feature of these species is a clear preference for the presence of dense undergrowth and shrubs in forest and forest edges. This discrepancy in the indices can be attributed to the paucity of such habitats in our region. In Dnipro parks and squares, the removal of fallen leaves has the effect of significantly reducing the area available to blackbirds for the search of food. Furthermore, the majority of trees in parkland areas possess semi-arched and openwork crowns, in addition to an absence of sufficient undergrowth density and an inadequate quantity of shrubs. This results in a lack of suitable nesting, sheltering, and foraging areas for these species.

It is noteworthy that the case of *Corvus monedula,* which has a hemeroby index of 21.0 for the city of Dnipro, is particularly intriguing. Despite its preference for open spaces with single trees or buildings for nesting, *C. monedula* has not yet fully adapted to urbanised conditions in the city of Dnipro. It is mostly found only on the outskirts of the city. However, the data from central Italy demonstrate a notable divergence, with the hemeroby index of *C. monedula* reaching 87.0, indicating its remarkable adaptation to the urban environment within the European region. The elevated level of hemeroby suggests that the Italian jackdaw has been able to optimise the advantages of urban living by capitalising on the resources generated by human activities. This notable discrepancy between Ukraine and Italy may be attributed to a number of factors. In Italy, urban habitats may provide more nesting opportunities and also provide constant access to food resources, particularly as a result of human activity.

The hemeroby index for *Jynx torquilla* is 23.0, as indicated by our data set, while the corresponding figure for European data is 43.6. The preferred habitat of *J. torquilla* is open or semi-open areas with a high density of trees and shrubs, which provide the necessary resources for nesting and sheltering. For *J. torquilla*, the availability of hollows in which to construct nests is of critical importance, as the species is unable to construct such structures independently. In the city of Dnipro, *J. torquilla* is predominantly observed in semi-natural habitats, including parks, gardens, and other green spaces with a high density of mature trees. The lack of nesting sites in the city is a consequence of the felling of old trees in parks and squares, as well as the removal of excessive crowns. This has resulted in a notable absence of *J. torquilla* in urban areas. The scarcity of nesting sites is also a factor affecting *M. striata*. This is a diminutive bird that exhibits a preference for open and semi-open habitats with woody vegetation, frequently situated in proximity to tall forest edges. The most typical habitat of *Muscicapa striata* is deciduous and mixed forests, which feature a considerable number of aged trees and open spaces. It is frequently observed in urban green spaces, including parks and gardens, as well as forest edges and other locations with suitable nesting conditions. The hemeroby index for this species in the city of Dnipro is 34.5, while in central Italy the hemeroby index for *M. striata* is 56.8. The relatively low level of adaptation to the urbanised environment in the city of Dnipro can be attributed to the absence of high-trunked stands. Similarly, the distribution of *Sturnus vulgaris* is constrained by the availability of suitable nesting sites. *S. vulgaris* is one of the most adaptable bird species, demonstrating the capacity to readily adapt to a range of habitats, including urbanised areas. This species is most commonly observed in open landscapes where sufficient food resources are available. The species *S. vulgaris* frequently nests in small colonies within tree hollows, although in urban areas it is able to utilise building niches and specially constructed nesting boxes. In the city of Dnipro, the hemeroby index for *S. vulgaris* is 45.2. However, in central Italy, the hemeroby index for this species is considerably higher, reaching 73.1. This indicates that *S. vulgaris* can effectively exist in areas with a significant anthropogenic impact. The relatively low values of the *S. vulgaris* hemeroby index also highlight the scarcity of old hollow trees in Dnipro city as a primary nesting site for the species.

