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STUDIES ON CENTIPEDE ECOLOGY (MYRIAPODA: CHILOPODA) A BIBLIOMETRIC REVIEW

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Abstract
As predatory soil macroinvertebrates, centipedes are often considered groups used for soil community studies. However, research explicitly targeting centipede ecology remains relatively scarce. This paper addresses this gap by conducting a formal literature review and scientometric analysis of worldwide publications on the ecology of centipedes, specifically focusing on research studies conducted in Romania. We utilized articles published after 1990 and available in Web of Science collections under Ecology Research Area. As supported by the authors' keywords co-citation networks, classical aspects of centipedes ecology, such as environmental requirements and tolerances of a particular species, seem to be hidden mainly within taxonomy and faunistic papers. Community ecology approaches are better delimited under the umbrella of biodiversity. Among these, ecotoxicology and food webs topics stand out, the latter being the subject of some of the most cited papers. The study also investigated collaboration groups and the countries supporting research in the field of centipede ecology. In Romania, Zachiu Matic studied the altitudinal distribution of centipedes in two mountain ranges, providing valuable insights into elevation limits for certain species. Additionally, Matic discussed synecological data on centipede communities in oak forests. Another researcher, Radu Gava, compared centipede diversity in different forest types, including oak, beech, and alder forests. Overall, the analysis revealed that the growth of articles on the ecology of centipedes had not followed a growing trend over the years, both internationally and locally. This stagnation suggests that certain limitations may still hinder research development in this field. However, the study sheds light on the existing research landscape and highlights specific areas for further investigation.

Keywords: bibliometric analysis, centipedes, ecology, research trends

1. INTRODUCTION

Centipedes are a worldwide spread soil macroinvertebrate group, with over 3000 described species (Lewis, 1981; Bonato et al., 2016); the class Chilopoda consists of five orders, representing the only group of predatory myriapods. Chilopoda belongs to the monophyletic subphylum Myriapoda (Miyazawa et al., 2014). These myriapods possess a distinct feature—a pair of venomous claws developed from a modified first appendage. While centipede's predatory behavior is commonly observed, some ecological studies suggest that certain species have a mixed diet, which implies that they can be classified as omnivores. (Scheu and Falca, 2000).

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Known primarily from the litter and soil interstitial environment (Tuf, 2015), centipedes can also inhabit forest canopies (Phillips et al., 2020) and also use stream habitats, being amphibious (Tsukamoto et al., 2021), potentially interacting with more species than those at soil level.
The capacity for dispersal among centipede species exhibits variability (Voigtlaender, 2011) but is generally limited, although some species can cross seawater barriers (Lewis, 1981). Their high-level endemism and extensive distribution, along with their importance and impact on other species along the food webs (Santonja et al., 2018), make them good subjects for biogeographical (Simaiakis et al., 2013; Simaiakis and Strona, 2015) and ecological studies (Grgic and Kos, 2005; Tuf, 2015; Horňák et al., 2020).
The attempt to understand the mechanisms responsible for the emergence of environmental patterns is a common objective of both biogeography and ecology, agreeing or not on specific interpretations (Jenkins and Ricklefs, 2011). While biogeography and ecology operate at different scales, they rapidly converge at intermediate spatial and temporal scales, which are highly relevant for conservation activities. However, there is a predominant focus on plants and vertebrates in these disciplines, with a noticeable bias against invertebrates. This bias stems from their limited visibility to the general public, the substantial knowledge gaps (in distribution, taxonomy, and ecology), and the sheer number of invertebrate species, which present significant challenges in research workload (Marsh et al., 2022). Vertebrates do not adequately protect invertebrates as umbrella species mainly because they respond differently to environmental factors (Heino et al., 2009; Oberprieler et al., 2019). While some charismatic groups of invertebrates like Lepidoptera have attracted more interest (Pierce et al., 2002; Zalucki et al., 2002), less attractive species such as centipedes are overlooked, and ecology information is still scarce.
We aimed to assess the current state of centipede ecology research and identify research trends and leading journals that published papers in the field. Additionally, we evaluated the collaboration between countries and authors. We also wanted to see the aspects that caught the attention of Romanian scientists over time. For this, we conducted a global literature review on the papers in the Web of Science database and employed scientometric analysis to illustrate the extent and topics of the articles we found.

