



Integrating hemeroby into environmental assessment: Trends and future perspectives

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Hemeroby is a widely used ecological concept designed to quantify the degree of anthropogenic disturbance in natural ecosystems. Since its introduction in the 1950s, it has evolved into a versatile indicator applicable across various spatial scales, land use types and ecological contexts. Despite its extensive use, the concept is methodologically diverse and is applied inconsistently, which limits its potential for standardized environmental assessment. In this study, we conducted a bibliometric analysis and topic modelling of 228 peer-reviewed articles to identify key research areas and emerging trends in hemeroby-related studies. Five major thematic clusters were identified: (1) landscape-scale disturbance; (2) naturalness assessment; (3) water quality and aquatic vegetation; (4) urban biodiversity; and (5) habitat degradation. The two most influential topics, urban biodiversity and habitat degradation, together account for over 60% of all publications. Latent Dirichlet Allocation (LDA) was employed to explore the thematic structure and relationships between topics. Citation analysis revealed that papers with moderate thematic novelty and interdisciplinary linkages tend to have higher citation rates. Studies focusing on habitat degradation (topic 5) were the most conceptually cohesive and widely cited due to the consistent application of phytosociological and floristic methods. In contrast, studies on water quality (topic 3) were less integrated into the hemeroby framework and showed lower conceptual cohesion. The concept of hemeroby has become increasingly prevalent in spatial ecological modelling, urban ecosystem assessment and life cycle environmental impact analysis (LCA). Recent advances have emphasized the integration of hemeroby with the functional traits of species, remote sensing and GIS-based land use mapping. Particular attention is given to its role as a proxy for landscape naturalness, and to its usefulness in detecting ecological thresholds, restoration potential and functional degradation in urban and semi-natural systems. The concept has also been adapted for evaluating the impact of human activity on soil (soil hemeroby) and freshwater habitats. However, challenges remain, including subjectivity in expert-based scoring, variability across regional applications and limited taxonomic resolution in certain groups. Future research should focus on standardising evaluation protocols, expanding the range of indicator taxa (e.g. soil fauna and microflora) and integrating hemeroby into broader ecosystem condition and nature-based solution frameworks. Hemeroby thus has great potential to inform policy, guide land use planning and enhance the effectiveness of environmental monitoring and biodiversity conservation in the face of increasing anthropogenic pressure.

Keywords: anthropogenic disturbance; ecological indicator; urban biodiversity; habitat degradation; naturalness; land-use impact; environmental assessment.

Introduction

Hemeroby is an ecological concept utilised to evaluate the extent of anthropogenic impact on natural ecosystems (Šantrůčková et al., 2025). The term derives from the Greek words *hémeros* (tame, cultivated) and *bios* (life), which literally mean "tamed life". The concept of hemeroby was first introduced by the Finnish botanist Jalas (1953, 1955) to evaluate vegetation changes under the influence of human activity. Following the seminal introduction of the concept by Jalas, it was further developed by Herbert Sukopp in the 1970s (Sukopp, 1972). Sukopp expanded the application of hemeroby by incorporating it into the analysis of urban ecosystems. The author developed a seven-level scale reflecting a gradient from natural to completely transformed environments (Sukopp, 2004). Kowarik's theoretical framework facilitated the integration of classical phytosociological methods with novel approaches to urban landscape analysis, employing hemeroby as a pivotal indicator of urban ecological stability (Kowarik, 1988). He proposed and developed systematic approaches to quantitatively assess the degree of transformation of natural habitats influenced by urban environments, formulating a clear methodology for determining levels of hemeroby in urban landscapes. Kowarik significantly expanded the concept, which was initially used primarily to assess plant communities, adapting it to the study of urban environments and green spaces. His work demonstrates that hemeroby is an

effective indicator of the condition of natural ecosystems and the extent of ecological degradation and transformation in cities (Kowarik, 1990). Kowarik created a theoretical framework that enabled the integration of classical botanical methods of phytointication with innovative approaches to the analysis of urban landscapes, utilizing hemeroby as a comprehensive indicator of urban ecological sustainability. Thanks to Kowarik's contributions, the concept of hemeroby has become widely adopted in urban ecology, serving as an essential tool in urban planning and environmental management, and remains a key method for assessing anthropogenic impacts on urban ecosystems (Hill et al., 2002). In the contemporary context, hemeroby is utilized as an indicator to evaluate the extent of ecosystem disturbance. Several methodologies have been developed for its assessment, including the landscape-based approach, the biotic approach, and its integration into life cycle assessment (LCA) (Fehrenbach et al., 2015a).

The landscape-based approach utilizes an analysis of changes in landscape structure and land use in order to assess hemeroby (Jasina-vičiūtė & Veteikis, 2022). The degree of anthropogenic disturbance is determined by examining the spatial organisation of landscapes and the types of land cover present (Walz & Stein, 2014). A fundamental aspect of this approach pertains to its emphasis on alterations in spatial patterns, particularly the proportions of natural, semi-natural, and artificial (anthropogenic) components within the environment. The key indicators of hemeroby in this context can be summarized as follows:

landscape fragmentation; building density; the proportion of artificial surfaces; and the loss of natural or semi-natural habitats (le Clech et al., 2024). This approach commonly relies on geographic information systems (GIS), remote sensing, and landscape metrics such as patch indices, fragmentation indices, and degrees of urbanization (Yorkina et al., 2020). The landscape-based approach is distinct from bioindicator-based methods in that it allows for the evaluation of hemeroby across vast regions with high spatial resolution. Additionally, it facilitates the examination of historical shifts and the forecast of future trends (Tukiainen et al., 2017). The main advantages of this approach are its capacity for the integrated evaluation of extensive territories, its consideration of various land use types, and the high repeatability of the methodology (Podpriatova et al., 2023). However, this approach has two limitations: insufficient consideration of local ecological conditions and the internal structure of plant or animal communities, which may be more sensitive to anthropogenic disturbances at the local scale. Consequently, the landscape-based approach is typically recommended for use alongside bioindicator methods to provide a more comprehensive evaluation of ecosystem integrity.

The biotic approach uses indicator plant or animal species to determine the level of hemeroby (Komlyk et al., 2024). This method is based on species that respond sensitively to different degrees of ecosystem disturbance (Ponomarenko et al., 2024). Local-scale studies often use this method because it allows researchers to spot small changes in the types of species in communities (Zelenova et al., 2024). These changes are often hard to pick up on using metrics at a landscape level (Pinke et al., 2011). Comparing hemeroby with the concept of naturalness has revealed profound interrelationships, as well as notable differences, between these two indicators (Erdős et al., 2022). They are viewed as opposite poles along a continuum, ranging from a fully natural state (low hemeroby, high naturalness) to completely degraded conditions (high hemeroby, low naturalness) (Lisovets et al., 2024). Hemeroby has been shown to provide a more nuanced gradation at the degraded end of this spectrum, making it particularly suitable for assessing disturbed or anthropogenically altered sites (Kunakh et al., 2024). Methodologically, hemeroby is assessed through a system of indicator values assigned to species based on their tolerance of human-induced pressures (Fanelli & De Lillis, 2004). These hemeroby value systems typically range from five to ten levels, either developed through expert evaluation or derived from the empirical analysis of vegetation data. Hemeroby values enable the effective integration of information about complex degradation processes that cannot be measured individually (Zinnen et al., 2021).

Integrating hemeroby into Life Cycle Assessment (LCA) involves incorporating this indicator as a distinct criterion for evaluating the impact of human activities, products, or production processes on natural ecosystems (Lindner et al., 2019). A methodological framework designed for the comprehensive evaluation of the environmental impacts associated with a product, service, or technological process throughout its entire life cycle is known as Life Cycle Assessment (LCA). The life cycle in question covers the stages from raw material extraction and manufacturing to transportation, use, recycling, and final disposal (Brenttrup et al., 2004). The essence of LCA is to identify and quantitatively assess all potential environmental impacts related to a given product or process. These impacts include the consumption of natural resources, greenhouse gas emissions, water and air pollution, waste generation, and effects on biodiversity and ecosystems (Göel et al., 2025). A typical life cycle assessment (LCA) consists of four main stages: 1) Goal and scope definition. This stage involves specifying the purpose of the assessment and defining the system boundaries, which include temporal, spatial, and technological aspects. Additionally, the functional unit that serves as the basis for comparing environmental impacts is determined at this stage (Brugnoli et al., 2025). 2) Life cycle inventory (LCI). In this stage, data are collected and processed regarding resource inputs and emissions at each phase of the product's or process's life cycle. The third stage is the life cycle impact assessment (LCIA), which involves evaluating and classifying the collected data according to various environmental impact categories, including global warming, eutrophication, acidification, toxicity, resource depletion, and ecosystem degradation (Lehtilä et al., 2025).

