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Review

Mapping 50 years of contribution to the development of soil quality biological indicators

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ABSTRACT

Biological indicators of soil quality express the capacity of a soil to maintain its ecosystem functions and services between socio-ecosystem inflection thresholds; therefore, they are determinants in management and land use decisions. However, their development until a few decades ago was limited for several reasons: reductionism and early development of other dimensions, such as physical and chemical indicators or their methodological complexity, thus affecting the importance given to biological factors and the integral evaluation of soil quality or health. Thus, this review presents a mapping of the scientific contributions of the last 50 years oriented to the theoretical and methodological development of biological indicators of soil quality, identifying their development and application in these decades. We conducted a bibliometric analysis that allowed us to present an overview of the field with respect to scientific production: temporality, geographical origin, institutional origin, journals that promote the development of the field, articles with greater influence by citation in the field of study, and the co-occurrences of these indicators in research. This analysis was complemented at the second stage by a systematic review of the literature with the greatest impact by citation. We found 2320 scientific papers distributed mainly in the United States (17.8%), China (12.2%), Brazil (8.3%), India (6.3%), and European Mediterranean countries, such as Spain, France, and Italy (14.2%). Our review showed 25 biological indicators with the highest occurrence; for example, microbial biomass (118), enzymatic activity (90), and organic matter (78); other indicators, such as earthworms, nematodes, or springtails, are also reported. All indicators showed relationships, to a greater or lesser extent, with soil biodiversity and its functions in the landscape. Important advances in soil indicators have developed gradually in the last few decades, with scientific efforts mainly concentrated in developed and emerging countries. In the last decade, the production curve continues with a growth trend., and research questions in the field revolve around the linkage of diversity and function from a molecular point of view. The scope goes beyond productivity, manifesting the real need to conserve and manage the ecosystem services of a limited and non-renewable natural resource. Pioneering research should begin to report on the scope of soil biological monitoring and its influence on policy, management, and land use. Finally, the promotion of research networks with developing countries can foster the development of regional and local soil monitoring policies in these regions.

1. Introduction

In the 21st century, soil quality depends on socio-ecological interrelationships that integrate the interactions of physical, chemical, biological, and anthropic dimensions (Bonilla-Bedoya et al., 2022; van Bruggen & Semenov, 2000). Soil quality is the ability of soil to function

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within ecological and social tipping points that determine biological productivity, agricultural production, environmental quality, plant, and animal health, and collective well-being (Bünemann et al., 2018; Doran & Parkin, 1994; Gil-Sotres et al., 2005; Mathias et al., 2020).

In this context, variations in soil quality biological indicators deliver key information on soil functions that are complemented by physical or chemical data (USDA, 2015). This information would express the capacity of a soil to maintain its ecosystem functions and services between socio-ecosystem inflection thresholds (Mathias et al., 2020). However, the early development of other fields, reductionist approaches, or other methodological factors, such as the complex observation of soil organisms, limited the advances in the soil biological dimension, marginalizing its development within soil sciences (Doran & Zeiss, 2000; Bastida et al., 2008). This scenario impacted both the importance given to biological factors and the evaluation of soil quality health (Paz-Ferreiro & Fu, 2016).

Further, the application, monitoring, and analysis of soil biological parameters is key information in land use and management decisions (Bispo & Oliveira, 2007; Bispo et al., 2009; Muñoz-Rojas, 2018; Pulleman et al., 2012; Jenny, 1980; Visser & Parkinson, 1992), including land use practices, the intensity and frequency of anthropogenic disturbances, and the input of organic matter through vegetation (Nunes et al., 2020) as determinants for soil biodiversity. Thus, there is currently a growing momentum both in academia and in politics for biological monitoring aimed at understanding soil quality at different spatial scales and in different world regions such as (Bünemann et al., 2018; Rutgers et al., 2009) Europe, (Huber et al., 2008; Rutgers et al., 2009), the United Kingdom (Loveland & Thompson, 2002; Merrington et al., 2006), North America (Acton & Gregorich, 1995; Stott & Moebius-Clune, 2017), Australia (Gonzalez-Quiñonez et al., 2011), and Asia (Teng et al., 2014).

However, soil biodiversity is composed of both species diversity and biological functions distributed in ecological complexes, such as soil microhabitats or large terrestrial landscapes (Bispo & Oliveira, 2007; Bispo et al., 2009; Turbé et al., 2010). Soil–organism interactions are essential for biogeochemical and physical ecosystem processes, including nutrient cycling, water-holding capacity, storage, filtration, buffering, and transformation of compounds, and provision of physical stability and landscape support (Bonilla-Bedoya et al., 2017; Blum, 1993; Koch et al., 2013; Pulleman et al., 2012; Young & Crawford, 2004).

Quantifiable biological and functional variations with high sensitivity to perturbations (Barrios, 2007; Bastida et al., 2008) determine the inflection thresholds of biological indicators. These variations are derived from interactions between soil and species, groups of species, or communities of organisms, which allows inferring the effects of disturbances on soil and environmental quality (Garbisu et al., 2007; Da Silva Souza et al., 2014; Mothersill & Seymour, 2016). In this context, several studies have reported biological indicators of soil quality (Bünemann et al., 2018; Huber et al., 2008; Rutgers et al., 2009; Stone et al., 2016;); however, their application in national, regional, or global monitoring is limited (Stone et al., 2016).

Moreover, the systematization of soil organisms and microorganisms continues to be a complex challenge; it is estimated that soil microorganisms represent about 98% of terrestrial life (Pace, 1996). A well-developed soil could contain thousands of species of soil animals, with a much larger number of microbial taxa; however, less than 1% of soil organisms have been classified (Sanderman & Amundson, 2014).

Thus, the high diversity of species in soil prompted initial proposals for grouping soil biodiversity (Swift et al., 1979), which continue to be applied today (Barrios, 2007; Guilland et al., 2018). These proposals consider: i) microflora 1–100 μm (Fierer and Jackson, 2006; Ibekwe et al., 2002; Nielsen et al., 2002); ii) microfauna 5–120 μm (González et al., 2001); iii) mesofauna 80 μm–2 mm (Römbke et al., 2005; Ruf, 1998; Da Silva Souza et al., 2014), and iv) macrofauna 500 μm–50 mm (Jouquet et al., 2022; Pérès et al., 1998; Römbke et al., 2005). However, along with this grouping, other proposals have also integrated the relationships between soil organisms and microorganisms with ecosystem functions. In this sense, perhaps the most relevant indicator is soil organic matter (Bonilla-Bedoya et al., 2013; Bonilla-Bedoya et al., 2022; Van-Camp et al., 2004) since it is the main source of food and energy for living organisms and an indisputable factor in the biological functioning of soil (Van-Camp et al., 2004).