2. MATERIALS AND METHODS

We retrieved scientific articles for this study from the "Web of Science Core Collection" (WoS) database, which is a comprehensive research publication database covering approximately 34,000 journals (Birkle et al., 2020). To make the search process more manageable, WoS offers relevant search filters (Visser et al., 2021). We searched topics using keywords such as "centipede*", "chilopod*", and other terms related to specific centipede taxa below Class categories. Using this method, we searched the title, abstract, author keywords, and Keywords Plus® to analyze the literature concerning centipedes thoroughly. The resulting list was refined by the Web of Science category "Ecology." After reviewing the titles and abstracts, we excluded papers irrelevant to our subject. We used a final list of 130 scientific articles we acquired in April 2022 for the bibliometric analysis.
Part of the analysis involved utilizing Microsoft Excel functions and encompassed several aspects. These included examining the annual trends, studying the focus of the research at the class or species level (including the nomination of centipede species), identifying top-cited papers and journals, and analyzing the geographic distribution based on the primary author's affiliation.

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To perform further bibliometric analysis, we employed VOSviewer 1.6.18 software (van Eck and Waltman, 2010) with a precisely defined thesaurus (to eliminate items redundancy) for each assessment. The initial analysis conducted involved examining the co-occurrence of keywords, which measures the relatedness of keywords based on the number of documents in which they appear together. In this analysis, a minimum threshold of three occurrences of keywords (including both authors and KeyWords Plus) was used. We maintained the default clustering resolution and the normalization method based on association strength in generating the maps.
For a local perspective on the subject, we also searched the non-indexed scientific literature on centipedes published in Romania in known local scientific journals aiming to identify research that aimed to solve ecological problems.

3. RESULTS AND DISCUSSIONS

A total of 1886 papers on centipede topics were obtained from the Web of Science database search, and we analyzed the distribution across different academic disciplines. It is worth mentioning that a significant portion of these publications fall under Zoology and Entomology category. Among the initial list, 192 papers were identified as belonging to the field of Ecology. A thorough examination of their titles, abstracts, and in some instances, full texts led to the selection of 130 papers that were considered genuinely focused on ecological aspects. In addition, only 32 of these papers specifically addressed research on the Class Chilopoda or centipede species, indicating a narrower but still important focus within the larger ecological context.
We retrieved articles on centipede ecology (treating the subject at the level of the entire trophic web or the species level) published between 1976 and 2022, with the majority appearing after 1991. Even though the total number of centipede-related papers included in the Web of Science (W.O.S.) exceeded 50 articles per year starting in 2005, the documents categorized under “ecology” consistently maintained a relatively constant trend, never surpassing ten papers per year (Figure 1).

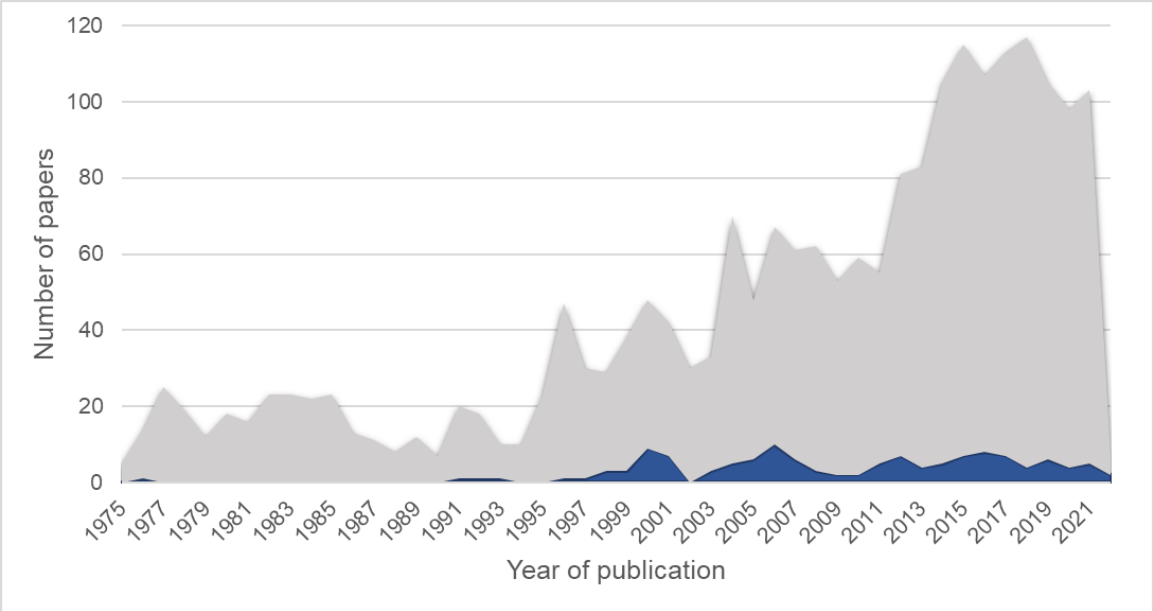

Figure 1. Yearly publication trend on topics concerning centipedes in general (grey area) and ecology of centipedes in particular (blue area)