The final stage involves interpreting the results, which includes analysing the outcomes, identifying (stages or processes with the most significant negative impact), and formulating recommendations to mitigate environmental consequences. Life cycle assessments (LCAs) are widely utilized across various sectors, including industry, agriculture, construction, and transportation, as well as in the development of environmental policies and sustainability strategies (Finkbeiner et al., 2025). The integration of new ecological indicators, such as hemeroby, significantly enhances the accuracy and comprehensiveness of environmental impact evaluations, promoting more balanced resource use and a more responsible approach to environmental stewardship (Zhen et al., 2025). Hemeroby is used as an indicator of environmental change resulting from different land use and resource management practices. It assesses the degree of deviation from the natural state throughout the entire life cycle of a product or service (Rafaii & Abdullah, 2024). It facilitates the evaluation of the loss of naturalness in areas impacted by human activities and enables the comparison of the environmental consequences of various technological solutions. This is particularly important in the context of global environmental issues such as biodiversity loss, climate change and ecosystem degradation. Integrating hemeroby into life cycle assessment (LCA) enables the ecological cost of different stages of product manufacturing to be determined, and strategies to be developed to reduce negative impacts and maintain or restore natural conditions in the areas being used (Eberle & Mumm, 2024). Including hemeroby in life cycle assessments enables companies and organisations to take a more systematic and responsible approach to planning activities and choosing the most environmentally acceptable options for resource and land use (Furtado et al., 2024).

The concept of hemeroby is widely utilized in ecological research and nature conservation (Carruthers-Jones et al., 2025). In urban planning, for instance, it is employed to evaluate the ecological condition of urban ecosystems and to identify priority areas for greening and restoration (Fernández-Cabello et al., 2025). In agriculture, hemeroby is used to analyse the environmental impact of land use and to develop sustainable farming practices. In conservation efforts, it facilitates the effective identification of areas that require special attention in the context of biodiversity preservation. Despite its effectiveness, hemeroby still requires more standardized assessment methods. The primary challenges are related to the subjectivity of expert evaluations and the variability of methodologies, both of which complicate inter-regional comparisons. Therefore, further research should focus on developing unified international standards, integrating hemeroby with other environmental indicators, and applying modern remote sensing technologies. Hemeroby is a highly useful and promising concept that can significantly enhance the effectiveness of ecological monitoring and natural resource management, particularly in the face of increasing anthropogenic pressure on ecosystems. It serves as a vital tool for assessing the degree of human impact on ecosystems. Its application aids in detecting the level of environmental disturbance and in developing restoration strategies. The continued development and standardization of hemeroby assessment methods will contribute to more effective natural resource management and biodiversity conservation.

The study aims to systematise and analyse scientific publications on hemeroby to identify key research areas, particularly the use of hemeroby as an indicator of environmental disturbance, the assessment of landscape structure, the application of indicator species, and the evaluation of conditions in urbanized areas. Additionally, the study seeks to determine the internal structure of the hemeroby research field by analysing thematic clusters and the spatial distribution of publications within the semantic space. Special attention will be given to factors influencing the citation frequency of publications, such as proximity to the thematic centroid and the substantive focus of the research. Finally, the study aims to outline prospects for the further development of the hemeroby concept, including its integration into life cycle assessment (LCA), the application of geoinformation methods, and the unification of assessment methodologies, with the goal of enhancing the interregional comparability of results.

Material and methods

Topic modelling is a class of statistical models that automatically detects latent topics within a collection of documents. These models assume that each document is a mixture of topics, with each topic represented as a probability distribution over words. This approach enables the reduction of a high-dimensional text space to linguistically and semantically meaningful features known as topics, significantly enhancing the interpretability of the data (Kherwa & Bansal, 2018). The Latent Dirichlet Allocation (LDA) model was used to perform the thematic analysis of scientific publications. This is a probabilistic mixed-membership model that allows each document to have a distribution over topics, and each topic a distribution over words. LDA effectively uncovers latent thematic structure in text corpora by jointly modeling terms and documents. Parameter estimation in LDA was performed using collapsed Gibbs sampling, an efficient variant of the Markov Chain Monte Carlo (MCMC) algorithm in which topic and word variables are iteratively updated based on conditional probabilities. This approach provides robust posterior estimates of document-topic (θ) and topic-word (ϕ) distributions, which were subsequently used for visualization, clustering, and regression modeling. The analysis of publications related to the concept of hemeroby was conducted using automated bibliometric processing and topic modeling. Data were retrieved from the Scopus database on May 25, 2025, using the search term “hemeroby” across all fields. This query returned 228 publications from 1980 to 2025. The data were converted into a RIS file containing bibliographic metadata such as titles, abstracts, and keywords. The file was cleaned and transformed into a tabular format using a custom function `parse_record()` that extracted metadata based on tags. After preprocessing, a document-term matrix (DTM) was generated using the `CreateDtm()` function, which applied lemmatisation, stop-word removal, and text normalization. A Latent Dirichlet Allocation (LDA) model with 5 topics ($k = 5$) was trained on the cleaned DTM over 500 iterations with a burn-in period of 180 iterations and hyperparameters $\alpha = 0.1$ and $\beta = 0.05$. For each document, the most probable topic was identified based on the θ distribution, and documents were thematically classified by topic and year of publication. Citation information from the N1 tag in the RIS file was extracted and stored in the variable `cited_by`. A logarithmic transformation was applied using the formula $\log_{10}(\text{citations} + 1) = \log_{10}(\text{cited_by} + 1)$. Cosine similarity between topic vectors (θ) was used for multidimensional scaling (MDS), which enabled visualization of documents in topic space. For each topic, centroids were calculated, and the distance from each document to the corresponding centroid was computed using either Euclidean distance or Jensen–Shannon divergence. Quantile regression was used at $\tau = 0.8$ to assess the relationship between thematic coherence (distance to topic centroid) and citation count. The analysis was conducted separately for each topic. Statistical significance was evaluated using bootstrap estimation of standard errors with 5000 replications. For each model, pseudo- R^2 was also calculated as:

$$R^2 = 1 - (\sum \rho(y_i - \hat{y}_i)) / (\sum \rho(y_i - \tilde{y}))$$

where $\rho(u) = u \times (\tau - I(u < 0))$, $\hat{y}_i$ is the predicted value, and $\tilde{y}$ is the median of y .

A control sample of 40 randomly selected publications (“Reference group”) was formed for each topic and compared with the actual data using a GLM model with a Topic $\times$ YearsSince interaction. The creation of the document-term matrix (DTM) and topic modeling using Latent Dirichlet Allocation (LDA) was carried out with the `textmineR` package (Jones, 2021). Lemmatisation was performed using the `textstem` package (Rinker, 2018), while text preprocessing, stop-word removal, and stemming were conducted using the `tm` (Feinerer et al., 2008) and `SnowballC` (Bouchet-Valat, 2023) packages. Quantile regression via the `rq()` function was performed with the `quantreg` package (Koenker, 2024). Multidimensional scaling (MDS) was applied to visualize the thematic distances between scientific publications. The input matrix consisted of cosine distances computed between topic distributions (θ) derived from the LDA model. These distances characterize the degree of difference between the thematic profiles of documents. Classical MDS (via the `cmdscale` function in

R) was used to project the high-dimensional space of thematic distances into a lower-dimensional space (4 components), preserving the relative positions of documents. The first two and the last two coordinates were used to construct two-dimensional plots, allowing for the identification of thematic clusters and evaluation of within-topic variation. Each publication was visualized as a point on the MDS plane, with topic affiliation indicated by colour. For each topic, 68% coverage ellipses (using the `dataEllipse` function) were drawn to visualize the zone of highest thematic concentration.

