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Review

Vegetation Dynamics Studies Based on Ellenberg and Landolt Indicator Values: A Review

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Abstract: Understanding the dynamics and system of interrelationships between habitats and plant communities is key to making reliable predictions about sustainable land use, biodiversity conservation and the risks of environmental crises. At the same time, assessing the complex of environmental factors that determine the composition, structure and dynamics of plant communities is usually a long, time-consuming and expensive process. In this respect, the assessment of habitats on the basis of the indicator properties of the plants is of great interest. The aim of our study was to carry out a comprehensive review of vegetation dynamics studies based on the Ellenberg and Landolt indicator values in the last five years (2019–2023). We identified their strengths and priority areas for further research, which will contribute to improving the ecological indicator values for studying vegetation dynamics. The analysis of publications was carried out based on the recommendations of PRISMA 2020 and the VOSviewer software(version 1.6.18). The wide geographical range and high reliability of Landolt and Ellenberg indicator values for the study of different plant communities and variations in their dynamics are demonstrated. At the same time, the application of these environmental indicator values has its peculiarities. For example, the Ellenberg indicator values show a wider research geography and are more often used to study the dynamics of forest ecosystems than the Landolt indicator values, which are more often used to study disturbed landscapes and the dynamics of individual species. However, these methods have been used with almost the same frequency for grasslands, wetlands and coastal vegetation. The citation analysis confirmed the high interest in the environmental indicator values and their widespread use in research, but also revealed the weak development of a network of relationships. This suggests that modern researchers are not well aware of, and rarely use, the results of research carried out in recent years, especially if they are based on indicator values other than those used by them. At the same time, a number of unresolved issues are clearly identified, which require additional research and a consolidation of research teams if they are to be addressed more successfully. We hope that the results of this meta-analysis will provide the impetus for further development of the concept of environmental indicators and help researchers to overcome the current questions around applying indicator values in the study of vegetation dynamics, as well as help researchers to understand the strengths of this methodology.

Keywords: bioindication; ecological indicator values; environmental gradients; plant community

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1. Introduction

Throughout the world, natural ecosystems are under increasing pressure from anthropogenic factors and climate change [1–3]. The frequency and intensity of extreme natural events are increasing, triggering rapid degradation of natural ecosystems and regional environmental crises. At the same time, the adaptive capacity of natural ecosystems cannot always compensate for the impact of external influences, leading to a loss of stability and even greater degradation [4]. These phenomena are becoming important factors in reducing the economic well-being and food security of populations in many countries, and their impacts are increasingly being felt at the global level [5,6]. Understanding the dynamics and systems of interactions between habitats and plant communities is key to making reliable predictions in the field of sustainable environmental management, biodiversity conservation and risks of environmental crises [7–10].

It is repeatedly emphasized in the literature that there is still an acute lack of information on regional dynamic characteristics [11,12] and environmental characteristics [13–15] for accurate assessment of vegetation dynamics and prediction of restoration success. GIS technologies are being actively developed for these purposes [12,14,16,17]. However, the complexity of analyzing vegetation dynamics based on remote sensing methods of territories is emphasized, and these technologies, despite their rapid development, still do not solve all problems [1]. In this context, the importance of studying vegetation dynamics using ground-based methods is increasing, as successional analysis makes it possible to distinguish between restoration dynamics and degradation. At the same time, the assessment of a complex of environmental factors that determine the composition, structure and dynamics of plant communities [14,18] is usually a long, time-consuming and expensive process. In this context, the assessment of habitats based on ecological indicator values is of great interest [19–21]. One of the advantages of this methodology is the ability to assess the cumulative impact of factors on the ecosystem, as ecological indicator values link vegetation characteristics and gradients of leading environmental factors [21].

Cajander [22] and Iversen [23] proposed the hypothesis that the species composition of plant communities could be used to assess environmental factors. Using this hypothesis, H. Ellenberg developed a quantitative approach [24]. Based on his approach, the first scoring systems for environmental indicators were subsequently proposed [25,26].

The Ellenberg indicator values were developed on the basis of field observations mainly in Germany and the Alps [26]. The 2494 species and intraspecific taxa of plants were characterized in relation to six factors: light availability, temperature, continentality, soil moisture, soil reaction and soil fertility (nitrogen content). The relationship of species to moisture is described by 12 scores, and the remaining parameters have 9 scores (1 means low and 9 means high). Soil salinity is recorded separately on a three-point scale.

The Landolt indicator values were developed for the flora of Switzerland [27]. More than 3400 plants were characterized [28] in relation to eight factors: six factors similar to Ellenberg and two additional factors—soil dispersion/aeration and humus content. Each environmental factor is evaluated with five scores, where one means low and five means high. Landolt indicator values are used less frequently than Ellenberg indicator values [29]. However, they are most effective in the analysis of alpine communities [30].

Landolt and Ellenberg indicator values are tables where the relationship of a species to individual factors is expressed as a score reflecting the position of the species' ecological optimum on the factor gradient. The final score of the plant community is based on scores of all plant species. There are different methods for calculating the final score [31]. The most commonly used method is to average the scores of all species by factors, weighted by the species abundance [32]. The ecological optimum of a species by factor is determined by the point of its location on the factor scale. The score of a species is, according to some researchers, the median of its realized niche, which may be quite different from the optimum [33].

Research on the improvement and calibration of ecological indicator values is relevant and in demand [21,34]. The adaptation of Landolt and Ellenberg indicator values for new regions has been carried out, and their effectiveness has been proven [35,36]. New ecological indicators are being developed on their basis. For example, a large international team of authors developed the ecological indicator values based on the Ellenberg indicator values for almost 9000 European vascular plant taxa [37]. In the same year, new European indicator values of niche position and niche width for 14,835 taxa were proposed based on more than 30 different ecological indicators [21]. In addition, the pan-European databases of marsh vegetation were extensively analyzed to identify their sensitivity to the hydrological regime [38]. The authors developed ecological indicator values for the majority of European marsh plants, and the inclusion of bryophytes significantly improved the phytoindication of water table depth.

The successful development of ecological indicator values for studying vegetation dynamics is impossible without an analysis of the current state of the question and an assessment of the effectiveness of various ecological indicators for these purposes. There are a number of literature reviews devoted to various aspects of ecological indicator values [29,39–41]; however, no detailed systematic analysis of vegetation dynamics studies has been carried out using this method. The question of using ecological indicator values to study vegetation dynamics has been little considered in previous reviews, despite its extreme relevance.

The aim of our research was to review the studies of vegetation dynamics carried out on the basis of the Ellenberg and Landolt indicator values over the past 5 years, analyze the current state of the question, assess the effectiveness of these ecological indicators to solve the tasks set and identify their strengths, as well as questions that arise in the research process. In addition, we identified priority areas for further research, which will contribute to the improvement of the ecological indicator values for studying vegetation dynamics. Our research analysis also included an assessment of the distribution of articles by year and keywords, citation analysis of articles and journals using modern neural network data analysis methods, and identification of the most important articles and journals by the number of citations as a quality criterion.

The scientific novelty of our research review lies in the completeness of the analysis of the latest studies devoted to vegetation dynamics and carried out using the Ellenberg and Landolt indicator values. We applied strict objective criteria to the search, selection and analysis of publications, as well as used modern methods of data analysis. This review not only allowed us to trace the geography and directions of the research being conducted but also to obtain answers to a number of questions that are important for the development of the concept of ecological indicator values, as well as allowed us to identify priority areas for further research. For example, we analyzed issues such as the transformation of ecological niches in different bioclimatic zones; the lag effect; the synergistic effects of different types of dynamics; the convergence of plant communities; and the difficulty of constructing effective models of vegetation dynamics.