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A considerable percentage of the papers (44%) focused on centipedes at the supra-specific level, primarily identifying the individuals as belonging to the Chilopoda class during field studies or experiments without specifying the exact species (Figure 2). Similarly, a significant proportion (37%) mentioned identifying centipede to species level in either the methods or results section, but only 25% provided explicit species inventories within the main text or supplementary materials. Of the articles examined, only 23 focused on and identified one to three species of centipedes, delving deeper into aspects of their ecology. The centipede species most commonly mentioned include those belonging to the order Lithobiomorpha, such as *Lithobius crassipes*, *Lithobius curtipes*, *Lithobius mutabilis*, and *Lithobius nodulipes*, as well as species from the order Geophilomorpha, such as *Strigamia acuminata* and *Geophilus flavus*. The lack of progress in ecological studies on centipedes, despite the considerable advancements in various data sampling and processing techniques, along with a substantial number of papers focusing on invertebrates at higher taxonomic levels, migth be atributed to the lack of capacity for taxonomic identification and variable coverage of taxa grups by specialits (Engel et al., 2021; Hochkirch et al., 2022).

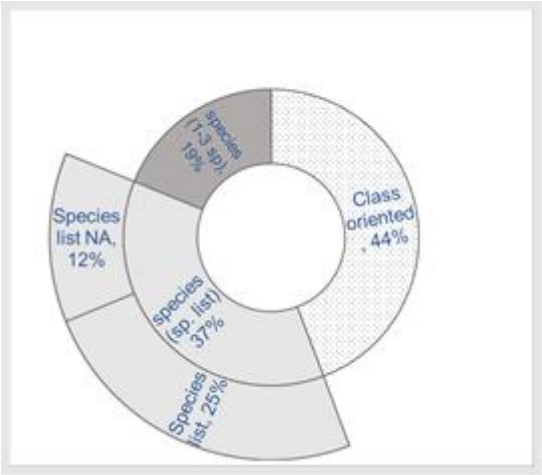

Figure 2. Percentage of papers oriented towards different taxon level identification

The articles analyzed here appeared in 59 journals published by 38 different publishers. Also noteworthy is that several journals have made significant contributions to the field of centipede ecology, with five or over papers published in each of the following: Pedobiologia, International Journal of Soil Biology, European Journal of Soil Biology, Oikos, Biodiversity and Conservation, American Midland Naturalist, Ecology, and Journal of Biogeography. Interestingly, four of these journals also published highly cited papers. Upon analysis of the primary focus of these influential papers (Table 1), a conspicuous pattern arises, highlighting research regarding the soil food web and the management of habitats. Between 80 to 263 citations were received by the top ten articles. Interestingly enough, only the first two top articles focused on species level (for specimens from Class Chilopoda and other invertebrate groups).

A bibliometric map was generated to illustrate keyword co-occurrence. The initial identification process yielded a total of 832 keywords. Nevertheless, upon implementing the criterion of a minimum of three occurrences, just 92 keywords were chosen as fit for examination. The software VOSviewer was employed to group the keywords mentioned above into six distinct clusters based on their degree of relatedness. Point size is used in bibliometric maps to express the frequency of relevant keywords, while the width of lines and closeness of points reflects the relationship between items. Figure 3 depicts the clusters in the map, each of which is distinguished by a unique color, thereby facilitating a thorough analysis of the map's item connections and frequencies. The first cluster, marked with red, covers terms related to land use, habitat classification, habitat administration, climate change, and ecological disturbances such as floods and fires and their repercussions on soil-dwelling organisms, particularly macrofauna and, consequently, centipedes. These subjects fall under the broader scope of biodiversity. The second group (symbolized in blue) corresponds to the decomposition process, with a particular focus on the decay of litter and wood in

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temperate forests and the invertebrate assemblages linked to these ecological processes. Next, the third cluster, denoted by light blue, encompasses recent colonisations, community patterns, and environmental biogeography terminology. The fourth cluster (in violet) comes from research papers that look into subjects such as invasive species and the impact of centipede species on indigenous fauna, particularly in island ecosystems.