However, challenges for the development and application of international and national soil quality standards continue at different spatial scales (Stone et al., 2016). Thus, from a global approach, the challenges focus on the multitude of physical, chemical, biochemical, and microbiological processes taking place in soil, the highly natural diversity manifested in this component, and its wide spatio-temporal heterogeneity (Bünemann et al., 2018; Fazekašová,2012). At the local scale, difficulties concentrate on the selection of relevant attributes, the interpretation of measurements, the quantification of anthropogenic effects on land use, and the quantification of trade-offs between ecosystem services (Bünemann et al., 2018).

Further, the rapid, vertiginous increase in the volume of scientific publications aimed at deepening the knowledge of soil biological indicators (Bünemann et al., 2018; Martínez-Salgado et al., 2010) also generates difficulties in the systematic updating of biological indicator knowledge (Bornmann et al., 2021; Fortunato et al., 2018). Thus, bibliometrics complemented by qualitative knowledge analysis assumes a more important role in the synthesis and systematization of the existing knowledge base (Snyder, 2019).

We proceeded to map the scientific contributions of the last 50 years related to the development of biological indicators of soil quality and systematize the biological indicators (organisms and functions) with greater application in recent years. To achieve this objective, we first generated a bibliometric analysis with respect to scientific production, considering temporality, geographical origin, habitat types, institutional origin, journals that drive the development of the field, and articles with greater influence by citation in the field of study. This overview is complemented at the second stage by a systematic review of the documents with the greatest impact by citation. Thus, we present a proposal of indicators derived from this review. Lastly, we discuss the trends, variations, and challenges facing soil sciences in the development and application of these indicators.

2. Methods

To generate a mapping of the advances of soil sciences in the field of soil quality and the development of biological indicators derived from the organisms and functions interacting in it, we first applied a bibliometric analysis—a systematic, transparent, and reproducible review method that was further complemented with a qualitative analysis of the literature (Aria & Cuccurullo, 2017). Both approaches are complementary and relate a high volume of information to a thorough review of documents that develop trends in the field (Pan, 2016). Thus, in the first phase, their application allowed us to generate a framework analysis of the scientific production, showing an overview of the field (Cobo et al., 2011). In the second phase, we discuss these developments considering the 20 manuscripts that showed the greatest impact on scientific citation (Fig. 1).

The bibliometric analysis considered articles indexed in the Scopus database until August 2021. The search criteria were TITLE-ABS-KEY (biological AND indicators OR bioindicators AND of AND soil AND quality OR health). No temporal filters or additional filters, such as stage of publication or type of journal, were applied. The search yielded a total of 2,320 documents, all of which were analyzed.

Different data libraries are available for bibliometric analysis, including ScientoPyUI, BibExcel, CiteSpace, SciMAT, Sci2Tool, and BiblioTools (Chen, 2016; Cobo et al., 2012; Pan et al., 2018; Ruiz-Rosero et al., 2019). To delimit software that fits our objective, we considered criteria such as user interface, the amount of bibliometric analysis

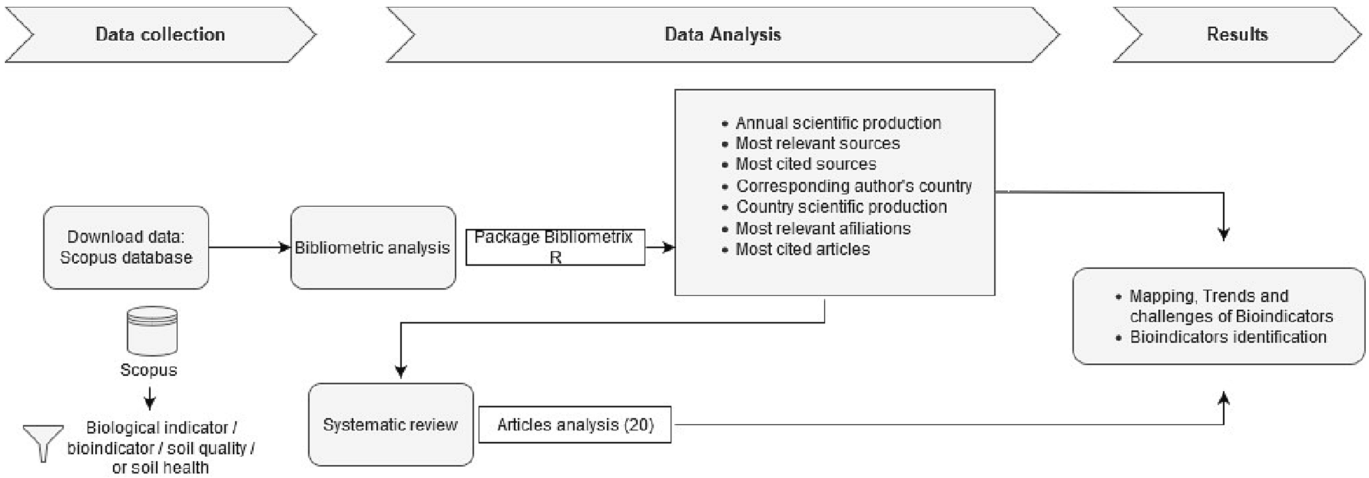

Fig. 1. Methodological scheme applied in the research.

offered by a single program, the quality of visualization of the generated graphics, the ability to import and export data, the open software nature, and compliance with the general scientific mapping workflow (Aria & Cuccurullo, 2017; Börner et al., 2003; Moral-Muñoz et al., 2020).

Thus, the R package Bibliometrix (Aria & Cuccurullo, 2017; Corvo et al., 2021) was chosen. Through its application, a scientific mapper was generated that provided information concerning annual scientific production, most relevant sources, most cited sources, corresponding author's country, country scientific production, most relevant affiliations, and most cited articles (Belter, 2015; Donthu et al., 2021). To identify which habitats were the most frequented study areas for soil biological indicator research, we conducted an independent co-occurrence analysis by including the first level of the IUCN habitat classification scheme: Forest, Grassland, Wetland, Desert, Savanna, Shrub land and Rocky (Jung et al., 2020).

Finally, to identify the biological indicators of greatest relevance and occurrence in the literature, we first developed a systematic review of the 20 articles that presented the highest citation, and then complemented it with bibliometric analysis using VOSviewer software (Sood et al., 2021; Van Eck & Waltman, 2010). This has the advantages of generating clear, readable groupings and showing the overlap of hard labels. Thus, for network mapping, which complements the information used to identify biological indicators, we considered keywords with a minimum of 50 co-occurrences.