The target audience for this review comprises researchers in the fields of ecology, terrestrial ecosystem dynamics and biodiversity conservation, as well as representatives of natural resource management and nature conservation. This study provides an impetus for the consolidation of researchers working in different countries, which will contribute to the more successful development of the Ellenberg and Landolt indicator values and expand the boundaries of their application.

2. Materials and Methods

We conducted this study using the PRISMA guidelines [42] and the guidelines for environmental science studies [43]. These guidelines aim to make a systematic review reproducible, with a clearly stated and understandable methodology, and to minimize the subjectivity of the conclusions and the possibility of misleading the reader. Google Scholar, ScienceDirect, Mendeley and SciProfiles were selected to search for information. Search queries included “Landolt indicator value”, “Landolt indicator values” and “Ellenberg indicator value”, “Ellenberg indicator values”. Articles were analyzed over the last 5 years (2019–2023). This research stage was conducted in the period from April 1 to 20 May 2024. Via this search, a large number of datasets were identified for the period under consideration. The search returned 8890 records for Ellenberg indicator values and 8920 records for Landolt indicator values (Figure 1).

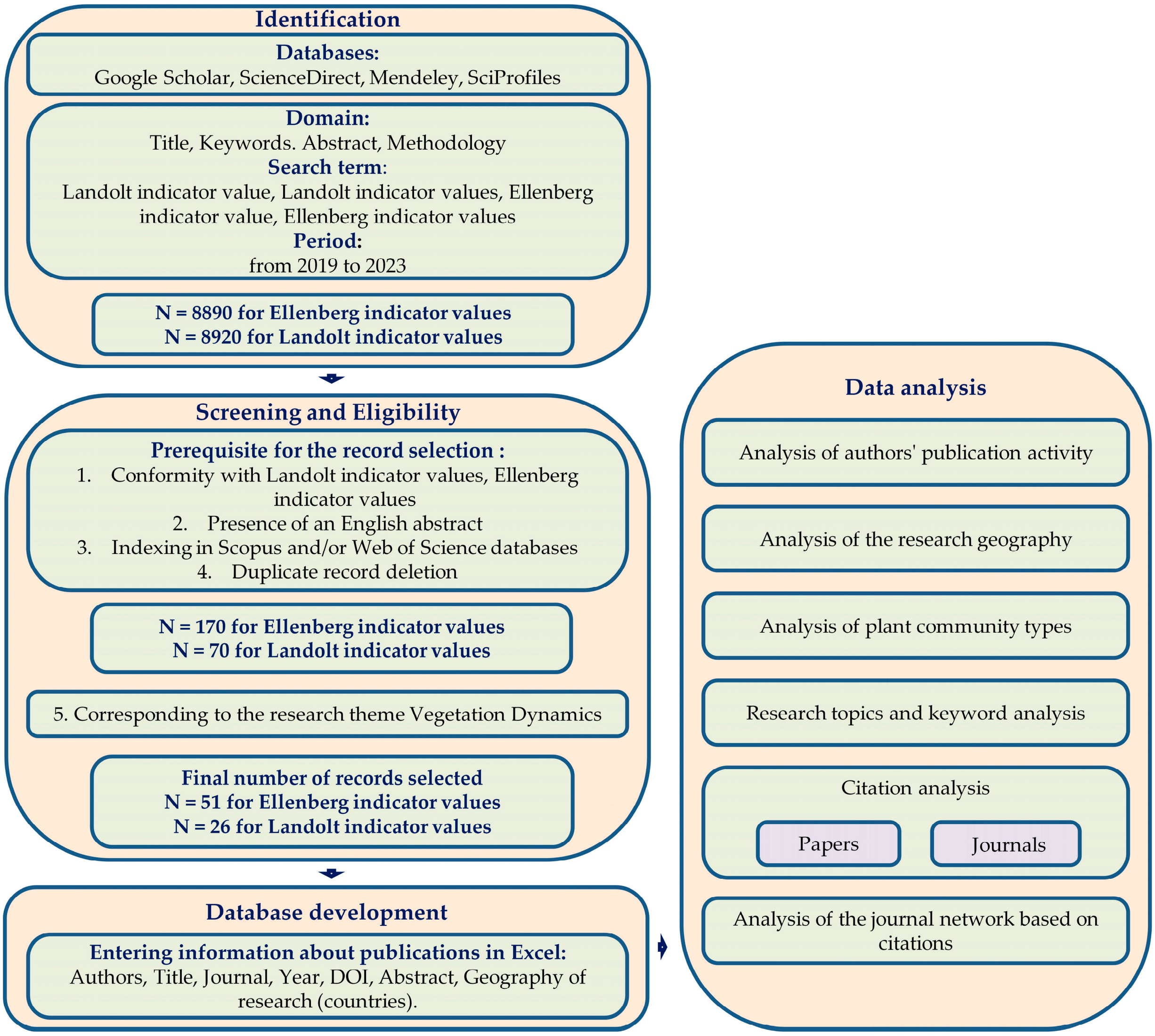

Figure 1. Schematic diagram of the research analysis.

However, the number of irrelevant records and duplicates was quite high. Furthermore, our task was to eliminate papers of low scientific quality. Indexing in Scopus and/or Web of Science was used as a quality criterion. In this way, only 170 articles were selected based on the values of the Ellenberg indicator, which was one of the main methods of analysis, while 70 articles were selected for Landolt indicator values (Figure 1). Further, articles on vegetation dynamics were selected based on the title and abstract. Due to the complexity of organizing an objective automated search, this stage of the work was carried out manually. This can be explained by the large number of keywords corresponding to the scientific topic of vegetation dynamics. The analysis included all papers dealing with vegetation change, succession, climate change, anthropogenic change, the influence of grazing, fire and other factors concerning vegetation. If there was any doubt when deciding whether to include or exclude an entry from the analysis, we read the full text of the paper and only then made a decision. As a result, 51 articles were selected for Ellenberg indicator values and 26 articles for Landolt indicator values (Figure 1). We entered the following information about the selected articles in Excel: year of publication, authors, title of the article and journal, DOI and abstract. Figure 2 shows the distribution of studies by year.

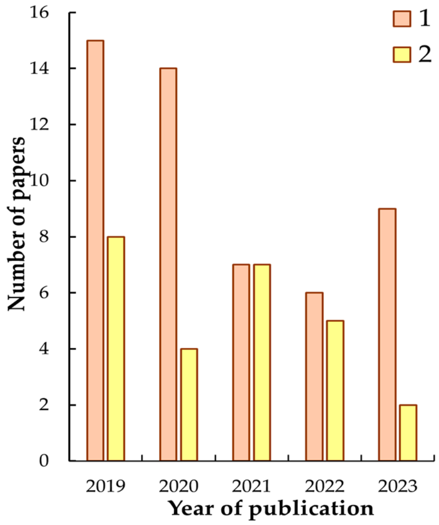

Figure 2. Distribution of the number of studies using Landolt indicator values by year. Distribution of the number of studies on vegetation dynamics that use Ellenberg (1) and Landolt (2) indicator values.