Table 1. Highest article citations, publishing journal, and leading subject

Article	Journal	Main subject	Total citations
(Scheu and Falca, 2000)	Oecologia	FOOD WEB	263
(Pollierer et al., 2007)	Ecol. Lett.	FOOD WEB	244
(Chen and Wise, 1999)	Ecology	FOOD WEB	207
(Pfiffner and Luka, 2000)	Agric. Ecosyst. Environ.	HABITAT MANAGEMENT effect on soil invertebrates	181
(Scheu and Schaefer, 1998)	Ecology	FOOD WEB	156
(Scheu et al., 2003)	Oikos	FOOD WEB	136
(Lovell et al., 2007)	Biol. Conserv.	BIODIVERSITY ASSESSMENT	119
(Báldi, 2008)	J. Biogeogr.	HABITAT MANAGEMENT	114
(Kaspari and Yanoviak, 2009)	Ecology	FOOD WEB	90
(Blanchart et al., 2006)	Eur. J. Soil Biol.	HABITAT MANAGEMENT effect on soil invertebrates	80

The fifth and sixth clusters gravitate around food webs, a highly linked keyword in co-ocurence map. The green group examines predator-prey interactions between centipedes and their prey or predators at the individual/population and intraguild levels. The yellow cluster delves into the more intricate soil community levels, employing methods that investigate the pathways of nitrogen and carbon uptake and transfer within food webs.

The co-authorship network depicted in Figure 4 reveals that 42 researchers have authored at least two publications on the ecology of centipedes, but collaboration is not intense. Active myriapodologist are seldom involved in ecology projects, which also underlies the "taxonomic impediment" and lack of more solid bridges between disciplines (Engel et al., 2021; Raposo et al., 2021). The largest and most intricate group, consisting of ten researchers, appears to be led by Sheu S., highlighting their significant impact on the discipline. Additional contributors to the field include Langel L., Maraun M., Rall B.C., Ferlian O., and Eitzinger B., who have made notable contributions through the publication of multiple articles and the establishment of robust collaborative relationships. Upon analyzing the publication chronology, it is evident that Langel L. was actively publishing in 2006, whereas Sheu S. emerged as a prominent figure in 2011, coinciding with the activity of Maraun M. during the same period. The temporal proximity of some of the most recent members' inclusion in the group between the years 2014 to 2016 indicates their

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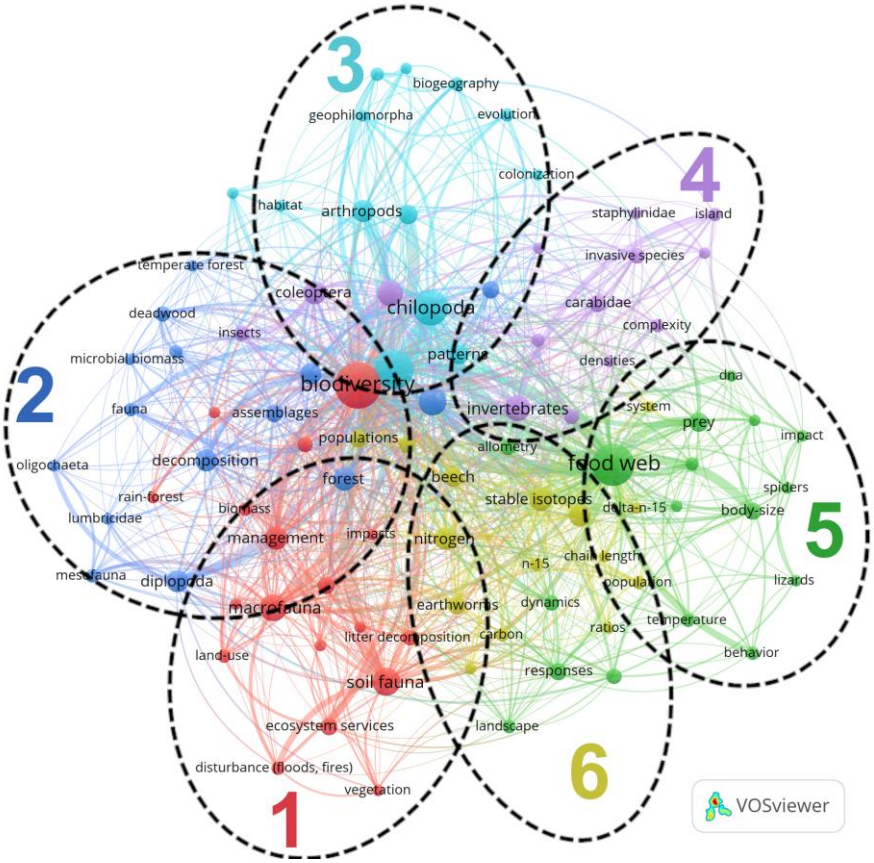