3. Results

The bibliometric and qualitative analyses yielded a mapping of soil science advances in the development of biological indicators for monitoring soil quality. We found that the database analyzed yielded 2,320 papers published in the period 1972–2021. These documents included 1,946 scientific articles, 9 books, 86 book chapters, 133 conference papers, 2 data papers, 3 editorials, 1 erratum, 3 letters, 3 notes, 117 reviews, and 2 short surveys. This volume of publications showed a positive growth rate in the development of research aimed at explaining the role of the biological dimension of soil (Table 1, Fig. 2).

Table 1
Variation rate by decade, 1970–2021.

Publication Periods	Number of Publications	Growth rates
1970–1979	8	–
1980–1989	12	0.5
1990–1999	98	7.16
2000–2009	496	4.06
2010–2019	1456	1.92
2020–2021	354	–

Considering the spatial dimension, the volume of publications was distributed in various regions of the world, but was mainly concentrated in the United States (17.8%), China (12.2%), Brazil (8.3%), India (6.3%), and European Mediterranean countries, such as Spain, France, and Italy (14.2%). Publications from these countries exceed 50% of global scientific production. By contrast, the sum of the production of developing countries, such as Bolivia, Ecuador, Peru, Zimbabwe, Nigeria, and the Philippines, among others, does not exceed 1% of the contributions in the field (Fig. 3). Regarding the leadership of articles or authorship of correspondence, our results show a similar pattern, led by the United States, with 16.5% of the total number of principal authorships, followed by China (13.5%), Brazil (7.2%), and India (6.2%).

On the other hand, we found that 25% of the scientific production (577 papers) studied soil biological indicators in specific natural habitats (Fig. 4). These researches were most frequent in forests (62.91%), grasslands (18.37%), wetlands (11.09%); and at a lower mean in habitats such as desert (3.63%), savanna (2.07%), grazing lands (1.03%) and rocks (0.86%).

With respect to the scientific institutions that promote research aimed at the biological monitoring of soil quality (Table 2), our results show that research centers located in the United States (Cornell University, Michigan State University, Colorado State University, University of California), Holland (Wageningen University), Brazil (Sao Paulo), China (Chinese Academy of Sciences), and Belgium (Ghent University) have the most influence in this field of knowledge. However, the volume of publications involving institutions from two or more countries is lower. This indicates low international collaboration in the development of biological indicators of soil quality (Fig. 5), with its exceptions; for example, more than 50% of the research led by Belgian research institutions shows collaboration with institutions from other countries (Fig. 4).

Further, several journals and conferences have promoted and disseminated knowledge on biological indicators of soil quality (Fig. 6). The five journals with the highest number of articles disseminated were: Soil & Tillage Research (75), Ecological Indicators (73), Applied Soil Ecology (71), Science of the Total Environment (71), and Geoderma (52).

With respect to the identification of the biological indicators of soil quality with the greatest application or discussion in the scientific literature, our systematic review of the 20 papers with the highest citation impact (Table 3) showed that the three papers with the highest citation impact: Doran and Parkin (1994), Dick et al. (1996), and Doran and Zeiis (2000) correspond to chapters and articles resulting from the proceedings of the 1992 and 1998 American Society of Agronomy Symposium: i) Defining Soil Quality for a Sustainable Environment, and

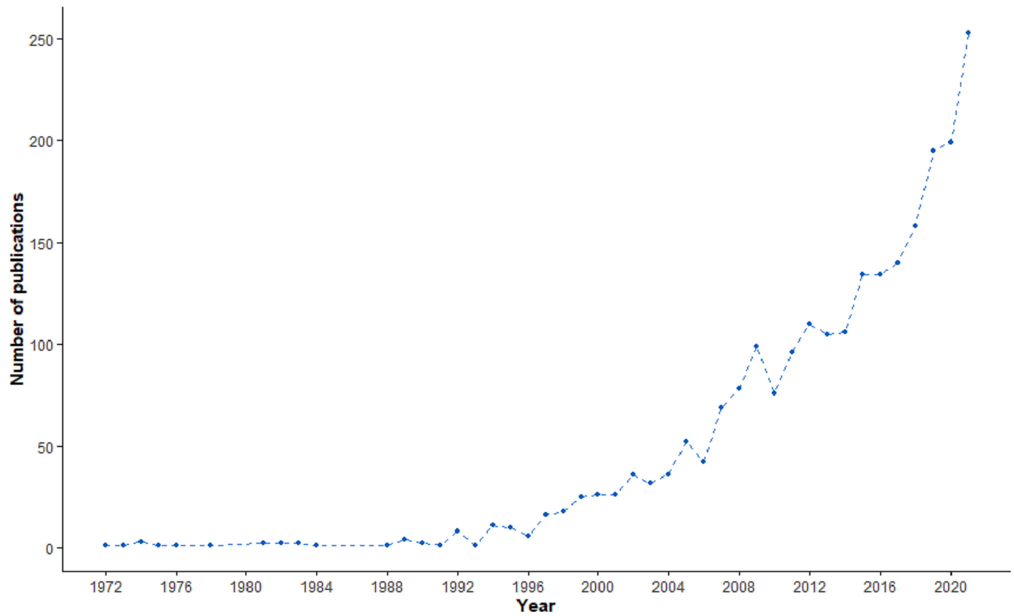

Fig. 2. Evolution of the number of scientific publications on biological indicators of soil quality, 1972–2021.