The data analysis was carried out using the VOSviewer software(version 1.6.18) [44]. VOSviewer is recognized as an effective and convenient tool for analyzing bibliographic data and visualizing research results in various scientific fields [45–47]. In this study, VOSviewer was used to analyze keywords, citations of articles and journals. The data were uploaded to VOSviewer based on the DOI. A text file containing the DOIs of all selected publications was used for this purpose. The method used in VOSviewer allows you to efficiently cluster a large number of records and create visual maps of the network of relationships. These maps are very clear and intuitive. The clustering method used is based on the latest developments in network science and bibliometrics and is an alternative to multidimensional scaling [48,49], while the maps created are more structured [44]. This clustering method is used both in VOSviewer and in other software products [50,51]. The Map Wizard offers a choice between two counting methods when creating a map. In this study, full counting was used. When displaying a map, VOSviewer uses a special algorithm to determine which markers can be displayed and which cannot, so that markers do not overlap. The larger an individual area of the map increases, the more placemarks become visible. This is very useful when working with large maps. The relationship network maps created with VOSviewer were supplemented with tabular information to improve our understanding of the maps and to detail and strengthen the results.

3. Results

Previous studies [29,41] have shown that the Ellenberg and Landolt indicator values are effective in solving various questions: from classifying and orchestrating a wide variety of vegetation in different climatic zones, to improving the methodology for assessing habitats, to analyzing the ecological niches of individual plant species.

However, despite the fact that the directions of modern research using the Ellenberg and Landolt indicator values are very diverse, they are quite often used to study vegetation dynamics. This question was the subject in 37% of all studies using the Landolt indicator values and 32% of studies using the Ellenberg indicator values.

3.1. Frequency of Studies by Country

Most studies on vegetation dynamics based on the Ellenberg indicator values were conducted in Germany (35%), and most of those on the Landolt indicator values were conducted in Switzerland (38%) (Table 1). The geography of studies on the Ellenberg indicator values was much wider than on the Landolt indicator values.

Table 1. Distribution of countries by the number of studies (2019–2023) conducted on vegetation dynamics using the Ellenberg and Landolt indicator values.

Country	Ellenberg Indicator Values		Landolt Indicator Values	
	Number of Studies	%	Number of Studies	%
Germany	18	35	0	0
Switzerland	0	0	10	38
Italy	4	8	5	19
Austria	0	0	3	12
Slovenia	1	2	3	12
Russia	1	2	2	8
Czech	4	8	0	0
England	3	6	0	0
Poland	3	6	0	0
France	2	4	1	4
Estonia	2	4	0	0
Slovakia	2	4	0	0
Denmark	2	4	0	0
Georgia	0	0	1	4

Note: Single studies based on the Ellenberg indicator values—Finland [52], Sweden [53], Hungary [54], Malta [55], Spain [56], Lithuania [57], Belgium [58].

3.2. Types of Plant Communities

Studies of vegetation dynamics based on ecological indicator values were carried out both for the flora of large areas (Ellenberg—12%; Landolt—31%) and for vegetation types (Table 2). Ellenberg indicator values were used more often to study the dynamics of forest ecosystems [59–63]. Both ecological indicators values were applied with almost equal frequencies for meadows and pastures [64–67], as well as wetlands and coastal vegetation [55,68–70]. Landolt indicator values were used more often to assess vegetation dynamics in disturbed landscapes, for example, quarries [71], as well as to study the dynamics of individual species such as alpine orchids [72] and *Pinus nigra* plantations [73]. A special mention should be made of the study on the flora of urban areas using the Ellenberg indicator values [74].

Table 2. Main types of plant communities for which the dynamics were studied using the Ellenberg and Landolt indicator values over the past five years.

Plant Communities	Number of Studies, % of Total for Each Ecological Indicator	
	Ellenberg	Landolt
Forest	39	15
Meadows, grassland	29	23
Wetland, riparian vegetation	14	12
Plant communities of disturbed landscapes	2	8
Individual plant species	0	8

3.3. Keyword Analysis and Research Topics

We analyzed keywords (occurring five or more times in the title and abstract of the article) using VOSviewer and identified four clusters of studies on vegetation dynamics (Figure 3), which are marked in different colors.

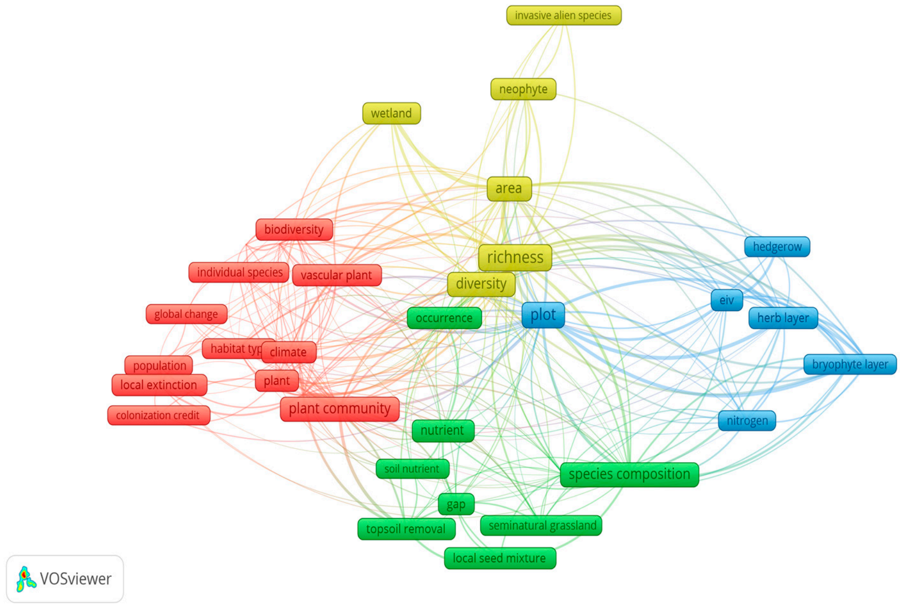

Figure 3. Keyword relationship network analysis. Different clusters are highlighted in color.

Cluster 1 (red) is associated to a greater extent with the use of Landolt indicator values, which are more often used to study mountain ecosystems and climate change [72,75–81]. We came to this conclusion after a detailed study of the full texts of the papers in question. Despite the fact that mountain ecosystems are not included in the list of keywords for this cluster, the vast majority of papers are devoted to the European Alps and other mountain areas. This cluster includes the article by a team of Austrian authors devoted to the dynamics of local habitats of non-forest plants in the European Alps in connection with climate change [77]. The authors used temperature indicator values, which indicate the thermophilicity of species. The study was large-scale: 1576 sites located in Austria, Switzerland, Italy, Slovenia and Germany were surveyed, and distribution patterns of 135 plant species were compared with field data. It was found that 60% of the studied species did not disappear from all sites that the models classified as unsuitable, and 38% of the species failed to colonize all sites that, according to the models, became suitable for their growth. Overall, 93% of the species showed at least one type of delayed response. The authors emphasized that they included only the most common species in the analysis and suggested that the figures they obtained characterizing the lag effect may be underestimated. This study was undoubtedly of great importance both for the development of the concept of ecological indicators and for improving the conceptual foundations of the theory of plant community dynamics, their vulnerability and sustainability, which was confirmed by the high citation rate of this publication (will be discussed further in Section 3.4). In addition, Landolt indicator values were used to study natural regeneration of forest vegetation [73,82,83], Douglas fir regeneration in forest stands in Switzerland [84], vegetation restoration after cessation of grazing [70], the long-term effects of vegetation restoration on landslide slopes and quarries [71] and the influence of sediment transport through erosion sites on plant communities [85]. It is worth mentioning separately the study by a small team of researchers from Slovenia, which was devoted to the regeneration gap in a high alpine forest and addressed the problem of microsite niche partitioning [82]. The authors examined canopy gaps of different sizes in 50-year-old stands of mixed mountain forests composed of *Picea abies*, *Abies alba* and *Fagus sylvatica* and compared them with each other and closed canopy sites based on the regeneration criterion, as well as environmental factors (light climate, humidity of the upper soil layer, microsite relief and soil features). Landolt indicator values for nutrients and direct light were used. The practical significance of the study was to derive silvicultural prescriptions for facilitating natural regeneration leading towards gradual conversion. Another large-scale study in this cluster was devoted to the long-term dynamics of the displacement of orchid species ranges along the elevation gradients of the European Alps [72]. The Landolt indicator values were used for the ecological characterization of the habitat (light, soil moisture, temperature and realized breadth of the thermal niche in the study area based on annual mean temperature). The authors investigated populations of various orchid species in the province of Trento in northeastern Italy, covering more than 6.2 thousand km^2 with an altitude range of 66–3769 m. This region is a hotspot for plant species biodiversity. The study revealed a widespread decline in orchid populations, with the exception of the most thermophilic species and wetland species. It was found that more than 50% of species could not fully track climate changes and lagged behind climate warming. The study highlighted the importance of long-term population monitoring at a high spatial scale in order to be able to better understand the effects of global climate change on plant species.