Figure 4. Keyword co-occurrence map based on centipede ecology papers

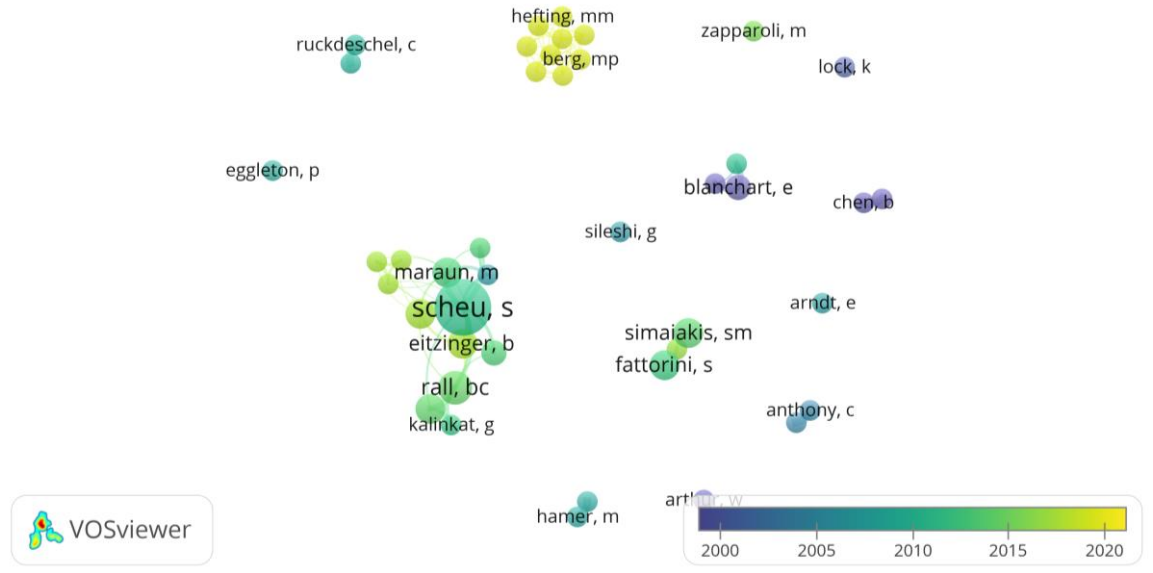

Figure 3. The co-authorship network (color represents the average year of the publications of each author)