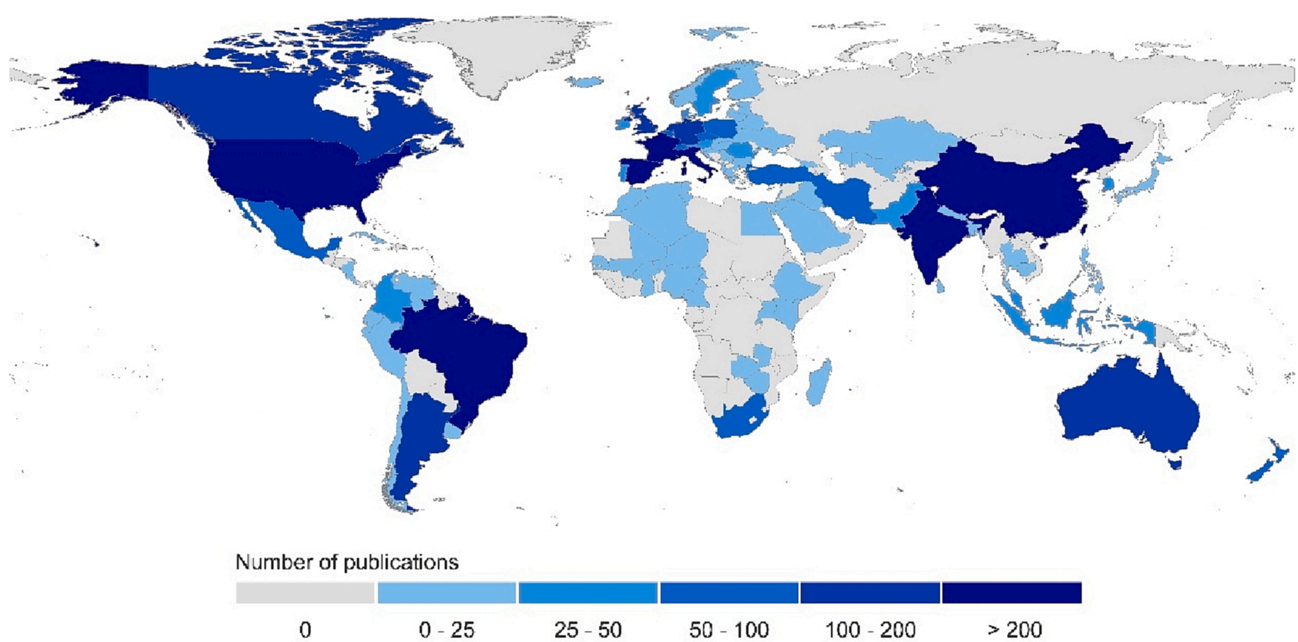

Fig. 3. Country scientific production considering biological indicators of soil quality.

ii) Soil Health: Managing the Biological Component of Soil Quality. Although these documents present some indicators derived from the interaction of soil organisms with mineral soil, they mainly provide the theoretical basis for establishing the biological parameters of soil quality.

These papers are complemented by other theoretical and methodological proposals aimed at quantifying biological indicators of soil quality with emphasis on food supply services; for example, Reeves (1997), Ghani et al. (2003), Haynes (2005), Fließbach et al. (2007) and Doran (2002). Other papers with a similar thread but that also make an effort to integrate the relationship of these biological indicators of soil quality with services that go beyond provisioning and include other ecosystem services are Barrios (2007) and Kibblewhite et al. (2008). Some documents prioritize the application of these indicators in the field of ecosystem conservation and restoration. For example, Schoenholtz et al. (2000), van Bruggen and Semenov (2000), Bastida et al. (2008), and Janvier et al. (2007).

Other contributions with important citations are some articles that have a bearing on the role of soil biological indicators for environmental contamination; for example, Marc et al. (1999), Driscoll et al. (2001), and Adriano et al. (2004). Our results yielded among the most cited articles aimed at the study of specific groups, such as invertebrates (Lavelle et al., 2006), carabid beetles (Kromp, 1999), and spiders (Marc et al., 1999). Our results also show some widely cited publications aimed at generating new alternative indicators to those applied in recent years, derived from methods oriented toward linking soil quality and biodiversity from a molecular approach (Janvier et al., 2007; Bastida et al., 2008).

Complementing these results, our bibliometric analysis yielded 25 biological indicators that were identified from the co-occurrence of the

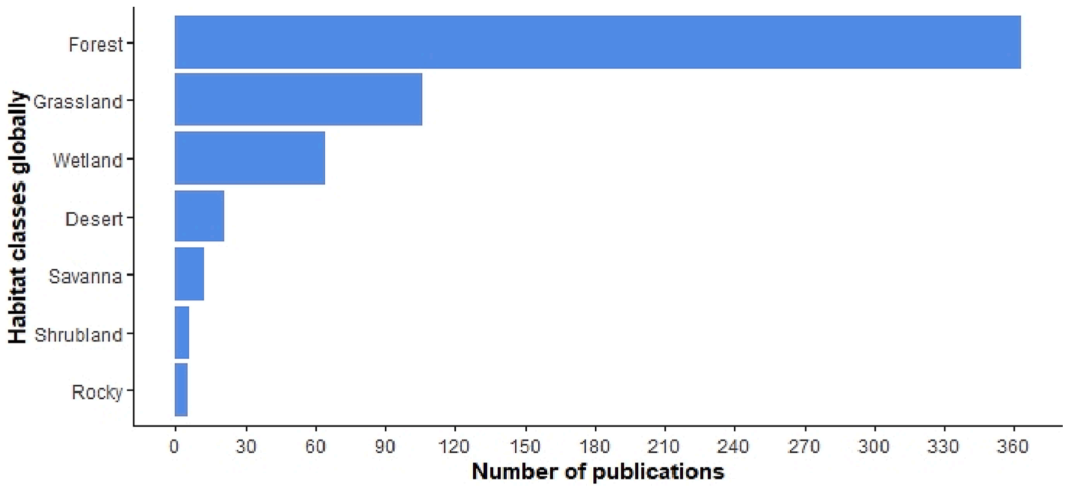

Fig. 4. Research of biological indicators of soil quality considering specific natural habitats.

Table 2
Most relevant affiliations in the publication related to biological indicators of soil quality.

Affiliation / Country	Articles
Wageningen University & Research (Netherlands)	40
Cornell University (USA)	35
Michigan State University (USA)	34
University of São Paulo (Brazil)	29
Chinese Academy of Sciences (China)	27
Colorado State University (USA)	27
University of California (USA)	21
Ghent University (Belgium)	19
University of Missouri (USA)	19
Manaaki Whenua – Landcare Research (New Zealand)	18
Agriculture and Agri-Food Canada (Canada)	17
Washington State University (USA)	15
Indian Agricultural Research Institute (India)	16
University of Florida (USA)	16
Punjab Agricultural University (India)	15
Beijing Normal University (China)	14
Southwest University (USA)	13
University of Buenos Aires (Argentina)	13
University of Nebraska	13
Aarhus University	12

keywords provided by the authors of all the papers related to biological indicators of soil quality analyzed (Figs. 7 and 8). Thus, microbial biomass (118 occurrences) is the most analyzed biological indicator, followed by enzymatic activity (90) and organic matter (78). Although our list includes well-known biological indicators, such as earthworms (26), nematodes (21), or bacteria (15), most of the indicators refer to organisms belonging to the soil microfauna (Fig. 7). This segment of the soil fauna, despite having great diversity and playing a fundamental role in soil nutrient cycles, is still lagging behind in terms of research, taxonomy, and conservation (Barrios, 2007; Darby & Neher, 2016).

Our mapping showed a clustered network of keyword co-occurrences over time in relation to biological indicators of soil quality (Fig. 9). Bibliometric analysis with VOSviewer software yielded 14,970 keywords. Of this, we identified 74, with a minimum of 50 occurrences. Thus, our network mapping showed four clusters of co-occurrences. The clusters were: i) studies of soil organic compounds, organic carbon, and soil quality (red): "soil quality," "organic carbon," "soil fertility," "biogeochemistry," "organic compounds," "soil degradation," and "soil conservation"; ii) studies of agriculture and soil biodiversity (blue): "agriculture," "biodiversity," "soil biota," "earthworm," and "land use change"; iii) soil contamination bioindicator studies (green): "bioindicator," "biomarkers," "heavy metal," "soil pollutants," and "bioaccumulation"; and, iv) studies of soil microorganisms and microbial activity (yellow): "enzymatic activity," "fungi," "bacteria," "microbial activity," and "soil microorganism" (Fig. 9).