Results

The document-term matrix (DTM) was constructed based on the titles, abstracts, and keywords of the publications. It provides a numerical representation of the corpus, where each row corresponds to a document and each column represents a unique term or n-gram. The values in the matrix indicate the frequency of the corresponding term within each document. Preprocessing steps included converting text to lowercase, lemmatisation, filtering out stop words, and removing digits and punctuation. This matrix served as the input data for topic modelling using Latent Dirichlet Allocation (LDA). The pseudo- R^2 was calculated to assess model quality, yielding a value of 0.21. This indicates that approximately 20.6% of the variation in term frequencies within the corpus is explained by the model’s latent topics. This level of explanatory power was achieved through comprehensive TF-IDF filtering, which emphasised the most informative terms, and by restricting the vocabulary to semantically meaningful lemmatised units of medium and longer n-grams. The resulting pseudo- R^2 is considered satisfactory for corpora of scientific texts and suggests the presence of a clear thematic structure within the dataset. Publications on the topic of hemeroby are categorised into five latent themes, each representing a distinct aspect of the relationship between ecological processes and anthropogenic impacts (Table 1). Articles assigned to each theme share similar keyword spectra, facilitating a meaningful interpretation of these topics. The first theme addresses landscape patterns, spatial indices, and manifestations of human disturbance. The second theme pertains to ecosystem naturalness and the use of indicators for assessing forest systems. The third theme concentrates on water quality, particularly in river ecosystems, along with relevant ecological indicators. The fourth theme encompasses urbanised landscapes, biodiversity, and conservation measures. Finally, the fifth theme relates to plant community structure, habitat conditions, and ecosystem disturbances.

Table 1
Interpretation of latent topics derived from keyword modelling in publications related to hemeroby

Topic	Top keywords	Short title	Full title
T1	landscape, human, pattern, index, disturbance, landscape pattern, spatial	landscape disturbance	indexes and spatial patterns of human disturbance in landscapes
T2	forest, naturalness, indicator, impact, natural, ecosystem, assessment	naturalness	naturalness as an ecosystem-based indicator for assessment in ecosystems
T3	quality, water, ecosystem, index, river, water quality, environmental	water quality	indication of aquatic ecosystem quality: river and water-based assessments
T4	landscape, urban, ecological, biodiversity, conservation, ecosystem, model	urban biodiversity	landscape-scale modelling of urban ecological and biodiversity dynamics
T5	species, plant, community, vegetation, habitat, study, disturbance	habitat disturbance	hemeroby as an indicator of habitat disturbance

The most frequent topics were T5 (78 publications) and T4 (70 publications), followed by T1 (37) and T2 (29), while T3 was the least represented with only 14 publications. This distribution highlights a predominant focus on habitat disturbance and urban biodiversity within the analysed corpus (Fig. 1).

The overall number of publications has grown steadily since the 1990s, with a particularly sharp increase after 2010 (Fig. 2). The most intensive growth is observed in the topics Habitat disturbance (T5)

and Urban biodiversity (T4), both of which exhibit a consistent up-

ward trend from 2000 onward.

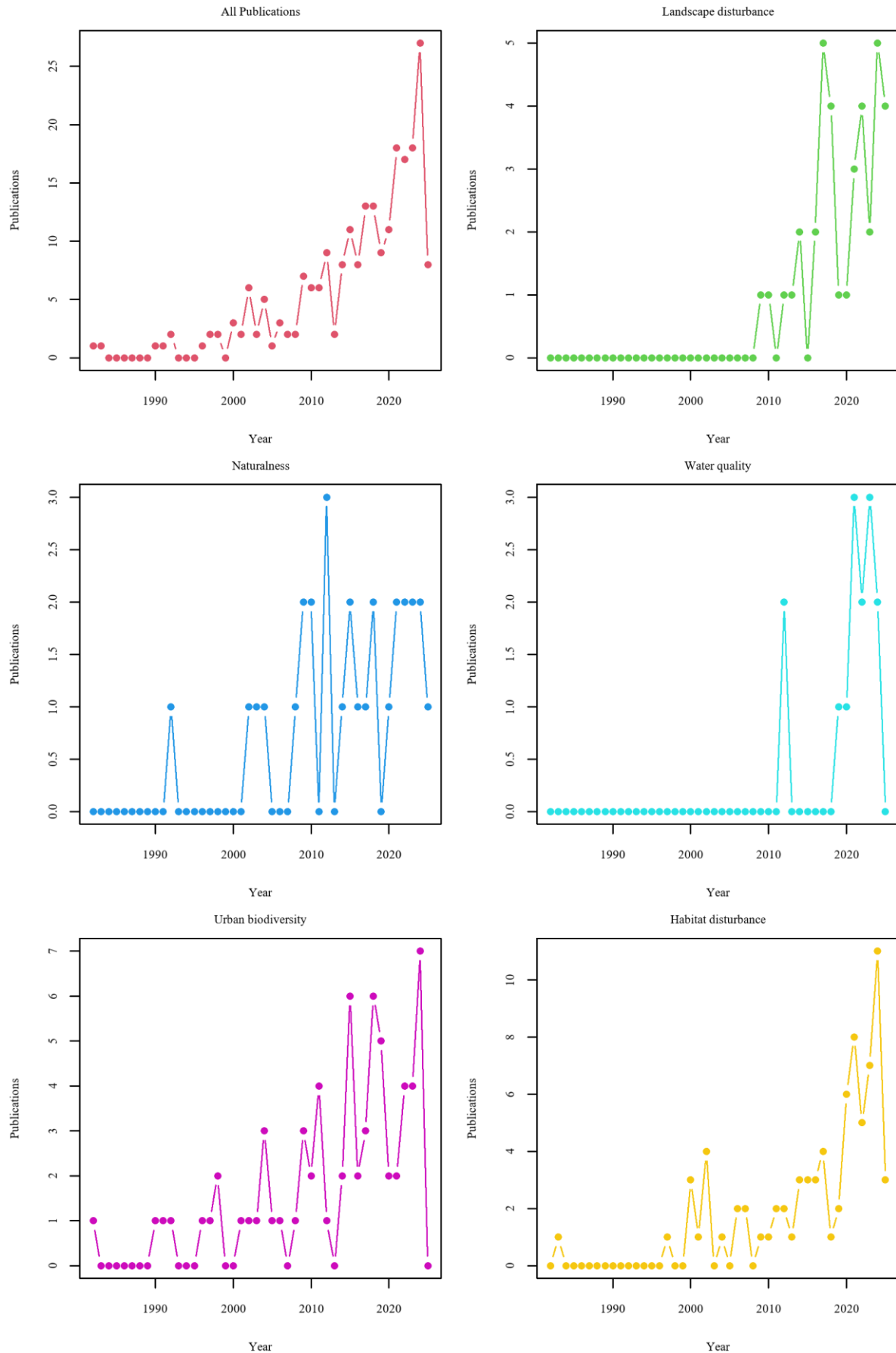


Fig. 2. Temporal trends in the number of publications related to hemeroby (1980–2024), based on data retrieved from the Scopus database: the top-left panel shows the annual total number of publications; the remaining five panels illustrate the yearly distribution of publications assigned to the five latent topics identified through topic modelling; these trends reflect the evolving research focus on hemeroby-related issues across different thematic domains

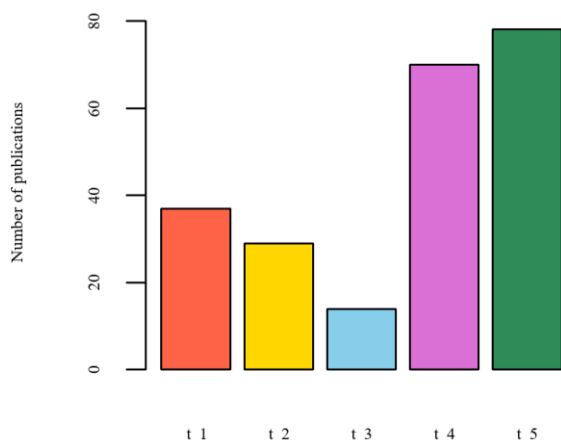


Fig. 1. Distribution of publications across the five latent topics identified through keyword modelling of hemeroby-related literature: T1 – landscape disturbance (indexes and spatial patterns of human disturbance in landscapes); T2 – naturalness (naturalness as an ecosystem-based indicator for assessment in forest systems); T3 – water quality (indicators of aquatic ecosystem quality: river and water-based assessments); T4 – urban biodiversity (landscape-scale modelling of urban ecological and biodiversity dynamics); T5 – habitat disturbance (plant community composition as an indicator of habitat disturbance)

The topic landscape disturbance (T1) began to appear in the literature after 2005, showing moderate but stable growth. Naturalness (T2) displays an irregular pattern with isolated peaks, particularly around 2010. Water quality (T3), while relatively recent, shows a noticeable rise after 2015, although its overall frequency remains the lowest among the topics. These trends reflect a growing scientific interest in

the impacts of anthropogenic change on ecological structure and function across spatial and thematic dimensions.