The remaining three clusters include studies conducted primarily on the basis of Ellenberg indicator values. Cluster 2 (green) includes keywords related to research aimed at studying the dynamics of semi-natural meadows, for example, a study on modeling vegetation changes in different types of semi-natural meadows in Western and Central Europe [86]. The authors conducted a meta-analysis of vegetation resurveys, where 23 datasets were analyzed, including 13 datasets on wet meadows, 6 on dry grasslands and 4 on other meadows. The period between studies varied up to 75 years. Edaphic conditions were assessed using the average values of Ellenberg indicators for soil moisture, nitrogen and pH. The research results confirmed the widespread deterioration of semi-natural meadows, with the greatest vulnerability identified in highly productive meadows. It was revealed that the main reasons for vegetation changes are fertilization and nitrogen deposition. Cluster 2 also includes a study conducted by a team of authors from Germany and Switzerland devoted to the investigation of the stability of pastures under a high intensity of land use [87]. The soil properties were analyzed using the Ellenberg indicator values. The study found that 34% of plant species react negatively to a high intensity of land use and only 10% of species show a positive relationship. It was also revealed that fertilization and the mowing frequency are the main factors transforming the pasture structure, while the effect of grazing intensity is less pronounced.

An article by a large international team of authors [11] was devoted to the study of the anthropogenic transformation of plant communities based on the Ellenberg and Landolt indicator values. This study was aimed at identifying indicators of disturbances and identifying optima along the gradients of natural and anthropogenic disturbances. The authors analyzed 6382 species of vascular plants that grew in more than 700,000 sites, representing more than 200 habitat types. The study considered five factors: disturbance intensity, disturbance frequency, mowing frequency, grazing intensity and soil disturbance. The research results have both practical significance for the development of a strategy for sustainable use of meadows, and theoretical significance for the large-scale analysis of meadow ecosystems and macroecology. Other studies based on the Ellenberg [88] and Landolt [65,89,90] indicator values were also devoted to anthropogenic transformation of meadows. We consider it important to mention studies devoted to restorative successions. For example, Ellenberg indicator values were used to study the impact of clear-cutting of the invasive *Robinia pseudoacacia* L. on the restoration of former meadow vegetation [91], to assess pasture restoration using native seeds [92] and to follow 50-year successions on arable plant communities of corn fields [93]. It is worth noting a study that analyzed the potential impact of calcareous meadow succession on a community of moths (>1000 species) [94]. The authors assigned Ellenberg indicator values to each main larval food plant species used by lepidopterans. The changes in average values of these indicators were applied to test for possible consequences of the changes in habitat structure and quality. Also included in cluster 2 is an article devoted to the influence of the microclimate on the species composition and response to drought of calcareous meadow vegetation using mean weighted Ellenberg indicator values and linear mixed models, which deserves special attention [95]. The researchers confirmed that a warmer, drier microclimate favored the development of specialized vegetation in the past, but this may no longer be the case with ongoing climate change.

Cluster 3 (blue) contains keywords related to studies on forest vegetation and the relationships between the moss and herb–shrub layers and the age and composition of forest stands. We would like to note a study of the impact of windstorms on the adaptation of vegetation to a warmer climate, which was conducted by scientists from France [59]. The authors assessed the changes in plant communities in the canopy windows of the forest stand compared to undisturbed forest areas based on floristic studies (139 permanent sample plots) conducted in 2002 and 2018 in forests affected by windstorms in 1999. The community temperature index and community light index were calculated using Ellenberg indicator values for each sample plot. The authors proved that the community temperature index increased significantly over the studied time period (by an average of 0.11 °C per decade). The community light index decreased during the same period, indicating that the community thermophilization was not a direct result of the formation of canopy gaps. The authors compared the canopy gaps of the forest stand and undisturbed areas based on the models they developed, and they showed that after canopy closure, thermophilization in the canopy gaps of the forest stand is more pronounced in the mountains (+0.54 °C) than in the flat areas (+0.12 °C). An analysis of the species composition and ecological niches of the species allowed the authors to conclude that the differences between the forest vegetation restored in the canopy gaps and the vegetation of undisturbed forests are associated with the invasion of heat-adapted species and a reduction in the number of number of species adapted to cold. The authors proved that the disturbance regime plays a key role in the adaptation of forest communities to climate warming. This conclusion is important for a better understanding of adaptation mechanisms of plant communities.

A team of Hungarian authors conducted a study on factors of forest dynamics in karst habitats [54]. The authors sought to uncover the influence of the age of the forest stand and topography on the composition of subordinate forest layers. The assessment of environmental factors in the process of succession was performed on the basis of Ellenberg indicator values. The main result was the identification of clear relationships between the topography and species composition of forests, with the age of the forest stand also being a significant factor. This publication is interesting in the context of climate change, because the authors identified habitats that can serve as refuges for many plant species during global warming.

Also, anthropogenic transformation of forests was successfully studied using Ellenberg indicator values [96–98]. For example, one study focused on changes in forest understory cover from 1993 to 2016 in relation to forest management changes and local natural disturbances (storms) [99].

Nitrogen emissions into the atmosphere have increased sharply in the last 100 years. This has led to the threat of transformation of ecosystems and the nitrogen cycles occurring in them, reduction in biodiversity and changes in species composition. The search for solutions to minimize the consequences of these changes is reflected in modern publications. For example, scientists from Germany investigated the relationship between the composition of understory vegetation in temperate forests in six acidophilic and oligomesophilic forest types and environmental changes caused by atmospheric nitrogen deposition and altered forest management [98]. The authors compared the results of an earlier study of forest vegetation (from 1950 to 1976) with modern research from 2017 to 2018 and analyzed changes in the vegetation using Non-metric Multidimensional Scaling ordinations and Ellenberg indicator values. In all studied forest types, an increase in the number of nitrophilic species was noted, while in acidophytic and oligotrophic forests, a replacement of oligotrophic species by nitrophilic species was observed. The authors also noted that each forest type has its own characteristics that must be taken into account for sustainable forest management.

Another study was devoted to the effect of soil liming on forest types of *Pinus sylvestris*, *Quercus robur*, *Fagus sylvatica* and *Picea abies* in temperate forests of Central Europe [100].

A team of authors from Germany observed changes in the species composition of forests after liming of soils for 25 years. Environmental characteristics of all sites were analyzed using the average Ellenberg indicator values. The researchers concluded that liming has a significant but temporary effect on the species composition of subordinate layers. Therefore, liming can be applied to acidic soils in managed forests without fear of long-term changes in forest ecosystems.