4. Discussion

Our results showed a mapping of the scientific contributions of the last 50 years directed to the development of biological indicators of soil quality versus physical and chemical components that showed wide development since the beginning of the 20th century (Bastida et al., 2008; Hartemink, 2016). Thus, our data show a significant increase in scientific production directed to the development of these biological indicators of soil quality in the last five decades. Our map highlights the high importance given by the scientific community to the monitoring of soil health to ensure the maintenance of the different services offered by ecosystems and to consider the effects of soil management considering the great challenges of sustainability.

Therefore, the development, application, and monitoring of soil biological indicators is possibly the most transformative aspect in the framework of soil quality or health, since their variations give greater information on soil function compared to the physical or chemical information of the soil (2015). In this sense, such monitoring requires a global approach that integrates both regional and national scales, as well as land use and land cover prioritizing agricultural landscapes and natural habitats (Figs. 3, 4, 5). This possibly represents the most important contribution and challenge for soil sciences in a global framework focused on the transition to sustainability.

Our results show regional and national soil quality monitoring efforts that integrate the biological dimension. The most significant regional example is the European community (Fig. 3), and its efforts aimed at understanding, developing, applying, and monitoring soil biodiversity, its functions, its contribution to ecosystem services, and its relevance for the sustainability of human society (Turbé et al., 2010). However, despite being pioneers in a regional proposal, no national monitoring networks that fully include biodiversity are reported, except in the Netherlands, where the soil monitoring policy applied during the last 20 years is related to the promotion of research in the field of science (Table 2). Thus, Wageningen University & Research (Netherlands) occupies the first institutional place in the development of biological indicators that integrate both species diversity and soil biological functioning (Rutgers et al., 2008; Rutger et al., 2009). Another example provided is the United States, which, through the Department of Agriculture, also proposes and incorporates biological indicators of soil quality aimed at creating favorable habitat for the soil-food (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/biology/);

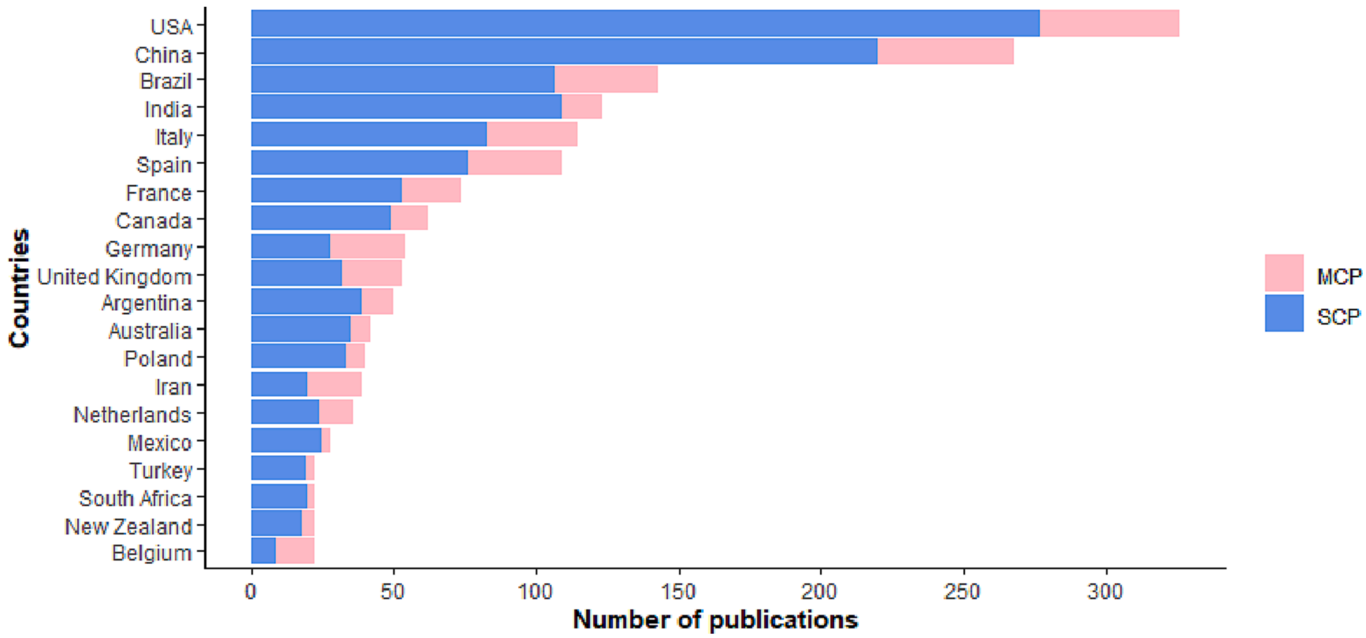

Fig. 5. Corresponding author's country of the top countries in the publications about biological indicators of soil quality (MCP = multiple country publications; SCP = single country publications).

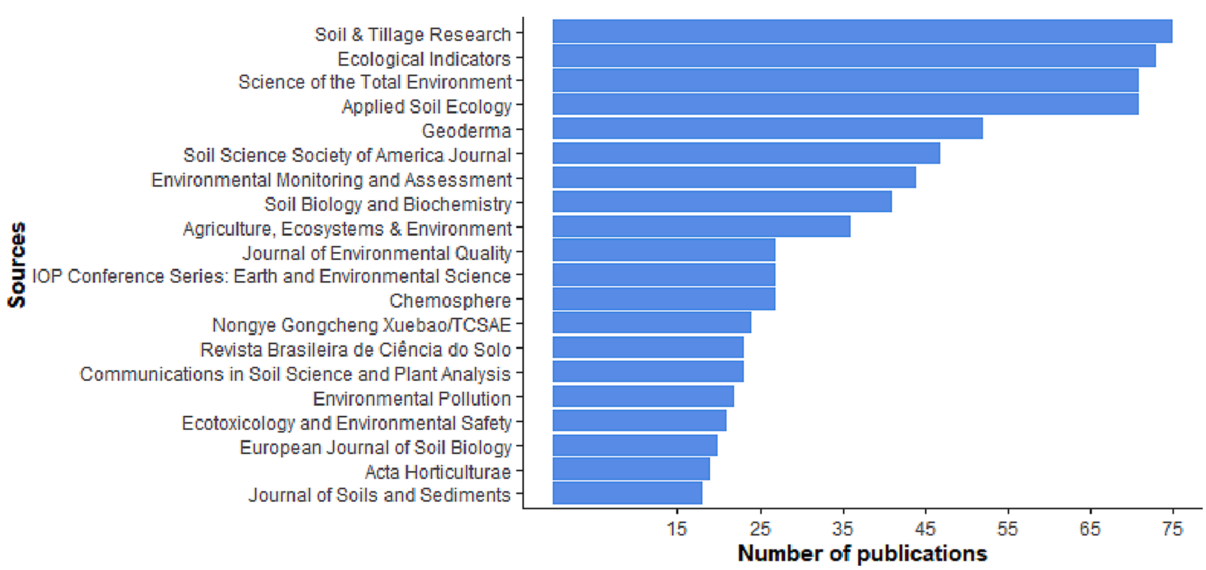

Fig. 6. Most relevant sources in publications about biological indicators of soil quality.

generating methodological tools aimed at sustainability in food supply but also at conservation and environmental management.