Dimension 1, as revealed by multidimensional scaling, represents the primary thematic gradient in the distribution of publications across dominant topics (Fig. 3). At one end of this dimension are documents associated with Theme 5 (habitat disturbance), which focus on assessing the bioecological characteristics of plant communities and their habitats. The opposite end is comprised of documents classified under Themes 1 (landscape disturbance) and 4 (urban biodiversity), which concentrate on the analysis of spatial structures, urban ecosystems, and anthropogenic impacts on landscapes. This first dimension delineates a continuum of scientific inquiry, ranging from studies of local environmental characteristics and biotic assemblages to broader landscape-scale and urban aspects of hemeroby assessment.

Dimension 2 reflects a shift from the analytical study of the spatial characteristics of anthropogenically transformed landscapes (Theme 1) to the assessment of forest ecosystem naturalness based on ecological indicators (Theme 2). Dimension 3 represents a conceptual gradient between two thematic groups: Themes 2 (Naturalness as an ecosystem-based indicator) and 3 (Plant community dynamics) on one side, and Theme 4 (urban ecological and biodiversity modelling) on the other. This indicates a transition from ecologically oriented research focused on naturalness assessment and plant community structure to more applied studies on urbanised landscapes and spatial biodiversity modelling. Dimension 4 evidently segregates Theme 3 (water quality) from all other thematic categories. This suggests that publications addressing indicators of aquatic environment quality and the status of rivers and aquatic ecosystems form a distinct conceptual cluster, significantly different from studies centred on forest, landscape, or urban systems. This dimension represents a water-oriented axis within the hemeroby research domain that structurally contrasts with terrestrial and anthropogenically transformed environments.

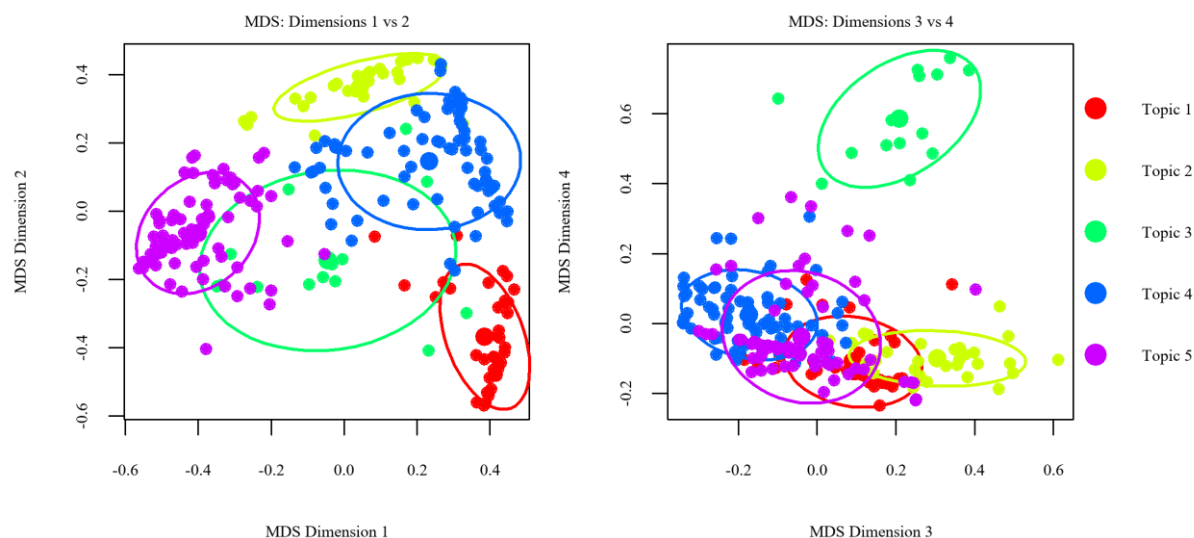


Fig. 3. Multidimensional scaling (MDS) visualization of document-topic distributions for the five latent topics identified in hemeroby-related publications: the left panel shows MDS Dimensions 1 vs 2; the right panel displays Dimensions 3 vs 4; each point represents an individual publication, coloured according to its dominant topic: T1 – landscape disturbance (indexes and spatial patterns of human disturbance in landscapes); T2 – naturalness (naturalness as an ecosystem-based indicator for assessment in forest systems); T3 – water quality (indicators of aquatic ecosystem quality: river and water-based assessments); T4 – urban biodiversity (landscape-scale modelling of urban ecological and biodiversity dynamics); T5 – habitat disturbance (plant community composition as an indicator of habitat disturbance)

Time since publication, topic, and their interaction collectively accounted for 54.4% of the variance in citation rates ($F = 46.6$, $P < 0.001$). As anticipated, citation counts generally increased over time ($\text{Beta} = 0.75 \pm 0.04$, $P < 0.001$). Overall, topics did not significantly differ from a random alternative in terms of citation levels ($F = 1.88$, $P = 0.097$). However, significant differences emerged between thematic groups. Citation levels for Themes 3, 4, and 5 were significantly lower than expected under a random alternative (Planned comparison $F = 8.16$, $P = 0.004$) (Fig. 1), while Themes 1 and 2 were associated with significantly higher citation levels (Planned comparison $F = 9.11$, $P = 0.003$).

A General Linear Model was fitted, including an interaction term between topic and publication age (YearsSince), to assess whether the relationship between the number of years since publication and the log-transformed citation count differs across thematic groups. The model revealed a statistically significant interaction for Topic 1 compared to the reference group ($\beta = -0.219$, $\text{SE} = 0.087$, $t = -2.51$, $P = 0.0125$), indicating a shallower citation slope in this topic. For all other topics, the interaction terms were statistically non-significant ($P > 0.27$), suggesting that the effect of publication age on citation rates did not differ substantially from the reference group. Specifically, the estimated differences in slope ranged from -0.043 to $+0.122$,

none of which reached significance. These results indicate that only Topic 1 exhibits a distinct temporal citation trend, while citation dynamics in Topics 2–5 closely resemble those of the reference category.

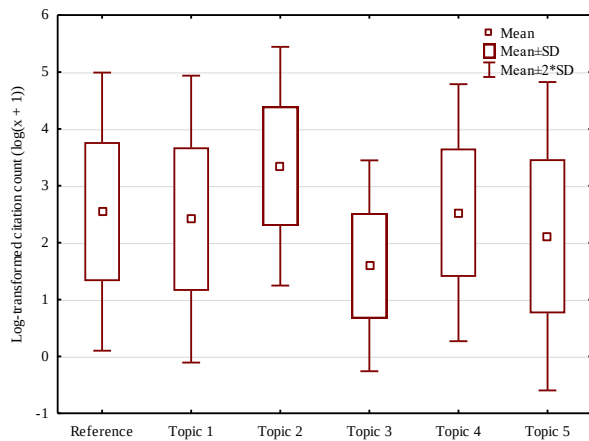


Fig. 4. Distribution of citation counts (log-transformed as $\log(x + 1)$) across topics identified in hemeroby-related publications. Boxplots represent the median, interquartile range (IQR), and data range for each topic: squares indicate the mean citation count; vertical lines show ± 1 and ± 2 standard deviations (SD) from the mean; "reference" corresponds to a random sample of publications and serves as the baseline category in the GLM model; T1 – landscape disturbance (indexes and spatial patterns of human disturbance in landscapes); T2 – naturalness (naturalness as an ecosystem-based indicator for assessment in forest systems); T3 – water quality (indicators of aquatic ecosystem quality: river and water-based assessments); T4 – urban biodiversity (landscape-scale modelling of urban ecological and biodiversity dynamics); T5 – habitat disturbance (plant community composition as an indicator of habitat disturbance)

The residuals of the global linear model, which accounted for the effects of topic, publication age, and their interaction on citation count, were analysed separately for each thematic cluster using generalized additive models (GAM) (Fig. 4). All clusters exhibited a pronounced nonlinear response, with local maxima at intermediate values of thematic distance. This finding indicates that the highest citation

counts were observed for publications that were moderately distant from the thematic centre, thereby avoiding both overly typical and highly peripheral works. An additional panel displays the Jensen-Shannon divergence (JSD) distance values at which the response function reached its maximum for each thematic cluster.