Cluster 4 (yellow) is associated with the study of wetlands. They are vulnerable ecosystems under the conditions of modern anthropogenic impacts and global warming. The transformation of the wetland habitat caused by both anthropogenic and climatic factors can lead to the extinction of species, degradation of plant communities or their complete destruction. Therefore, wetland ecosystems are given close attention in modern research. For example, a team of scientists devoted a study to the extinction of plant species growing in wetland in eastern Switzerland [90]. The area of wetlands has decreased by 90% over the past 150 years in this region. The study was aimed at identifying the effect of wetland area on the diversity of different groups of plant species. The state of the habitat was assessed on the basis of Ellenberg indicator values. The authors analyzed both the current situation and historical data, and they made predictions for the future. One of the research results was the identification of a lag effect for long-lived vascular plants and its absence for bryophytes. The authors called for increased protection of these vulnerable ecosystems and expressed their hope that due to the lag effect, this will help preserve both species and ecosystems as a whole.

It is also worth noting the study devoted to investigation of the diversity of halophilic vegetation in one of the most important Maltese wetlands, the territory of Il-Ballutta' Marsaxlokk Natura 2000 [55]. The authors identified the most important factors that determine the structure of plant communities. Nutrients and temperature were noted first and foremost among them. The advantage of this study is that it harmoniously combined the use of ecological indicator values and the Braun–Blanquet approach. This undoubtedly increases the depth of data analysis and the validity of conclusions and provides an understanding of the limits of applicability of the research results. Therefore, the results of this study can be successfully used for landscape planning and other management actions.

A team of Czech scientists [101] not only studied vegetation changes and habitat transformation of calcareous fens in the Inner Western Carpathians but also drew attention to the synergistic effects of environmental factors. Changes in fen composition were interpreted using the Ellenberg indicator values. Another work by the same group of authors [38] was devoted to assessing indicator values for soil moisture and water table depth in European mires and associated grasslands. The authors describe their research as a first step towards the goal of creating a pan-European indication system and developing large-scale vegetation databases. For each vascular plant and bryophyte species occurring in 24,091 vegetation-plot records of European mires, they developed an updated system of Ellenberg-like Ecological Indicator Values.

The above analysis shows that although keywords are clustered according to the similarity of plant communities, different types of vegetation dynamics are well represented in modern research. Quite a lot of research on vegetation dynamics is devoted to anthropogenic changes. This direction of research for Landolt indicator values made up 15% of the total number of studies on dynamics performed using this ecological indicator over the past five years, and for Ellenberg—25%. Restorative successions are the subject of 31% of studies based on the Landolt indicator values, and for the Ellenberg indicator values—14%. Climate changes are addressed in 6% of all publications using Ellenberg indicator values, and 31% for Landolt indicator values.

It makes sense to briefly consider keywords that have not formed clusters. For example, despite the fact that research interest in the Arctic is increasing, keywords related to Arctic vegetation have not formed a separate cluster. During the study period, only individual studies of Arctic territories were conducted based on Landolt indicator values [79]. The same can be noted for urban plant communities and man-made landscapes. Despite the relevance of the problems, only a few studies have been conducted on these topics over the past 5 years using the ecological indicators of Landolt [71] and Ellenberg [74]. Paleobotany is the next scientific field which is only slightly covered in modern research. The use of Ellenberg indicator values in paleobotanical studies has yielded excellent results in studying the 10,000-year history of the Saaremaa (Estonia) mires [102]. This study is also interesting because it explored an important problem that usually escapes the attention of researchers: the relationship between floristic richness and phylogenetic diversity. Estonian researchers also studied pollen from three lakes of the semi-boreal zone of Northern Europe and attempted to reconstruct climate-driven dynamics of vegetation composition, anthropogenic deforestation, species responses to climate cycles, and environmental variables associated with plants during the Holocene at local and regional scales [103].

Another scientific direction that has received almost no attention from researchers is the identification of relationships between the functional characteristics of plants and environmental factors. However, this direction is of particular interest in the context of vegetation dynamics [76]. An example of such a study was the modeling of future climate change and land use based on a sample of 1095 plant species from northern Italy using four plant traits (crown height, leaf area, specific leaf area, leaf nitrogen content) and Landolt indicator values [76].

3.4. Citation Analysis

The citation analysis clearly demonstrates the high interest in ecological indicators and that they are in demand among researchers. We found that 93.5% of the modern articles (2019–2023) devoted to vegetation dynamics and performed using ecological indicator values were cited at least once (Figure 4).

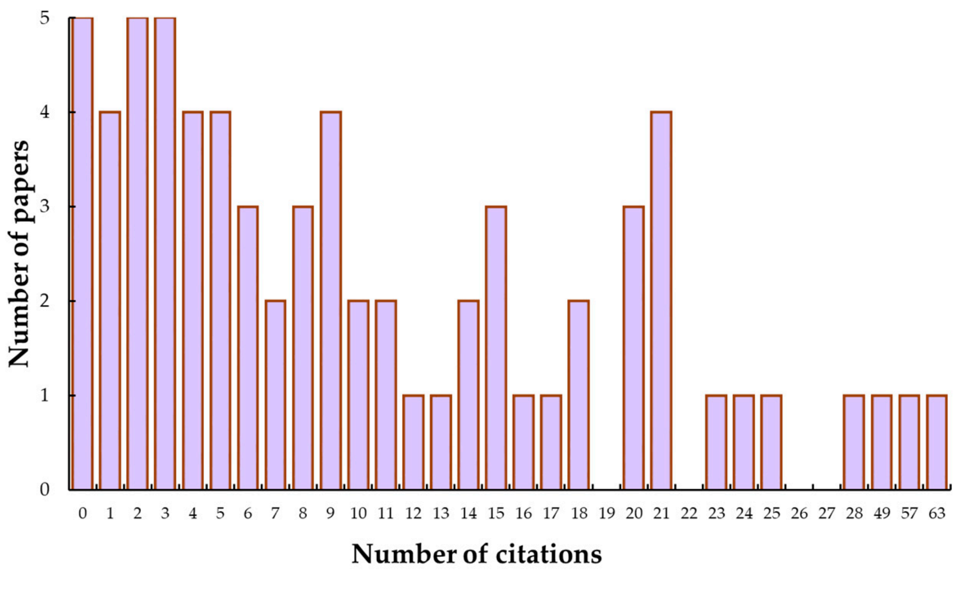

Figure 4. Distribution by citation of modern articles (2019–2023) devoted to vegetation dynamics and Ellenberg and Landolt indicator values.

In addition, the figure shows the presence of a large number of highly cited articles. For example, 58.4% of articles were cited 5 or more times, and 37.7% 10 or more times. The percentage of articles with 20 or more citations was also very high, amounting to 18.2%. Articles with the highest citations should be noted separately. As shown in Figure 5, they formed an isolated group of four articles.

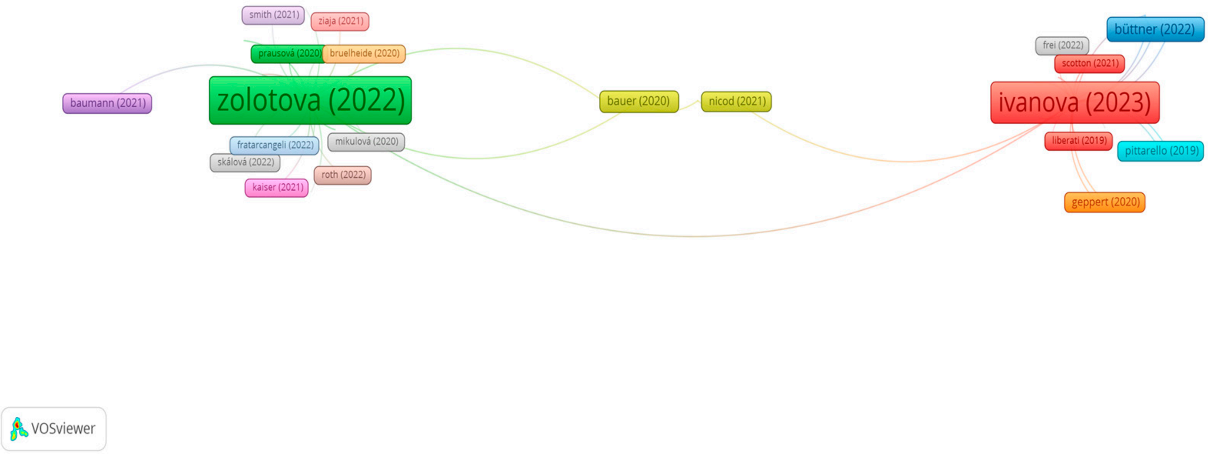

Figure 5. Citation-based analysis of the article interconnection network.