However, we observed well-established and relatively recent national experiences in monitoring biological indicators of soil quality. Our results suggest that this dynamic could be related to the development of the green revolution in countries with high agricultural production (Fig. 3). This process could be one of the drivers of concern for soil conservation and therefore the development of research in the specific field. For example, through the Natural Resources Conservation Service and the Department of Agriculture, the United States incorporated biological indicators of soil quality aimed at maintaining soil health, primarily for agricultural production; later, new ecosystem services sustained in ecosystem functions were integrated (Ditzler & Tugel, 2002). Other examples of the effect of the green revolution on soil resources, as well as efforts to integrate biological indicators and quality monitoring, are found in India (Singh, 2000), China (Pingali & Rosegrant, 1994), and the United States, among others.

Another element to consider is the need to boost the application and periodic monitoring of biological indicators of soil quality in different habitat types (Fig. 4). Our results show how research interest in the last decades was mainly focused on environmental variations and agricultural management. However, efforts in natural habitats are relatively more recent and focused on forests and their management (Aspetti et al., 2010, Zhao et al., 2013); while the study of soil biological indicators in other habitats remain a research challenge, their future results will contribute to improve both management strategies as well as restoration needs of these habitats.

With respect to the evolution of scientific literature related to biological indicators of soil quality, this study identified three periods of production: i) between 1970 and 1990, a nascent scientific production was observed with a stable annual production pattern; ii) between 1991 and 2010, the production pattern was exponential, adjusting to a

Table 3
Articles under systematic review showing the highest citation and complementary to bibliometric analysis.

Author/Year/ Total Citations	Total Citations	Propose/Indicators
Doran and Perkin (1994)	1498	*Approaches to defining and assessing soil quality:* Microbial biomass C and N Potentially mineralizable N Soil respiration Biomass C/total org. C ratio Respiration/ biomass ratio
Dick et al. (1997)	958	*Soil enzyme activities/Biodiversity measurements as process-level biological indicators and functional diversity of communities:* Enzyme
Doran and Zeiss (2000)	940	*Usefulness of soil organisms as indicators of soil quality/ Indicators for measuring sustainable production strategies:* Direction/change in organic matter levels over time Soil water storage Soil surface properties Soil physical condition/compaction Nitrate levels in soil and water Pesticide quantity and toxicity Input/output ratios of costs, energy, and renewable/non-renewable resources. renewable/non-renewable resources Leaching losses/soil acidification Soil and water nitrate levels
Lavelle et al. (2006)	879	*Linkages between invertebrates and other soil organisms and their importance for continued soil functioning:* Soil invertebrates, Ecosystem engineers, Self-organized systems, Bio-indicators: Invertebrates
Reeves, (1997)	860	*Comparative long-term crop and tillage analysis and soil management recommendations/ Long-term experiments, Conservation tillage, Soil quality:* Soil organic matter
Driscoll et al. (2001)	798	*Ecological effects of acid deposition and the relationship between emission reductions and ecosystem recovery:* Acidification
Ghani et al. (2003)	751	*Changes in biological and biochemical properties of soil caused by ecosystem changes:* Hot water-extractable C (HWC), Water-soluble C (WSC) , hot-water extractable total carbohydrates, Microbial biomass-C and N and mineralizable N.
Haynes, (2005)	667	*Non-living labile organic matter fractions and their value as indicators of agricultural soil quality:*Organic matter: light fraction (LF) sand size fraction (SSF) .
Kromp, (1999)	623	*Carabids in sustainable agroecosystems and the importance of carabids in natural pest control:* Carabids
Adriano et al. (2004)	561	*Key biogeochemical processes regulating the bioavailability of metals in soils and natural remediation as a cleanup tool:* Microbial activity of the soil–plant system the influence of trace elements on microbial population and functions and the influence and the role of microbes on the transformation of elements
Barrios, (2007)	483	*Direct effects and indirect impacts of soil biota on ecosystem services and land productivity in agricultural landscapes:* Decomposers, elemental transformers, soil ecosystem engineers, soil-borne pest and diseases, and micro regulators
Fließbach et al. (2007)	481	*Long-term changes in soil organic matter and pH in organic and conventional cropping systems and normal and reduced fertilization intensity:*Dehydrogenase activity, basal soil respiration and metabolic CO2 (qCO2), carbon (Cmic) and nitrogen (Nmic) quotient of soil microbial biomass estimated by chloroform fumigation extraction (CFE) , the ratio of Cmic to Nmic as indicators of community structure and the ratio of Cmic to Corg as an indicator of soil organic matter quality. Community structure and the ratio of Cmic and Corg as an indicator of soil organic matter quality.
Schoenholtz et al. (2000)	463	*Use of soil chemical and physical properties as determinants of forest soil quality:*Organic C, mineralizable N, mineralizable N (anaerobic incubation) , microbial decomposition of soil organic matter
Carter, (2002)	462	*Review the context and approach to soil quality, with specific emphasis on soil organic matter:* Macroorganic matter C and N Light fraction C Microbial biomass C Mineralizable C and N
Kibblewhite et al. (2008)	454	*Soil health in agricultural systems and ecosystem services:* Decomposers, nutrient transformers, ecosystem engineers, biocontrollers
Bastida et al. (2008)	421	*Classical biological parameters that can be used to assess soil quality and the information that can be obtained with new indicators and tools:* pH, organic matter, microbes' biomass C, respiration or enzymatic activities. It also proposes indicators derived from: infrared spectroscopy microbial diversity and gene abundance linking diversity and function from a molecular point of view: stable isotopes probing binding DNA or RNA metaproteomics: high specificity indicators
Anderson, (2005)	402	*Organic indicators of water and soil quality: Fecal Indicator Bacteria:* Fecal Indicator Bacteria
Doran, (2002)	394	*Soil health and global sustainability and proposed indicators of soil quality and health:* Soil organic matter change with time, relative to local potential Soil depth of topsoil and rooting relative to local potential Soil protective cover (%), effective continuous or stratifiedLeachable salts (NO_3) at planting and post-harvest as indexed by soil electrical conductivity
Marc et al. (1999)	383	*Biological control based on spiders and their application as bioindicators, the role of spiders as indicators of heavy metal pollution (atmospheric or soil pollution):* Ground spiders and spiders living in herbaceous vegetation Spider communities in shrubs and trees, aerial dispersal
Janvier et al. (2007)	371	*Cultural practices used to control soil-borne diseases and their limitations, soil parameters to study soil suppression, and potential indicators of soil health*: Quantitative microbial parameters Diversity and structure of microbial communities
Doran and Parkin, (1997)	366	*Indicators of soil quality and health with a minimum data set:* Texture, depth of soil, infiltration and bulk density, soil organic matter, electrical conductivity, extractable N, P and K, microbial biomass C and N, potential