Discussion

Thematic structure and citation dynamics in hemeroby research. Hemeroby represents a significant research trend focused on assessing anthropogenic impacts on ecological systems. Over the past few decades, there has been a consistent increase in attention to this scientific issue, accompanied by a growing number of publications. This rise in publications is linked to the diversification of scientific approaches used to evaluate human impact and the various directions in which the concept of hemeroby is applied. The analysis revealed that five thematic groups effectively encompass various aspects of hemeroby-related research. However, it is important to note that the thematic landscape represents more of a continuum of meanings rather than a collection of discrete research directions. Simultaneously, each group of meanings forms a distinct conceptual framework that either explicitly or implicitly serves as a foundation for scientific inquiry. Citation patterns serve as a clear indicator of the popularity of ideas. Our findings suggest that articles closely aligned with the thematic centroid, which represents the most typical formulation of a topic, tend to receive relatively high citation counts. However, the highest citation levels are observed in studies that demonstrate a certain degree of originality, as indicated by their distance from the centroid. In some thematic contexts, the issue of hemeroby may be secondary, and distancing from the centroid can be interpreted as a shift toward an alternative, more appealing thematic focus. This may explain why a greater distance from the centroid is sometimes associated with increased citation rates. The relationship between citation frequency and distance from the centroid appears to be largely neutral, which may indicate a relative equivalence between the concept of hemeroby and competing conceptual frameworks. Latent topics can be identified through keyword analysis, and this identification can be verified and meaningfully interpreted by examining the most frequently cited publications that are closest to the thematic centroid.

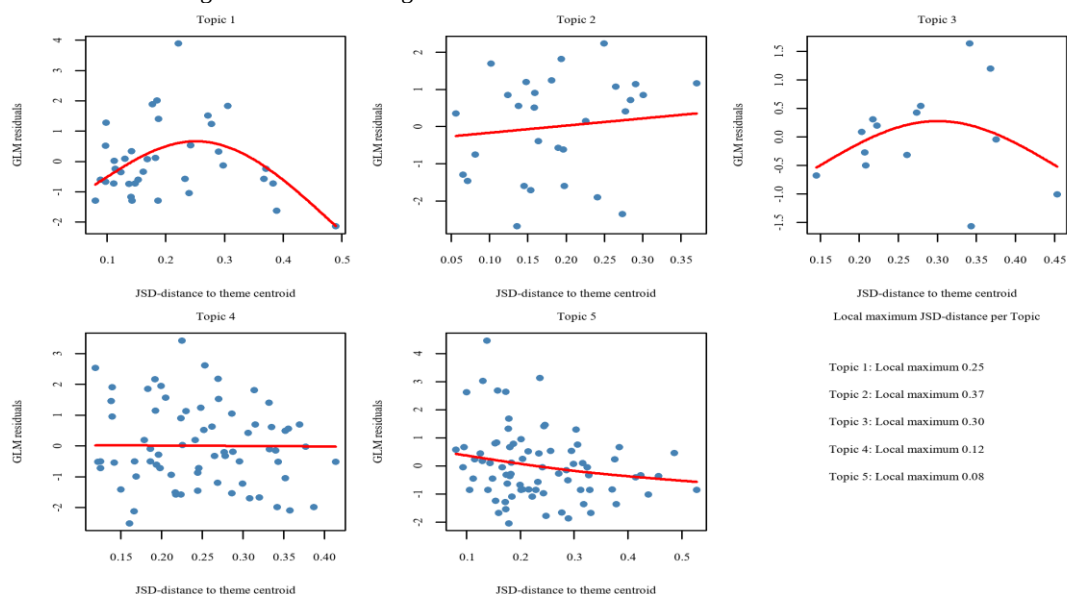


Fig. 5. Partial effect of JSD-distance to the theme centroid on residual citation impact across five thematic clusters (Topics 1–5), based on Generalized Additive Models (GAM); each panel shows the relationship between the distance to the thematic centroid and the residuals of a global GLM model predicting log-transformed citation counts; red lines represent smoothed GAM fits; panel 6 summarizes the JSD-distance values at which the fitted response reaches its maximum for each topic, indicating the optimal thematic distance associated with peak citation influence; T1 – landscape disturbance (indexes and spatial patterns of human disturbance in landscapes); T2 – naturalness (naturalness as an ecosystem-based indicator for assessment in forest systems); T3 – water quality (indicators of aquatic ecosystem quality: river and water-based assessments); T4 – urban biodiversity (landscape-scale modelling of urban ecological and biodiversity dynamics); T5 – habitat disturbance (plant community composition as an indicator of habitat disturbance)

Landscape disturbance. The number of articles addressing the issue of hemeroby has been steadily increasing since the early 1990s. The topic of hemeroby's contribution to assessing landscape-level disturbances is relatively recent and has shown dynamic growth since the late 2000s. As a result, this thematic area significantly contributes to the overall body of hemeroby research, accounting for 16.2% of all publications. In terms of its position within the thematic space, the issue of hemeroby and landscape disturbance represents a significant expansion of conceptual boundaries, as it occupies a peripheral location in the space defined by the first two dimensions revealed through multidimensional scaling. Notably, this thematic group has proven to be highly productive, as evidenced by the relatively high citation rates of related papers.

On the other hand, this topic displays a weaker temporal trend in publication output, which may indicate an ongoing search for its conceptual core: while new articles quickly gain attention, their influence is often displaced by successive waves of publications. This idea is supported by the observation that the most productive publications are typically situated at a distance from the thematic centroid. It should also be noted that the thematic centroid was calculated as a mean over the entire study period, and at the time of publication, an article may have been located at a different distance from the centroid. This thematic direction is noteworthy for applying landscape ecology tools to the assessment of hemeroby. Within this approach, hemeroby is evaluated based on landscape maps, where each land-cover type is assigned a specific hemeroby level using expert judgment (Tian et al., 2020; Wu et al., 2021). Studies with a semantic meaning close to the thematic centroid reveal that retrospective analysis of landscape structure provides an opportunity to identify trends whereby increased human activity is accompanied by spatial expansion of areas with high levels of heterogeneity and transformation of landscape mosaics. The assessment of hemeroby must account for both spatial and temporal variability, as human impact on landscapes varies across time and regions (Sun et al., 2012).

Landscape metrics such as fractal dimension, landscape diversity, landscape complexity, and fragmentation are found to correlate with hemeroby levels (Fuqiang et al., 2017). Remote sensing data have shown that rising hemeroby levels are associated with increased fragmentation and simplification of landscape structure (Gao et al., 2024). The hemeroby index is viewed as a spatially aggregated indicator based on land-use categories derived from satellite imagery. Hemeroby demonstrates relationships with landscape metrics that reflect the degree of anthropogenic transformation. Increased hemeroby levels are linked to higher patch density, edge length, shape complexity, and fractal dimension. Conversely, the Shannon diversity index shows a negative correlation, decreasing as anthropogenic pressure intensifies. Hemeroby is thus associated with the structural complexity and fragmentation of landscapes driven by human activities (Zhou et al., 2018).