The most cited articles are listed in Table 3. The publications are grouped by year, as citation depends on the age of the article. This table shows the three most cited articles for each year within the time interval under study.

Table 3. Most cited articles for 2019–2023 on vegetation dynamics using Ellenberg and Landolt indicator values.

Authors	Indicator	Research Topic	Journal	Crossref Citations	References
		2019			
Rumpf S.B., Hülber K., Wessely J., Willner W., Moser D., et al.	Landolt	Local habitat dynamics of non-forest plants in the European Alps related to climate change	*Nature Communications*	63	[77]
Diekmann M., Andres C., Becker T., Bennie J., Blüml V., et al.	Ellenberg	Modeling of long-term changes in the vegetation cover of different types of semi-natural grasslands in Western and Central Europe	*Journal of Vegetation Science*	57	[86]
Busch V., Klaus V.H., Schäfer D., Prati D., Boch S., et al.	Ellenberg	Studying the stability of temperate grasslands under a high land use intensity	*Journal of Vegetation Science*	49	[87]
		2020			
Dietz L., Collet C., Dupouey J.L., Lacombe E., Laurent L., Gégout J.C.	Ellenberg	Influence of windstorms on the adaptation of temperate forests to global climate warming	*Global Ecology and Biogeography*	28	[59]
Geppert C., Perazza G., Wilson R.J., Bertolli A., Prosser F., et al.	Landolt	Range shifts of alpine orchids under global climate change in the European Alps	*Nature Communications*	25	[72]
Diaci J., Rozman J., Rozman A.	Landolt	Microsite niche partitioning in a high alpine forest	*Forest Ecology and Management*	24	[82]

Table 3. *Cont.*

Authors	Indicator	Research Topic	Journal	Crossref Citations	References
			2021		
Haselberger S., Ohler L-M., Junker R.R., Otto J-C., Glade T., Kraushaar S.	Landolt	Primary vegetation succession on proglacial slopes of the Gepatschferner	*Earth Surface Processes and Landforms*	14	[85]
Scotton M., Andreatta D.	Landolt	Anti-erosion rehabilitation	*Science of The Total Environment*	12	[71]
Kapfer J., Popova K.	Landolt	Changes in subarctic vegetation	*Journal of Vegetation Science*	9	[79]
			2022		
Scherrer D., Bürgi M., Gessler A., Kessler M., Nobis M.P., et al.	Landolt	Climatic changes in the Swiss flora	*Ecological Indicators*	11	[81]
Roth M., Müller-Meißner A., Michiels H.G., Hauck M.	Ellenberg	Forest dynamics	*Forest Ecology and Management*	10	[98]
Kaulfuß F., Rosbakh S., Reisch S.	Ellenberg	Grassland restoration	*Applied Vegetation Science*	9	[92]
			2023		
Midolo G., Herben T., Axmanová I., Marcenò C., Pätsch, R., et al.	Ellenberg, Landolt	Disturbance indicator values for European plants	*Global Ecology and Biogeography*	17	[11]
Zolotova E., Ivanova N., Ivanova S.	Ellenberg	Global overview of modern research based on Ellenberg indicator values	*Diversity*	9	[41]
Bátori Z., Tölgyesi C., Li G., Erdős L., Gajdács M., Kelemen A.	Ellenberg	Factors of forest dynamics in karst habitats	*Annals of Forest Science*	3	[54]

Figure 5 shows the network of interrelations of articles based on citations. Different clusters are highlighted in color. The lines show citations between articles. The thickness of the line depends on the number of citations. The contribution of an article to the formation of the network of interrelations is reflected by the font size: the more connections, the larger the font. The figure clearly shows three separate groups of articles. The first group (the first red one and the adjacent clusters) is associated with the use of Landolt indicator values in research. The second group (green and the clusters close to it) is related to the use of Ellenberg indicator values. The third group is a separate single cluster (yellow), which includes articles devoted to the study of vegetation dynamics of meadows in central Europe. There are practically no relationships between all the groups. At the same time, intracluster interactions are also expressed extremely weakly. In addition, it should be noted that there are a large number of clusters with a small number of articles, and the presence of publications that did not form clusters. This also indicates the weak development of the citation-based network of relationships and the fact that do not know and do not use the results of recent research. The connecting publications that unite disparate studies into a single scientific network are two modern systematic reviews [29,41].

3.5. Analysis of the Journal Interconnection Network Based on Citations

Figure 6 shows journals that have published at least two articles on vegetation dynamics based on Ellenberg and/or Landolt indicator values, which have at least three citations. The journal's contribution to the scientific field is reflected in the figure by the font size, which depends on the number of articles published. "*Applied Vegetation Science*" (seven articles) and "*Forest Ecology and Management*" (six articles) (Table 4) are the leaders in the number of published articles over the past 5 years. The "*Journal of Vegetation Science*" clearly stands out in terms of citation rates compared to other journals. Articles published in this journal over the past 5 years have received 133 citations (Table 4). However, these journals are not leaders in the number of relationships with other journals. The center of the interconnection network is "*Diversity*". This is this journal that unites disparate journals into a single scientific network.