(continued on next page)

Table 3 (*continued*)

Author/Year/ Total Citations	Total Citations	Propose/Indicators
		mineralizable N, Soil respiration, water content and temperature.
van Bruggen and Semenov, (2000)	363	*Relationship between soil health and soil ecosystem stability. Traditional and alternative approaches to the search for soil health indicators:*Stress factors (such as drying and re-wetting, mechanical disturbance, excess nutrients or excess nutrients or contaminants, or flooding with a microorganism) to soil samples that differ in handling history, and then management, and then monitor the extent of changes in microbial changes in microbial populations and the time required to return to dynamic to return to the dynamic steady-state conditions as observed prior to the application of stress.

growing interest; and iii) between 2011 and 2021, in which the largest number of articles was published, but with a lower growth rate than in the previous period (Table 1, Fig. 2).

The documents developed between 1970 and 1990, unlike the later periods, showed a low citation impact. This result would respond to the absence of an integrative theoretical basis for the biological indicators of soil quality. Considering our data, this phase of production showed isolated research initiatives aimed at using organisms as bioindicators of contamination. For example, Noshkin (1972), in studying the dissemination of plutonium and other transuranics in the aquatic environment, proposed the use of marine vertebrates and invertebrates as indicators of pollution; the work of Oyama et al. (1976) in the Arctic aimed at simulating anoxic environments to understand the dynamics of soil aerobic organisms; and Masson et al. (1989) quantified technetium emissions resulting from microbiological activity. However, in these years, systemic works were also developed that were not included in the database used for this review and did not enter the basis of our bibliometric analysis, given the concepts and approaches of that decade.

For example, from an ecosystem approach, Swift and Anderson (1979) presented a synthesis of scientific advances regarding the dynamics of decomposition. This paper was not indexed in the database used for this review and was not included based on criteria of our bibliometric analysis; however, it showed 5,687 citations in Google Scholar. Although its focus does not prioritize the role of soil organisms and their functions as indicators of soil quality, it is an important milestone in the development of soil biological indicators. Given the taxonomic diversity of soil (Pace, 1996; Sanderman & Amundson, 2014), the most cited contribution of this work is the description of the food web of the decomposer community as a fluid and interactive structure with individual species operating at several levels that could be distinguished as tropically different. This network is presented in a graphical and simplified form, considering the size of organisms in decomposer food webs by body width. This classification proposal was, in some cases, adapted, and, in other cases, improved by future research (Barrios, 2007; Decaëns, 2010; Guilland et al., 2018; Nielsen, 2019).

The second important period of production showed the highest growth rate (Table 1), coinciding with the publication of some of the works with the greatest impact of our research (Dick et al., 1996; Doran & Parkin, 1994; Doran & Zeiis, 2000). This scenario takes place in an environment of scarce systematized information (Doran & Parkin, 1994) and the manifest need to generate tools aimed at leading national and global programs for monitoring and evaluating soil quality to guarantee food and environmental services (Smith et al., 1994), a challenge that, as we will discuss below, is still timely.

The significant contributions in terms of citation impact of this period are: first, the recognition of the need to integrate physical, chemical, and biological indicators (Arshad & Coen, 1992; Doran & Parkin, 1994; Larson & Pierce, 1991); and second, the development of biological indicators that integrate the relationships between soil organisms and microorganisms with ecosystem functions (e.g., biogeochemical cycles of C and N).

Thus, until the end of the 20th century, research on soil organic carbon as a biological indicator of quality received a great deal of attention, being the most studied attribute in the long term, and its

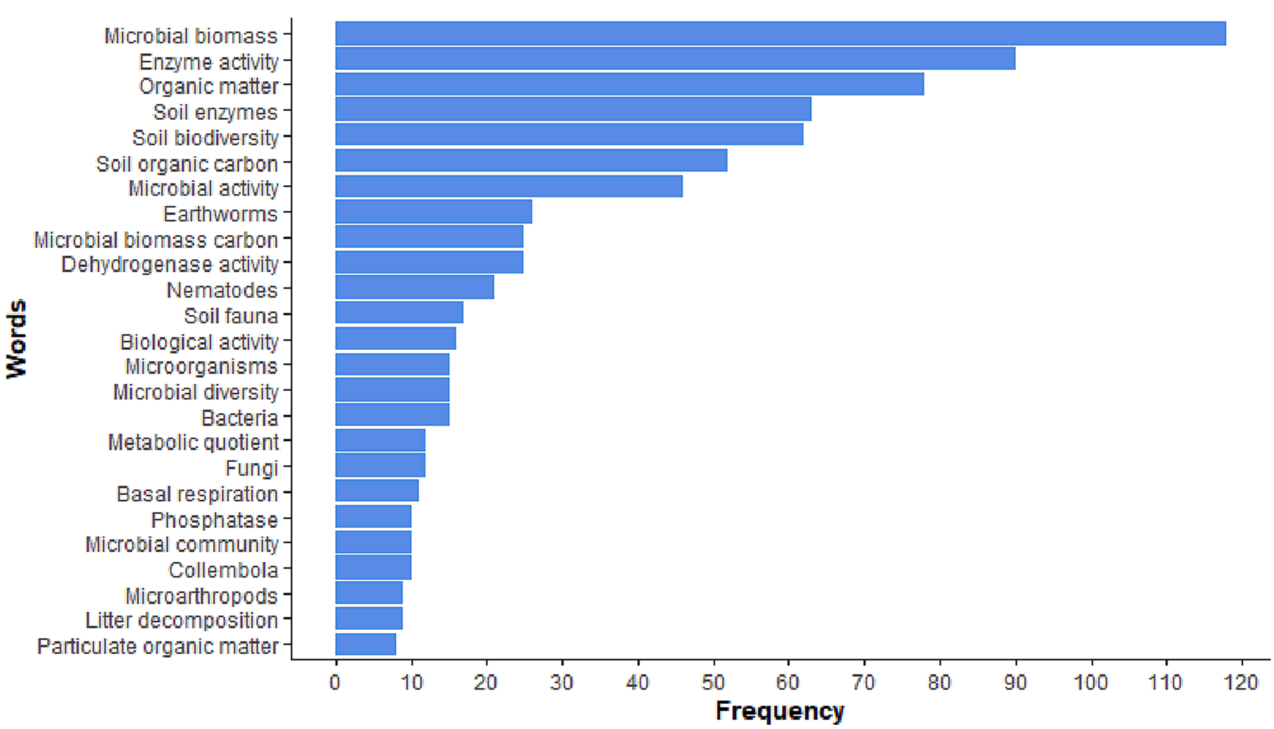

Fig. 7. Frequency of occurrences of biological soil indicators.