The concept of hemeroby has undergone certain transformations since its inception, as is noted in one of the most influential articles on this topic (Wellmann et al., 2018). The concept of hemeroby was originally developed for measuring human impacts on flora and vegetation (Jalas, 1953, 1955). The term was initially employed to denote the consequences of human activity on urban vegetation. The hypothesis was put forward that the hemeroby index ranges from an ahemerobic level, which corresponds to the absence of anthropogenic influence on a biocoenosis, to a metahemerobic level, where the biocoenosis is completely destroyed, for example under conditions of complete soil sealing (Sukopp, 1972). The concept was subsequently expanded to encompass a quantitative assessment of human impact on ecosystems (Kowarik, 1988). Subsequent advancements permitted the utilization of hemeroby for the purpose of land use classification and the evaluation of the effects of land use on the biosphere, with a particular focus on vegetation (Steinhardt et al., 1999). The proposal for two hemeroby-based indicators to monitor landscape conditions is presented herein. The first index is the hemeroby index, which represents the area-weighted average of hemeroby levels within a specific spatial unit. This indicator facilitates the evaluation of the cumulative anthropogenic pressure on the landscape, thereby enabling both spatial

and temporal comparisons. The second indicator is the proportion of nature-oriented areas, which includes patches with low hemeroby levels, ranging from ahemerobic to mesohemerobic. These areas are characterized by minimal or sporadic human intervention and are particularly significant for biodiversity conservation. The two indicators are complementary; the initial section provides a synopsis of the collective human influence, while the subsequent segment highlights the existence of ecosystems that are relatively natural yet, to some extent, modified (Walz & Stein, 2014). Landscapes with minimal human disturbance have been shown to foster highly dynamic and diverse vegetative communities, characterized by elevated levels of biodiversity. It is clear that areas with a high degree of naturalness or low hemeroby are best represented using the gradient model (GM) approach. In contrast, anthropogenic landscapes are primarily defined by homogeneous units with clearly delineated boundaries. Therefore, the patch-matrix model (PMM) is most effective for delineating these structures, as it allows for the differentiation of homogeneous land cover units or vegetation types with distinct boundaries. The quantitative assessment of these patterns can be enhanced through the use of landscape metrics, which articulate aspects related to composition and configuration (Lausch et al., 2015). The utilization of spectral traits (ST) and spectral trait variations (STV) has been proposed for the purpose of hemeroby analysis based on remote sensing (Wellmann et al., 2018). The acronym ST is used to denote a range of characteristics of plants, populations and communities that can be detected using remote sensing. These characteristics include anatomical, morphological, biochemical, biophysical, physiological, structural, phenological and functional traits. STV is defined as the alteration of spectral traits in response to physiological processes, the ageing process, and phenology. It also encompasses changes induced by stress, disturbance, and resource limitations in plants, populations, and communities (Cabrera-Bosquet et al., 2011).

The landscape disturbance approach offers several advantages, particularly due to the integration of remote sensing data, which enables comprehensive monitoring of land use changes and anthropogenic transformations over both time and space. The application of landscape ecology methods, including quantitative metrics such as patch density, edge density, fractal dimension, and diversity indices, provides a theoretically grounded and standardized framework for assessing the degree of landscape disturbance. This methodological approach is beneficial as it captures both spatial heterogeneity and temporal dynamics of human impact, which is especially important for evaluating hemeroby. The concept underpinning the study combines expert-based assessments of anthropogenic pressure across various land cover types with quantitative interpretations derived from satellite imagery. This approach facilitates the spatial aggregation of the hemeroby index. In doing so, the method demonstrates sensitivity to gradients of anthropogenic transformation, the spatial simplification of landscape mosaics, and the reduction in structural complexity. The primary drawbacks of this approach are rooted in its conceptual limitations and methodological rigidity. The application of such systems frequently relies on predefined, expert-based categorizations of land cover types. However, these systems can oversimplify complex ecological realities and restrict interpretative flexibility across diverse landscapes.

Naturalness, hemeroby, and life cycle assessment. The issue of naturalness accounts for 12.7% of all publications related to hemeroby. Interest in this topic is closely correlated with the overall number of publications on hemeroby, indicating a stable research focus that has received sustained attention since the early 21st century. In terms of its position along Dimension 1, as determined by multidimensional scaling, the concept of naturalness clarifies the landscape aspect of hemeroby. However, along Dimension 2, the topic of naturalness occupies a position that is opposite to that of the landscape aspect of hemeroby. Furthermore, its marginal placement along Dimension 3 suggests that the theme of naturalness significantly broadens the semantic scope of the hemeroby concept. Conceptually, naturalness and hemeroby are opposite yet complementary terms. Hemeroby is regarded as more sensitive to high levels of anthropogenic transformation, while naturalness is better suited for assessing ecosys-

tems that remain close to their natural state. In terms of citation rates, articles addressing naturalness, as well as those focusing on landscape disturbance, tend to be more influential than publications in other thematic areas. The greater the distance from the thematic centroid, the higher the citability. This suggests that, although the issue of naturalness has garnered consistent attention over the years, it remains unresolved. Furthermore, novel approaches to this problem often lead to high-impact publications. Studies that address both naturalness and hemeroby are also likely to be interdisciplinary, encompassing broader semantic attractors that contribute to their increased citation impact as thematic distance increases. Naturalness is understood as a multi-dimensional concept that encompasses structural, functional, and processual attributes reflecting an ecosystem's proximity to its natural state. In contrast, hemeroby is regarded as a comprehensive measure of anthropogenic influence, which is conceptually the inverse of naturalness. While both concepts describe a gradient ranging from natural to fully transformed conditions, naturalness is more context-sensitive and has broader applications, particularly in forestry and biodiversity conservation (Winter, 2012). The relationship between naturalness and hemeroby is conceptualized as an opposition, with hemeroby considered the inverse of naturalness. Naturalness indicates the degree to which an ecosystem has been preserved in its original state, while hemeroby reflects the extent of anthropogenic impact. Although these concepts are not perfectly symmetrical, they can be used together to assess the ecological status of areas undergoing changes in land use (Rossi et al., 2018). Naturalness is interpreted as the absence of human intervention, whereas hemeroby is understood as the level of anthropogenic pressure (McRoberts et al., 2012). The naturalness-hemeroby dichotomy is further explored within the context of Life Cycle Assessment (LCA). In this framework, hemeroby serves as an indicator of the distance from natural conditions, effectively representing the inverse of naturalness. It reflects the extent of environmental transformation. The concept of naturalness acts as the reference state against which the current condition of ecosystems under anthropogenic stress is evaluated. This synthesis facilitated the development of the Naturalness Degradation Indicator (NDI), which is based on the hemeroby scale and is used for quantitatively assessing the transition of marine ecosystems from natural to artificial states (Farmery et al., 2017). The concepts of hemeroby and naturalness have been integrated into international environmental impact assessment systems within the Life Cycle Assessment (LCA) framework to enable the quantitative evaluation of the ecosystem consequences of land use change on a global scale (Taelman et al., 2016). In this context, both naturalness and hemeroby are considered in the development of indicators for assessing land use changes in LCA. The hemeroby scale is utilized as a metric for expressing the loss of naturalness, and its updated values have been aligned with international land-use classifications (e.g., CORINE, IPCC), facilitating standardized assessments in global LCA studies. Naturalness and hemeroby are regarded as interdependent components of a unified scale that represents degrees of anthropogenic transformation in ecosystems (Fehrenbach et al., 2015b). The naturalness versus hemeroby framework is regarded as a fundamental concept for the spatial assessment of ecosystem services. Hemeroby serves as a spatial proxy indicator of naturalness loss, with higher hemeroby values indicating a reduction in naturalness. A key aspect of this approach is the use of hemeroby indices at a high spatial resolution to evaluate the capacity for ecosystem service provision. Instead of being viewed as separate entities, naturalness and hemeroby are understood as interdependent characteristics, facilitating the quantitative interpretation of landscape conditions for biodiversity conservation and sustainable land use planning (Londe et al., 2020).

The synthesis of the concepts of hemeroby and naturalness provides a coherent foundation for comprehensive ecological assessments of territorial integrity. This approach combines the sensitivity of hemeroby to anthropogenic impacts with the ability of naturalness to detect remnant natural conditions. It has been shown to enhance analytical capacity for studying land use change, conserving biodiversity, and evaluating ecosystem services. The integration of these concepts within global assessment tools, particularly in the framework of Life Cycle Assessment, facilitates the standardization of ecosystem trans-

formation quantification. The complementarity of these approaches promotes broader interdisciplinary integration, thereby amplifying the academic influence of related research. Despite their conceptual opposition, the integration of these factors has the potential to uncover novel avenues for developing composite environmental indicators and effective ecological planning. Future research should aim to clarify the conceptual boundaries between the two, harmonize assessment scales and methods across regions, and improve comparative interpretability. Promising directions for future research include the development of integrated indicators, increased spatial resolution, and the incorporation of both concepts into ecosystem modelling and planning frameworks.