The results of our study suggest that the *Carduelis carduelis* has a hemeroby index of 26.8, which indicates its relative ability to adapt to semi-natural environments. The *C. carduelis* is found in a variety of habitats, frequently selecting nesting sites in sparse forest areas with herbaceous vegetation, shrubs, or trees, or in areas with free-standing trees, which are characteristic of clump-mosaic habitats. These habitats provide the birds with access to plant seeds, which constitute the basis of their diet. In the central Italian region, the hemeroby index of *C. carduelis* is 60.8, indicating a high level of adaptation to the urbanised environment. A comparable scenario is evident in the case of *Upupa epops*, which exhibits a proclivity for open and semi-open habitats, such as meadows, gardens, vineyards, and pastures, where soil fertility is a determining factor. This species is typically observed in urban parks and gardens, as well as on the periphery of urban areas, where large open spaces with mature trees are present, providing suitable nesting habitats. In the city of Dnipro, the *U. epops* hemeroby index is 28.0, whereas in central Italy, the hemeroby index of the hoopoe is considerably higher, reaching 46.7. This is attributable to the milder climate and diverse plantations in the European region, which contribute to the availability of seeds and other feed resources throughout the year. This discrepancy in index values can also be attributed to the dissimilarity in the configuration and administration of urban green spaces, where organic components such as parks, gardens, and vineyards are more integrated in Italy, which contributes to the availability of feed resources throughout the year. This is likely attributable to the integration of natural elements, such as parks, gardens, and vineyards, within urban environments in Italy. This integration provides suitable nesting habitats and food sources for goldfinches and woodpeckers, enabling their successful establishment and sustenance even within urban areas. A discrepancy was also observed in the hemeroby index values for *Phasanius colchicus*. This is a large bird that exhibits a preference for open and semi-open habitats characterised by the presence of shrubs, forest belts, fields and meadows. *Ph. colchicus* is frequently observed in proximity to agricultural lands, where they construct nests on the ground, predominantly in dense grass or among shrubs, which affords them a degree of protection from predators. In Dnipro, the hemeroby index of *Ph. colchicus* is 28.2, while in the data from central Italy this value is 51.0. The discrepancy in hemeroby indices between Ukraine and Italy may be attributed to the incorporation of *Ph. colchicus* into the cultural and land use practices in Italy, which encompass hunting grounds and agricultural farms. In Dnipro, this species is predominantly observed in peripheral areas or regions with minimal anthropogenic influence, maintaining a semi-wild status. However, recent observations indicate an increasing penetration of urbanised areas due to the absence of shooting activities.

It is noteworthy that *Delichon urbica* exhibits a hemeroby index of 38.2 in Dnipro, which is considerably lower than the hemeroby index value of 89.0 observed in European data. *D. urbica* is renowned for its proclivity to construct nests on the eaves of buildings and utilise urban infrastructure for breeding purposes. It builds nests composed of clay and mud, which it attaches to the eaves of buildings, balconies, or other structures. This discrepancy can be attributed to the distinctive characteristics of urban development and the availability of nesting sites in both countries. In Italy, architectural elements are more conducive to the adaptation of this species. In the city of Dnipro, there has been a notable shift towards buildings with a more straightforward architectural style in recent decades. This has led to a reduction in the number of potential nesting sites available.

The hemeroby index values for species such as *Fringilla coelebs* and *Columba palumbus* in our study are markedly higher than those estimated for Europe. The former species, the chaffinch, is one of the most common birds in the forest zone, preferring deciduous and mixed forests, parks and gardens. In the city of Dnipro, the hemeroby index for *F. coelebs* is 41.8, which is significantly higher than the European value of 28.9. In the city of Dnipro, the species is frequently observed in urban parks, gardens, and forest park areas where there is an adequate supply of trees for nesting. It is one of the most abundant species in terms of individual numbers. The species *C. palumbus* represents the largest species within the Columbidae family. This species typically inhabits forested areas, but recent observations have documented an increasing presence in urban environments. It is able to integrate into urban landscapes with a large number of trees for nesting and access to food in parks and green areas. This species exhibits a preference for deciduous and mixed forests, as well as parks and green spaces that provide suitable nesting sites in trees. In Dnipro, the hemeroby index of *C. palumbus* is 44.5, while in the central Italian region it is 20.0. This discrepancy can be attributed to the differing timeframes under which the studies were conducted. The number of nesting sites in urban areas has been on the rise in recent years, suggesting that the current hemeroby index may also be higher in European regions.