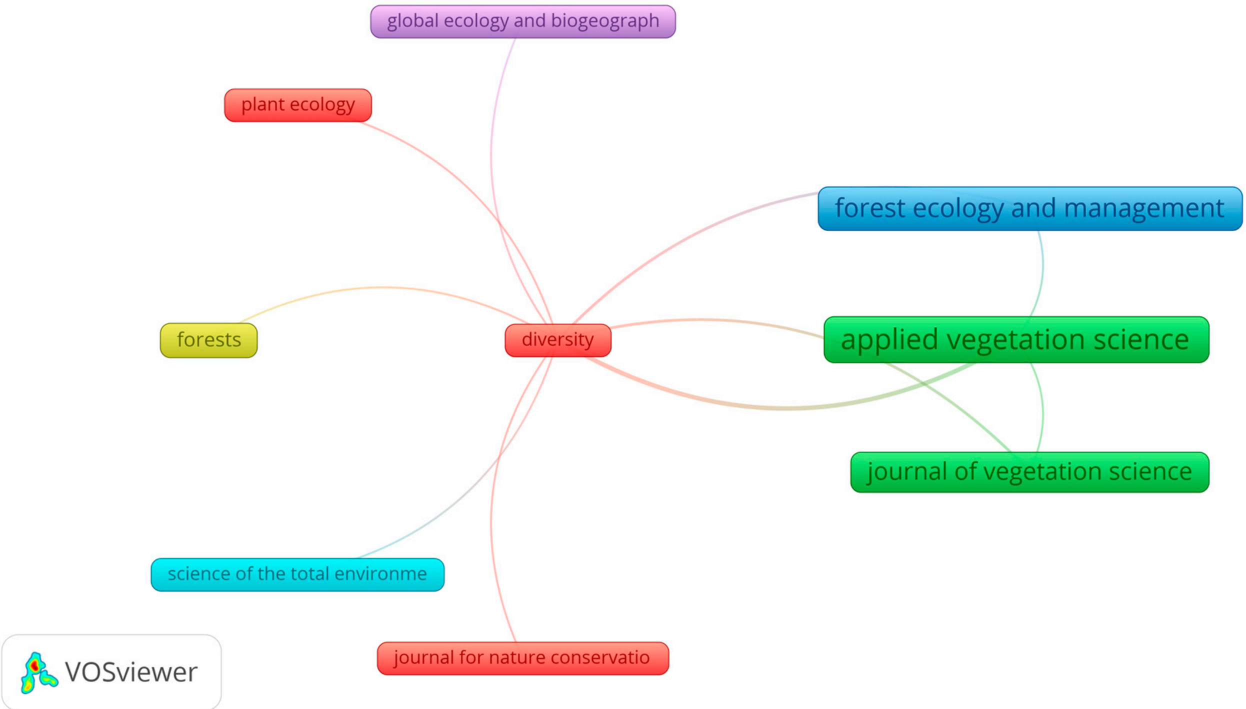

Figure 6. Analysis of the journal interconnection network.

Table 4. Analysis of publication activity, citations and the journal interconnection network.

Journal	Cluster	Number of Relationships	Number of Articles	Number of Citations
Diversity	1	8	2	14
Journal for Nature Conservation	1	1	2	4
Plant Ecology	1	1	2	6
Applied Vegetation Science	2	3	7	67
Journal of Vegetation Science	2	2	5	133
Forest Ecology and Management	3	2	6	66
Forests	4	1	3	35
Global Ecology and Biogeography	5	1	2	45
Science of the Total Environment	6	1	2	34

4. Discussion

Our research analysis showed that applying Landolt and Ellenberg indicator values is a widely used method in scientific research. The use of these methods to study vegetation dynamics has proven effective in studying different plant communities in different countries. At the same time, the geography in which the Landolt indicator values are used is not identical to the geography in which the Ellenberg indicator values are used. For vegetation dynamics, the greatest number of studies based on Ellenberg indicator values are found in Germany, Italy and the Czech Republic, and the greatest number of studies based on Landolt indicator values are found in Switzerland, Italy, Austria and Slovenia. The results obtained for the geography of research on vegetation dynamics are somewhat different from those obtained for all scientific fields to which the Landolt and Ellenberg indicator values are applied [29,41]. At the same time, the countries (Germany, Switzerland) where these ecological indicators were originally developed still clearly outperform other countries in terms of the number of publications.

Landolt and Ellenberg indicators are used in very similar ways. The importance of Landolt indicators for the study of mountain vegetation dynamics is enhanced by their focus on mountain areas. It is generally recognized that mountain ecosystems, on the one hand, are the most vulnerable to both anthropogenic impacts and climate change and, on the other hand, have a very heterogeneous and rapidly changing habitat [104,105]. Therefore, it is extremely useful to use ecological indicators as a primary or additional method in studies on the dynamics of mountain ecosystems.

Climate-induced changes in mountain vegetation occur earlier and are more pronounced than in the plains [106,107]. The heterogeneity of habitats and environmental factors is due to the heterogeneity of the landscape, which is characteristic of mountain areas. It therefore takes a lot of time and effort to identify changes in habitat and environmental drivers. On the plains, data from meteorological stations can be relied upon successfully, but in the mountains, even data from nearby stations do not accurately reflect habitat conditions and cannot provide information on the heterogeneity of environmental factors. In this case, indicator values can be extremely useful and can be chosen as the main method for determining the drivers of the environment and their dynamics. Indicator values make it possible to identify habitat heterogeneity and environmental drivers at almost any spatial scale with a high level of detail. This is important for planning sustainable management of plant communities, especially those that are actively used (e.g., for grazing or timber harvesting) and therefore under increased stress. In this situation, continuous monitoring of the status and dynamics of plant communities and environmental factors is required. Ellenberg and Landolt indicator values are well suited for these purposes due to their ease of use and high efficiency.

We expect that clearer results will be obtained by using the Landolt indicator values than by using the Ellenberg indicator values to study forest–tundra and forest–steppe ecotones, including the upper and northern treeline. Treeline surveys tend to focus on one tree species and do not assess habitat in sufficient detail [108–110]. Our recommendation is therefore that the indicator values should be used more widely in these plant communities.

In general, Ellenberg and Landolt indicator values have facilitated the resolution of many specific challenges within the general theme of identifying drivers of vegetation dynamics. The reason for this is that the determination of values for climatic and edaphic drivers is subject to a number of difficulties and is often not possible in large-scale studies. The indicator values, on the other hand, are relatively easy to apply. Their effectiveness was confirmed by the results of our review.

4.1. Problems of Studying Vegetation Dynamics Using Ecological Indicator Values

1. Long-term research on the structure and dynamics of plant communities and the creation of various geobotanical databases has led the scientific community to the era of large ecological datasets. On the one hand, this makes it possible to obtain more accurate regional assessments and forecasts of plant community dynamics, increase

the efficiency of nature management and conservation, and move to a new level of research: transcontinental and global [111]. On the other hand, there is an acute shortage of appropriate methods of analysis. The question remains of how widely ecological indicators can be used geographically. Modern research has shown that the geography of application of the Ellenberg and Landolt indicator values is expanding. Researchers are faced with the question of transformation of ecological niches in various bioclimatic zones. Nevertheless, the scale of transformation of ecological niches remains insufficiently studied, especially for man-made landscapes [112,113]. Understanding the transformation of ecological niches stimulates the adjustment of existing and the development of new regional ecological indicators with appropriate amendments. Moreover, the amendments may be relatively small if the countries are located close to the European countries for which the Ellenberg and Landolt indicator values were developed, in contrast to those that need to be made in more remote regions, including Russia. Thus, on the one hand, the development of regional ecological indicator values allows for a significant increase in their effectiveness within a particular region. On the other hand, it complicates the comparison of research results for different countries. In addition, the use of regional ecological indicators makes it difficult to move to the analysis of large territories, which requires the use of uniform ecological indicator values throughout the study area. There are currently no specific recommendations from the scientific community on how to adjust the estimates of indicators over large areas. Further specific studies are needed to reduce the risk of false results.

2. Changes in species composition occur gradually and do not always clearly follow the transformation of the habitat. The lag effect is manifested both in the emergence of new species that are better adapted to changing conditions and in the extinction of species for which environmental conditions have become unsuitable [77]. However, there are no precise quantitative estimates characterizing the delay time. In addition, it can be assumed that this effect will depend on the bioclimatic zone, different types of impacts and many other factors. This problem is closely related to the rapidly gaining popularity of the scientific field on the study of plant adaptation [114,115] and plant communities [116,117].
3. Climate change can lead to complex changes in the species composition, spatial structure, ecological processes and functional services of phytocenoses and distort the natural course of restorative and digressive successions. At the same time, the frequency and intensity of disturbances of terrestrial ecosystems that initiate restorative successions are increasing worldwide. Disturbances, their causes and their consequences are given close attention in modern science. However, there is still a lack of knowledge about restorative successions, despite their importance for sustainable nature management [118,119]. At the same time, despite the fact that synergistic effects from the imposition of different types of dynamics undoubtedly exist, this problem remains the least studied. Moreover, synergistic effects significantly complicate the study of both climate dynamics and restorative and digressive successions. This problem must be taken into account when using the ecological indicator values, as there is a possibility of obtaining false conclusions. However, modern research does not provide answers to these questions.
4. The issue of convergence of plant communities was not addressed in the studies based on ecological indicators that we reviewed. In a review devoted to Russian forest typologies, it was emphasized that this phenomenon is very often manifested both in clearings and in primary and secondary forests [120]. It has been established that in clearings and burnt areas, this is due to the fact that the same type of external influences similarly transform the habitat and so physiognomically similar plant communities are formed in different forest growth conditions [121]. On the other hand, the influence of the edificator is clearly manifested in primary and secondary forests. It affects the species composition and structure of subordinate layers, and phy-

tocenoses acquire physiognomic similarity in different habitats. Of course, the species composition of these plant communities is not identical, but to date, no quantitative assessment of the degree of variation in the convergence of plant communities has been carried out. We also did not find information on how much this phenomenon complicates the bioindication of the habitat based on ecological indicator values.