Hemeroby as an indicator of aquatic ecosystem quality: river and water-based assessments. The proportion of publications addressing water quality issues is the lowest among the three categories, at 6.1%. This can be attributed to the relatively recent focus on this topic, with publications in this area commencing only after 2010. However, it would be misleading to claim that the issue of water quality itself is new; rather, what is novel is the application of the hemeroby concept to the assessment of aquatic ecosystem quality. This research direction is also conceptually distinct, as evidenced by its position along Dimension 4, which is notably distant from the main body of hemeroby-related literature that predominantly addresses terrestrial ecosystem transformation. The application of hemeroby and naturalness indices has been utilized as a means to evaluate the ecological status of marine waters subjected to anthropogenic pressure. In the body of literature closest to the thematic centroid, hemeroby is considered a generalized indicator of the extent of human intervention in aquatic ecosystems. Research has shown that higher hemeroby values correlate with lower water quality. This relationship is substantiated by physicochemical parameters, such as transparency, biochemical oxygen demand (BOD), and nitrate concentration. Hemeroby is recognized as an informative and sensitive indicator of the health of marine ecosystems. It provides practical value for the monitoring and management of water resources amid increasing anthropogenic stress (Retnaningdyah et al., 2019). The concept has been employed to categorise river segments according to the extent of anthropogenic landscape transformation. A higher level of hemeroby has been shown to be strongly associated with the degradation of biotic components, particularly benthic communities, and with the disruption of channel morphology and surrounding areas. These findings lend support to the notion that hemeroby can serve as a reliable indicator of freshwater ecosystem health, making it a suitable metric for integrated assessments of hydromorphological quality within the context of ecological monitoring and river restoration planning frameworks (Retnaningdyah et al., 2024b). Hemeroby has been employed as a straightforward yet efficacious indicator of anthropogenic pressure in both riverine and coastal ecosystems. Combinations of parameters such as land use type, presence of infrastructure, pollution sources, and biophysical characteristics of water bodies have been utilised to classify ecosystems along the hemeroby scale (Gradiet Semiun et al., 2020). Hemeroby is used as an integrated indicator combining biophysical and social characteristics of an area such as pollution levels, human presence, and environmental changes. Lower levels of hemeroby correspond to greater species diversity of macroepiphytes, while higher hemeroby are accompanied by a decrease in species numbers and a reduction in the functional structure of communities (Ghazali et al., 2022). The combination of the hemeroby index with empirical data on fish diversity has enabled a quantitative linkage between the level of anthropogenic impact and the biotic structure of communities. Hemeroby is directly integrated into the analysis of the functional condition of aquatic biocenoses, rather than being used solely as a landscape-level or conceptual indicator (Retnaningdyah et al., 2024a).

In the most influential studies on hemeroby, the index has been assessed using landscape metrics, and a clear relationship has been established between hemeroby values and the level of anthropogenic eutrophication in river systems (Ji et al., 2021). The concept of hemeroby has also been extended beyond continental landscapes and river systems to include marine ecosystems. Coastal marine areas were as-

signed hemeroby values based on observations of population density, infrastructure, maritime activity, pollution intensity, and land use types. This classification was used to analyse the relationship between anthropogenic pressure and the biodiversity of marine macrophytes. Hemeroby has thus been applied as an integrated assessment indicator of environmental transformation (Silva et al., 2021). The hemeroby index was integrated with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model for spatiotemporal assessment of environmental quality in a river basin located in an arid climate region. Hemeroby was identified as the most significant predictor of environmental degradation among all the factors considered. Through spatial autocorrelation and regression analysis, a stable relationship was established between increasing hemeroby values and declining environmental quality, highlighting its role as a key indicator for watershed management under drought conditions (He et al., 2022). Hemeroby is also assessed using an indicator-based approach on a 9-point scale, serving as an index of species' tolerance to anthropogenic impact. Index values are calculated separately for aquatic and riparian zones through abundance-weighted averaging of plant species hemeroby scores, enabling a quantitative evaluation of human-induced environmental transformation in river ecosystems. The coherence of hemeroby indices for both plant and animal communities, across aquatic and terrestrial environments, confirms its effectiveness as a component of a multi-indicator bioassessment approach to ecosystem evaluation (Testi et al., 2012). Hemeroby in the assessment of water ecosystem quality has emerged as a novel research direction, wherein landscape and indicator approaches serve as alternative yet complementary methods for evaluating anthropogenic impact. Landscape hemeroby offers spatial generalization, while indicator hemeroby reflects biotic sensitivity to local changes. The concurrent application of these approaches enhances our understanding of degradation processes in aquatic systems and broadens the tools available for environmental monitoring.

Landscape-scale modelling of urban ecological and biodiversity dynamics. The assessment of hemeroby levels in urbanised areas is a well-established approach to applying this concept. Therefore, it is not surprising that landscape-scale modelling of urban ecological and biodiversity dynamics accounts for 30.7% of the total number of publications. This theme is practically synonymous with the general concept of hemeroby; therefore, the timing and dynamics of publications mirror the overall trend. In studies of anthropogenic landscape transformation, soil hemeroby is considered a generalised indicator of the extent to which soil properties deviate from their natural state due to human activity. The concept is based on the idea of a shift in soil condition from ahemerobic (almost undisturbed) to fully artificial, technogenic environments. Soil hemeroby is classified along a seven-level scale, with each level reflecting the intensity of human impact on soil and the degree to which its natural structure, function and ecosystem properties are lost. Key assessment criteria include land use type, the physical transformation of the soil profile, degree of compaction, depth of disturbance, presence of artificial materials and degradation of fertility and biotic diversity. Natural forests with undisturbed soil profiles are categorised as having the lowest level of hemeroby, while urbanised areas, where soil has been completely lost or replaced by construction materials, are classified as ultrahemerobic. The assessment relies on morphological indicators and considers the overall quality of the soil ecosystem, including the hydrological regime, biogeochemical cycles and biological activity. Spatial context plays a crucial role. Hemeroby values are assigned based on land use data (e.g. CORINE), enabling spatial analysis and the development of a generalised assessment of the impact of humans on landscapes (Haslmayr et al., 2016). Hemeroby is one of the five components used to create an integrated indicator that assesses the potential of urban ecosystems to provide the ecosystem service of maintaining habitats and conserving the gene pool. This assessment is based on a combination of criteria including the presence of protected areas, green space fragmentation, distance from the urban core, the presence of water bodies and the representation of key biological species. Hemeroby is considered a general indicator of naturalness. It is more precisely a measure of its loss due to urbanisation. This is without

delving into the conceptual or methodological nuances of the term (Semerdzhieva & Borisova, 2021). The concept of hemeroby is employed to articulate spatial gradients of naturalness and the extent of degradation of natural components within urban agglomerations. In this context, hemeroby functions as a tool for landscape-ecological modelling, facilitating the identification of areas subject to high anthropogenic pressure and zones demonstrating potential for natural restoration. Hemeroby has been utilised as one of the metric characteristics embedded in an integrated indicator system for the assessment of the ecological value of landscapes. The level of hemeroby is subject to variation due to urban transformations, a factor which is of particular importance in the modelling of future urban development scenarios (Grunewald et al., 2019). Hemeroby indicators have been employed in a systems-based approach to landscape ecological modeling to reflect the level of naturalness, the degree of human influence, and the functional changes in urbanized landscapes. Hemeroby has proven particularly informative for landscapes characterized by intensive land use, especially within urban agglomerations. A methodology has been proposed for incorporating hemeroby into multifactor analyses, which include variables such as biotic structure, landscape fragmentation, soil compaction, and infrastructural density. Hemeroby is utilized for the spatial modeling and mapping of degradation levels in urbanized areas. A high level of hemeroby correlates with low naturalness and functional ecosystem degradation, making it valuable for scenario planning that incorporates ecological risk, landscape service evaluation, and renaturalization potential. It serves as a core indicator in systems for assessing the condition of urban ecosystems at the landscape scale, providing a robust conceptual and methodological link between land use characteristics, biodiversity, and ecosystem functioning (Arnold et al., 2018). The hemeroby scale has been adapted to the modern CORINE Land Cover categories by assigning a corresponding hemeroby level to each land-use type. This adaptation has enabled the creation of a generalised spatial indicator of anthropogenic pressure. An increase in land-use intensity is associated with a higher hemeroby level and a reduction in biotic diversity. When integrated with GIS analysis and land-use data, the hemeroby index can effectively determine the naturalness level of landscapes, identify environmental degradation hotspots and support the planning of ecological restoration measures (Raszka & Kalbarczyk, 2015).