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relatively more recent involvement. This influential group, which aligns with clusters 6 and 7 identified through keyword analysis, is renowned for its research on the soil trophic web.
Furthermore, they have published four highly cited articles (Table 1) investigating nitrogen and carbon uptake and transfer pathways within soil animal food webs in European deciduous forests. These publications, authored by Scheu and Schaefer (1998), Scheu and Falca (2000), Scheu et al. (1998), and Pollierer et al. (2007), contribute significantly to the understanding of this field. Another identified group of 9 authors only worked at the class level of soil invertebrates and studied the dynamics of invertebrates communities in decomposing deadwood and the impact of bark traits on the abundance of invertebrate groups. Led by Zuo J. and Cornelissen J.H.C they found that in the early stages of decomposition, the community composition is different between tree species. It becomes more similar in later stages (Zuo et al., 2021). They noted that the abundance of centipedes is influenced by decaying bark thickness, related to microclimatic conditions (Zuo et al., 2016).
Other co-authorship clusters consist of only three or fewer collaborating scientists, each with their co-authors, who have not published more than one paper in the specific domain under study. Among these clusters, the group led by Simaiakis S.M. is more recently active, spanning from 2012 to 2016. Their research focuses on various ecological and biogeographical aspects of centipede species and assemblages. They have introduced species distribution modeling to investigate the range of habitat suitability and gain insights into the spatial distribution of centipede species. Their contributions shed light on understanding the factors influencing centipede species distribution and habitat preferences (Simaiakis and Strona, 2015; Georgopoulou et al., 2016).
What is important to underline is that the main authors identified through this strategy are not the most active members of myriapodologist associations. However, there is an exception in the case of Simaiakis S.M. When exploring the co-authorship map created from all the papers on centipede topics obtained from the WoS database search, Simaiakis S.M. remains prominent. On the other hand, other names are overshadowed by renowned scientists such as Edgecombe G.D. and Bonato L., to name a few. This finding suggests that experts in myriapodology are primarily active in domains like taxonomy, evolutionary biology and molecular biology. They rarely join teams studying ecology or leading this type of research.
Regarding the geographic distribution of centipede ecology research, several countries standed out as prominent contributors based on the primary authors' affiliations. Germany emerges as a key player, with solid collaboration and weighted co-authorship links with Austria. The United States exhibits robust partnerships with Italy and China. French authors have established research connections with scientists from Belgium and Mexico. The United Kingdom has collaborated with Malaysia and Germany, while Italy has established research partnerships with Portugal.
On a broad international scale, Romania is represented by the soil biologist Falca M. primary author of the highly cited paper published in the journal Oecologia (Scheu and Falca, 2000). Their study was localized, however, in northern Germany, in a beech forest, aiming to explain some questions regarding the soil food web and predator interactions. The most important finding was that centipedes (among other soil invertebrate groups considered predators) have a mixed diet and probably should be regarded as omnivores. They also suggested that higher taxa in soil food web analysis cannot capture the complexity of soil fauna interactions (Scheu and Falca, 2000).
We found that the number of papers explicitly addressing centipede ecology from Romania is quite limited. However, a few notable studies have contributed to our understanding of centipede ecology in the country. One such study conducted by Matic Z. focused on the altitudinal distribution of centipedes in two mountain ranges, namely Fagaras and Retezat (Matic, 1964, 1991). The research

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identified elevation limits for certain species and explored their distribution patterns. Additionally, Zachiu Matic gathered synecological data on centipede communities in oak forests, providing insights into the ecological interactions within these ecosystems (Matic and Hodoroga, 1985). In a more recent study, Gava R. (2004) quantified and compared the diversity of centipedes in different forest types, namely oak, beech, and alder forests. The research revealed that beech forests harbored the most diverse communities of centipede species, highlighting the ecological significance of this particular forest type for centipede biodiversity in Romania. Also, some papers deal with factors influencing community structures in scree habitats, marginally touching the subject of centipedes ecology (Nitzu et al., 2018).

Although our summary aimed to target the international situation, we only used papers published in the Web of Science to ease the use of the bibliometric software. Therefore the methodology could have easily overlooked information published in various local languages as proved for other invertebrates studies (Chowdhury et al., 2022; Amano et al., 2023). WoS categories, like many classification schemes, are not without flaws (Milojević, 2020), and some documents with prominent ecological subjects, like the paper of Lacasella and Zapparoli (2015) classified under Entomology and Biodiversity Conservation categories, might have been overlooked in our analysis. However, the methodology allowed a pretty thorough investigation of the broader state of this field.

4. CONCLUSIONS

Although there has been an increase in the number of documents within research publication databases that mention Class Chilopoda or centipede species in general, only a limited few actually delve into ecological aspects. Despite a general increase in publication efforts, this field seems stagnant.

Most of the studied research papers, identifies invertebrates only at higher taxonomic level, underscoring the limited involvement of taxonomists in ecological studies. Moreover, keywords analysis suggested that research directions are not well delimited, revealing a web of topics. Keywords cluster around biodiversity, management, wood or litter decay processes and soil food webs. The latter subject stands out, dividing into studies on predator-prey interactions and intricate community dynamics.

Several research teams emerged through co-authorship analysis, with Scheu S., the most prominent and cited author, significantly contributing with studies regarding soil food webs. Despite this, collaborative efforts among these groups appear to be limited and there are challenges in attracting taxonomists to participate in ecological studies. The main research centers primarily reside in Germany and the United States, with strong collaborative ties to other European countries and high citation scores.

Just a few notable studies, including research on the altitudinal distribution of centipedes, synecological data on centipede communities in oak forests, and diversity comparisons among different forest types, emerged in time from Romania.

This study contributes to our knowledge of centipede ecology and provides valuable insights into the research trends and focus areas in the field.

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