5. The above problems lead to a difficulty of constructing effective models of vegetation dynamics. Predicting vegetation dynamics, for example, based on process models or machine learning, requires large amounts of accurate and representative data to train algorithms and verify parameters. Moreover, the data should be obtained using the same methods. Therefore, it is extremely important to expand plant-based bioindication systems to the Eurasian scale. Our conclusion is in good agreement with the opinions of other researchers [38]. The current shortage of high-quality monitoring datasets, lag effects, convergence of plant communities and synergistic effects reduce the accuracy of available models and, consequently, forecasts. This complicates the development of a system of sustainable environmental management and biodiversity conservation and also requires additional research.

4.2. Priority Directions for Further Research

The improvement of methods for the assessment of environmental factors and monitoring, as well as the transition from the study of historical and modern conditions to the prediction of the future, remain relevant and in-demand scientific directions. In this regard, we believe that it is a promising direction to improve existing systems of environmental indicators based on criteria of scientific validity, comparability, accuracy (including for large areas) and sensitivity to change. Therefore, the following research directions could be a priority for future research:

1. Fill existing gaps in the study of vegetation. As accurate quantitative data are the basis for ecological analysis, further large-scale, multi-year studies are needed to collect data on the vegetation structure and dynamics, as well as field measurements to study habitat factors. This will complement existing databases and initiate the creation of new databases. If such data for in-depth environmental analysis have already been collected for the EU countries, there are still many "empty zones" outside this area that have yet to be filled in. This applies, for example, to the vast Russian Federation and CIS territories. The identification of knowledge gaps will provide a basis for identifying priority and under-researched areas for future research. Data collection will require more effort. However, this phase is urgently needed to provide a reliable basis for further research.
2. Verification of the effectiveness and development of a methodology for the correction of ecological indicator values for different bioclimatic zones and vegetation types. An example of this is a study by a large international team of authors on the development of the latest Ecological Indicator Values for Europe (EIVE) [21]. Here, they used 31 indicator value systems, including the Ellenberg, Landolt, Tsyganov, Ramensky and other indicator values. EIVE is by far the most comprehensive system of ecological indicator values for European vascular plants, containing data on 14,714 taxa for soil moisture (M), 13,748 taxa for nitrogen (N), 14,254 taxa for soil acidity (R), 14,054 taxa for light (L) and 14,496 taxa for temperature (T). However, there has been no evaluation of its effectiveness outside Europe, although such studies are highly relevant. For example, verifying the effectiveness of EIVE for the territories of the Russian Federation would significantly expand the boundaries of its application. Filling this gap is an urgent task. At the same time, the applicability, effectiveness and comparability of estimates for the ecological indicator values of Tsyganov, Ellenberg and Landolt have been verified for Russia [122]. The authors found that, despite the different ranges of scores for different indicator values, the normalized values of the corresponding indicators proved to be comparable and generally gave good results for studying successions in the complex pine (*Pineta sylvestris composita (nemoro-boroherbosa)*) sub-

zones of coniferous–deciduous forests. Assessments of environmental factors based on all three systems of ecological indicators correlated during the successional process. The approval of the indicator values of Ramensky, Tsyganov and Landolt for the conditions of the Voronezh region in Russia was reached when using the example of the study of post-fire successions [123]. The authors obtained a positive result for all three systems of ecological indicator values tested. However, the researchers did not draw clear conclusions about the limits of applicability of these developments and the need to adjust indicator values. Therefore, despite the positive results of testing the Ellenberg, Landolt, Tsyganov and Ramensky indicator values on the territory of the Russian Federation, these problems require more thorough and large-scale studies for different bioclimatic zones and types of plant communities, especially in man-made landscapes and urbanized areas. At the same time, the Braun–Blanquet approach can be used to classify vegetation [124], which is widely used by researchers in Russia and abroad and provides a reliable basis for ecological analysis [125]. The choice of a classification system is particularly important, since the logical and correct systematization of the data obtained is extremely important for drawing correct conclusions. That is why we are addressing this issue here.

3. To study the effects of a delay. For these purposes, specific studies are needed to obtain strictly quantitative data on the dynamics of both vegetation and habitat factors. The experience of an Austrian team of authors can be used to pursue this scientific direction [77].
4. Development of predictive models of plant community dynamics. The importance of accurate predictions of plant community and habitat dynamics for the conservation and restoration of natural ecosystems and their functions is beyond doubt. On the one hand, it will provide a reliable basis for land use and conservation, and on the other, it will help to verify the quality and depth of our understanding of the mechanisms of climatic and anthropogenic vegetation change. It is important to understand the peculiarities of both the transformation of ecological niches and the effects of delayed changes in species composition during climatic shifts and successions. Identifying these features and developing robust, rigorous quantitative adjustments will be key to successfully predicting vegetation dynamics under different future climate change scenarios.

5. Conclusions

We conducted a review of vegetation dynamics studies based on Landolt and Ellenberg indicator values. Based on the recommendations of PRISMA 2020 and the VOSviewer software(version 1.6.18), an analysis of publications for 2019–2023 was carried out. The wide geographical application and high reliability of Landolt and Ellenberg indicator values for the study of different plant communities and variants of their dynamics were demonstrated. At the same time, the application of these indicator values has its peculiarities. For example, the Ellenberg indicator values show a wider research geography and are more often used to study the dynamics of forest ecosystems than the Landolt indicator values, which are more often used to study disturbed landscapes and the dynamics of individual species. Meanwhile, it was found that these methods were used with almost equal frequencies for grasslands, wetlands and coastal vegetation. It was also found that climate-driven dynamics and regenerative successions were more often studied using Landolt indicator values than Ellenberg indicator values, which were more often used to study anthropogenic changes.

The citation analysis confirmed, on the one hand, the high interest in the indicator values and their widespread use in research, but, on the other hand, revealed the weak development of a network of relationships. This suggests that modern researchers are not well aware of, and rarely use, the results of research carried out in recent years, especially if they are based on indicator values other than those used by them. At the same time, a number of unresolved issues were clearly identified that require additional research and the consolidation of research teams to address them more successfully. These include the transformation of ecological niches in different bioclimatic zones; the lag effect; the synergistic effects of different types of dynamics; the convergence of plant communities; and the difficulty of constructing effective models of vegetation dynamics.

In conclusion, we can say that the Ellenberg and Landolt indicator values are excellent methods for ecological analysis of plant community dynamics and can provide a reliable scientific basis for developing solutions for the conservation and restoration of terrestrial ecosystems and for sustainable land use. We hope that the results of this meta-analysis will provide an impetus for the further development of the concept of environmental indicators and help researchers to overcome the current questions around applying indicator values in the study of vegetation dynamics, as well as help researchers to understand the strengths of this methodology.

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