The species *Motacilla alba* is notable for its proximity to humans and its capacity to adapt to urbanised environments. This species is predominantly found in proximity to water, in open habitats such as fields and riverbanks. However, it is also highly prevalent in urban environments, particularly in public squares, roadways, and embankments. Our data indicates that the hemeroby index of *M. alba* is 52.6, while European data suggests a value of 71.6. In the European region, *M. alba* is well integrated into the urban environment, utilising both natural and artificial landscapes for nesting and foraging. The discrepancy in the hemeroby index values may be attributed to the prevalence of moistened lawns in Europe, which offers a greater array of habitats for *M. alba* in the context of urbanisation. Similarly, *Corvus cornix* is an adaptable species, renowned for its capacity to thrive in a multitude of habitats, including densely populated urban environments. This species is omnivorous, foraging for sustenance in both natural and urban environments. Its diet encompasses a range of resources, including human waste, insects, small animals, and plant matter. *C. cornix* is capable of nesting in a variety of urban environments, including parks, trees, and even buildings, demonstrating an ability to adapt to different urbanisation conditions. In the city of Dnipro, the hemeroby index of *C. cornix* is 53.8, which indicates a high ability to adapt to an urbanised environment. In contrast, the hemeroby index of *C. cornix* in central Italy is somewhat lower, with a value of 47.6. The higher index of hemeroby of *C. cornix* in the Dnipro ecosystems compared to central Italy is likely attributable to the fact that this bird is an abundant urban species in Eastern Europe, including Ukraine, though it is also common in urban areas in Italy.

Conclusion

The utilisation of remote sensing data led to the generation of a map delineating the hemeroby of a contemporary metropolis. Information on landscape hemeroby was employed as a basis for assessing the hemeroby of urban birds. A comparison of hemeroby indicators between the city of Dnipro and Europe revealed a strong correlation, indicating a similar ecological response of species to anthropogenic changes in different regions and the relevance of hemeroby assessment. The species with the highest hemeroby scores in Dnipro typically exhibit similarly elevated values in European regions, thereby substantiating the hypothesis that they demonstrate comparable adaptability in disparate environmental conditions. The strong correlation observed indicates that anthropogenic factors exert a similar influence on birds across different geographic locations, thereby underscoring the universality of ecological patterns in urbanisation. It can be observed that eurytopic species with high hemeroby indices in both regions are the most successful in urbanised landscapes. They are capable of effectively utilising urban resources, exhibiting high levels of ecological plasticity and adaptability. These species proactively integrate into the urban environment, utilising buildings and infrastructure for nesting, and exploiting human waste as a food source. Conversely, species with low hemeroby remain confined to natural or semi-natural environments, exhibiting minimal adaptation to urban conditions. These species are reliant on natural ecosystems for nesting and feeding, which underscores their vulnerability to anthropogenic changes. This is particularly crucial in the context of rapid urbanisation, where the conservation of natural habitats is of paramount importance for the maintenance of biodiversity. It is crucial to consider these regional variations when developing effective strategies for the conservation and management of urban ecosystems. The maintenance of natural and semi-natural environments within urban landscapes will assist in the conservation of species with low hemeroby indices that are vulnerable to anthropogenic changes. Concurrently, an understanding of the ways in which eurytopic species adapt effectively to urban conditions can be employed to predict changes in urban bird communities and to plan management measures for these birds. The significant correlation between hemeroby indices across diverse geographical regions underscores the pervasive nature of ecological patterns and suggests that urbanisation exerts a comparable influence on avian species in varying ecological settings. This paves the way for the application of generalised approaches to the study and management of urban ecosystems, while taking into account local particulars. In light of these findings, it is imperative to adopt an integrated approach to biodiversity conservation in urban areas, one that considers both global trends and regional differences. This will contribute to the formation of sustainable and biologically diverse urban landscapes, thereby ensuring a balance between urban infrastructure development and conservation.

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