The most influential studies on this topic emphasise that hemeroby is an effective tool when integrated with landscape ecological metrics and remote sensing-derived indicators (Lausch et al., 2015). Hemeroby serves as an indicator of anthropogenic transformation in cultural landscapes. It allows researchers to trace the relationship between spatial structure and ecological processes, particularly environmental degradation resulting from human activity. As a comprehensive metric, it combines land-use intensity with the biophysical and ecosystem characteristics of areas, and is employed in spatial analyses of cultural landscape dynamics (Wrbka et al., 2004). Hemeroby is also incorporated as a key indicator in systems that assess the sensitivity of urban ecosystems to climate change. This enables links to be identified between land-use intensity and landscape vulnerability at the regional level (Zebisch et al., 2004).

Hemeroby as an indicator of habitat disturbance. The most significant aspect of hemeroby-related research is the issue of community composition as an indicator of habitat disturbance, accounting for over one-third (34.2%) of all studies. This area of research is arguably where the concept of hemeroby originated, but its current structure and focus have evolved since the early 2000s and continue to develop rapidly. In some respects, this line of research is complementary to, or in contrast with, the landscape-based approach to hemeroby. It is conceptually well-defined and coherent, resulting in a clear relationship: the greater the thematic distance from the centroid of the topic in question, the lower the citation rate of publications. In this context, hemeroby is interpreted as an indicator of ecological deviation from the natural state due to anthropogenic disturbance, particularly recreational pressure in urban environments. Traditional methods such as phytindication are limited in urban contexts as artificial plantings or invasive species often fail to reliably reflect the degree of disturbance to natural ecological gradients. Consequently, micromolluscs have

been proposed as sensitive indicators of hemeroby. These organisms have low dispersal ability and are highly sensitive to microecological conditions, making them particularly responsive to disturbance. Abiotic changes to the soil caused by recreational activities, such as compaction, reduced moisture and altered aggregate structure, create a gradient of recreational transformation closely linked to hemeroby levels. In this context, *Vallonia pulchella* emerges as a particularly responsive species, with its abundance declining noticeably even under moderate recreational pressure. Other species, such as *Cochlicopa lubrica* and *Acanthinula aculeata*, demonstrate greater tolerance, highlighting the importance of considering species-specific responses when assessing ecological disturbance at the community level (Budakova et al., 2021). Hemeroby is used to compare different land cover types. These include parks, built-up areas and natural patches. It can also detect spatial patterns of environmental degradation. Studies have shown that the degree of hemeroby correlates directly with the urban gradient: as artificial surface cover increases and building density intensifies, the level of hemeroby rises, indicating an escalation of ecological disturbance. In this context, hemeroby is also considered in relation to topographic changes and soil degradation, serving as an integrated indicator of the impact of human activity on urban landscapes (Kolbek et al., 2015). A study on aquatic macrophytes revealed that hemeroby and naturalness do not align along the same gradients, indicating that they should be regarded as complementary indicators of environmental condition. Hemeroby was found to be more sensitive to local disturbances, while naturalness reflected broader ecological integrity (Kunakh et al., 2024). The level of hemeroby reflects the extent of human impact on aquatic macrophyte communities. Plant assemblages with high hemeroby are typical of stagnant water bodies exhibiting signs of eutrophication, whereas more natural communities show lower hemeroby levels. Hemeroby serves as an effective tool for monitoring the condition of aquatic ecosystems and assessing the influence of anthropogenic factors within protected areas (Lisovets et al., 2024). The hemeroby of plant communities is regarded as a reliable indicator of the success of land reclamation in areas disturbed by open-pit mining. The hemeroby level is closely linked to the physical properties of technosoils. A decrease in hemeroby is associated with reduced soil penetration resistance, changes in aggregate structure, and increased soil electrical conductivity. Hemeroby can be effectively used for monitoring ecosystem recovery during the reclamation of disturbed areas (Kunakh et al., 2024).

The most influential articles on the topic propose new approaches for advancing the study of hemeroby. Functional traits of species have been shown to be key predictors of vegetation response to disturbance. Species with traits adapted to trampling and intensive land use exhibit greater resistance or recovery capacity following disturbances. Functional characteristics enable a generalized understanding of disturbance effects across different sites and regions in Europe (Bernhardt-Römermann et al., 2011). Hemeroby is used as a quantitative indicator of anthropogenic disturbance to assess the impact of urbanization on the flora of urban wastelands. It has been found that elevated levels of hemeroby are associated with the presence of concrete surfaces and gravel, whereas sandy substrates and management practices such as mowing reduce it. Hemeroby negatively correlates with environmental resource availability and the abundance of native species, but positively with the proportion of neophytes and the level of urbanity. Hemeroby confirms its effectiveness as an indicator of the ecological condition of urban ecotopes (Godefroid et al., 2007).

The assessment of hemeroby in habitats is based on its interpretation as an indicator of anthropogenic disturbance, reflecting the degree of deviation from the natural state. The most common approach relies on the analysis of community composition, which has proven particularly effective in urban environments where traditional phytosociological methods have limited applicability. Hemeroby responds sensitively to substrate type, compaction, microclimate, and recreational pressure, demonstrating a high level of spatial differentiation. Its level correlates with urbanization gradients, the proportion of neophytes, as well as soil degradation and water eutrophication. At the same time, hemeroby has proven to be more responsive to local impacts than naturalness indices, as confirmed by studies on aquatic macrophytes. It is

also successfully used to monitor reclamation processes on technogenic sites, where its level is linked to soil physical properties. Research has shown that the functional traits of species may serve as key predictors of disturbance response, opening new avenues for assessing hemeroby through the lens of functional ecology.

Prospects for future research. Future research on hemeroby is expected to focus on several key directions. First, there is a need to expand the range of bioindicator groups, particularly by incorporating functionally significant but underrepresented taxa, such as soil invertebrates and microorganisms. This expansion would enhance the diagnostic capacity of hemeroby assessments, especially in urban and highly transformed landscapes. Second, integrating hemeroby with species' functional traits presents a promising avenue, as it enables not only the detection of disturbances but also a better understanding of the mechanisms underlying community resistance or vulnerability to anthropogenic pressures. Third, advancing spatial ecological modelling that incorporates urbanization gradients, climate change, and land-use scenarios represents an important direction for the development of predictive tools. Finally, comparative interregional studies should be intensified to identify general patterns of biotic responses to disturbances across different biogeographic regions. Such efforts will also contribute to the standardization of hemeroby assessment methods, thereby enhancing its applicability for large-scale ecological monitoring.

Conclusion

The concept of hemeroby emerged in the 1950s as a measure of the extent to which natural ecosystems have been disturbed by human activity. Since then, it has become a key tool for quantitatively assessing environmental changes caused by human activity, and is widely used in environmental monitoring, evaluating naturalness, and informing land use decisions. However, over the decades of its development, a significant number of different methodological approaches and analytical tools have emerged, leading to diverse interpretations that are not always easily comparable. This highlights the need to systematise and synthesise scientific knowledge on hemeroby. This study presents a comparative analysis of hemeroby-related publications using bibliometric and topic modelling approaches to reveal the concept's internal structure. Based on an analysis of 228 articles, five main research directions were identified: (1) landscape disturbance, (2) naturalness, (3) water quality, (4) urban biodiversity and (5) habitat disturbance. The two most prominent directions in terms of publication volume were urban biodiversity and habitat disturbance, together accounting for over 60% of the total publication corpus. Using the LDA (Latent Dirichlet Allocation) method allowed thematic clusters to be identified and their internal features and intertopic connections to be examined. Habitat disturbance (T5) was found to be the most structured and conceptually coherent topic. It was characterised by high citation rates due to its stable conceptual foundation and the use of traditional methods, such as phytosociological and floristic analysis. Conversely, the water quality topic (T3) was found to be conceptually distinct and insufficiently integrated into the overall structure of hemeroby research. Citation analysis revealed that the most influential publications are those situated at a moderate distance from the thematic centroid. This suggests that papers with a certain degree of novelty and interdisciplinarity tend to be cited more frequently than those that are either too conventional or too distant from the main topic. According to GLM modelling, the citation rates of publications have steadily increased over time, though no statistically significant differences in growth rates across thematic areas were detected. The future of hemeroby research lies in developing standardized approaches for interregional comparisons, integrating species functional traits into the concept, applying high-resolution remote sensing and combining hemeroby with other environmental indicators. These advances will enhance the practical utility of hemeroby in ecological monitoring and the management of anthropogenically transformed ecosystems.

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