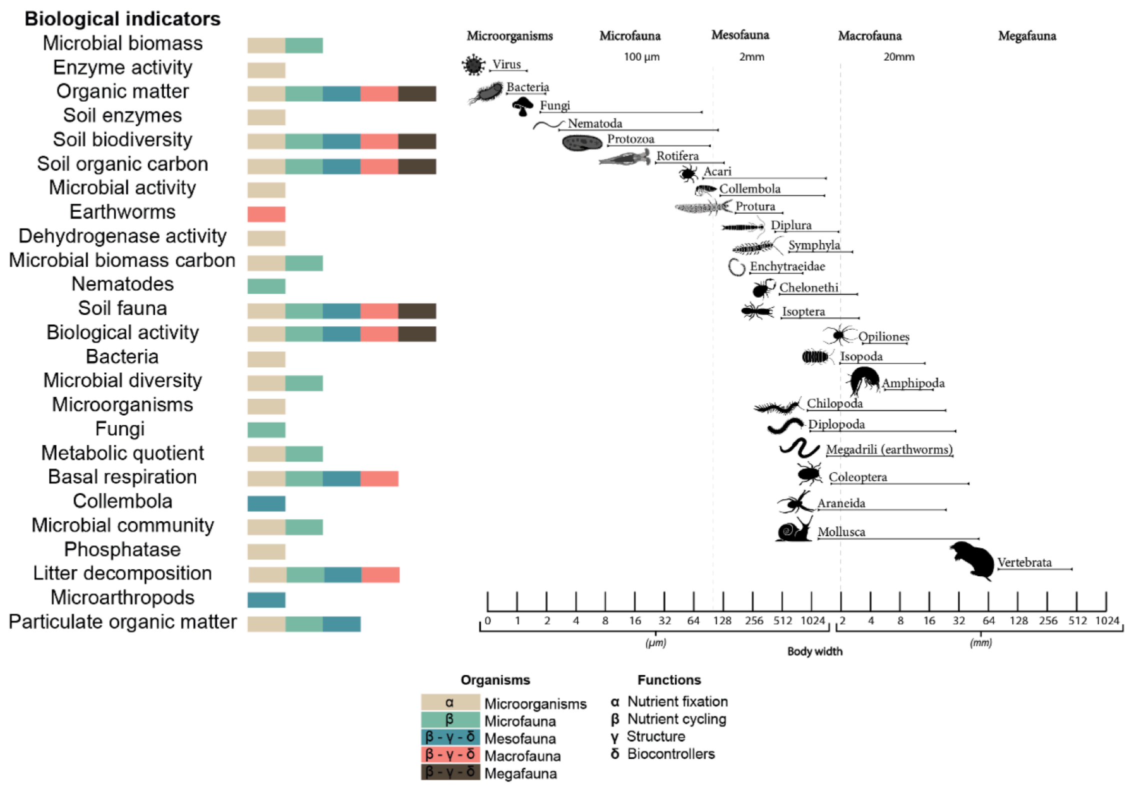

Fig. 8. The main biological indicators of soil quality identified in this review, and their relationship with organisms and functions (Barrios, 2007; Guilland et al., 2018; Nielsen, 2019; Swift et al., 1979).

constant application within the framework of agronomic sustainability and the development of agroecological techniques, such as crop rotation or conservation tillage (Larson & Pierce, 1991; Reeves, 1997). This approach was strengthened in the first decade of the 21st century, reaching a consistent level of detail with respect to this biological indicator and ecosystem services (Pulleman et al., 2012). Thus, theoretical and methodological proposals aimed at quantifying biological indicators of soil quality with emphasis on food supply services are explained (Doran, 2002; Ghani et al., 2003; Haynes, 2005; Fließbach et al., 2007; Reeves, 1997).

However, at the end of the first decade of the century, the wide range of processes that take place in the soil made it necessary to consider soil biodiversity beyond the trophic chain, giving way to functional groups, which are fewer in number compared to trophic groups (Kibblewhite et al., 2008; Turbé et al., 2010). To this end, classification proposals were presented, such as those by Lavelle (1997), Swift et al., 2004, Barrios (2007), and Kibblewhite et al. (2008), who related the maintenance of soil ecosystem services with the maintenance of ecosystem functions (for example, carbon transformations, nutrient cycles, the maintenance of soil structure, and the regulation of pests and diseases) and the functional assemblages of biological communities (decomposers, nutrient transformers, ecosystem engineers, and biocontrollers).

This approach would maintain its continuity in the final period of our analysis (2010–2021), with theoretical and methodological development aimed at filling information gaps, as well as the implementation of regional and national monitoring networks (USDA, 2015; Rutgers et al., 2008; Turbé et al., 2010). Thus, the conceptual and methodological evolution of these 50 years shows that soil health guarantees the maintenance of the different services offered by ecosystems, but its management also has a positive impact on the major challenges of sustainability. For this, its development, application, and monitoring require a global approach that integrates regional and national scales and that its viculent character is part of the design of a sustainable productive public policy. This possibly represents the most important contribution and challenge for soil sciences in the global framework of the transition to sustainability.

Overall, our analysis yielded 25 soil quality criteria/indicators with increased application over the last 50 years (Figs. 7 and 8). Each relates to both organisms and specific functions in the ecosystem. Thus, this proposal of indicators could be adjusted according to the specific monitoring objective; integrating a systematic perspective for decision making aimed at compensating the selection of one or several indicators from a multi-attribute approach (Veisi et al., 2016).

Then, it is recommended that the selection of soil quality bioindicators integrate different evaluation methods; for example, the analytical hierarchical process (AHP), a multi-objective decision methodology which could consider our network of four occurrence groupings (Fig. 9) to generate a weighted ranking of the exposed results considering the specific requirement of the monitoring strategy (Saaty, 2008; Liang et al., 2017). Future association of this type of analysis in new research would improve decisions when choosing soil quality indicators to be monitored.

Our results show that the dynamics of organic matter and its associated indicators undoubtedly represent the most important soil biological indicator. This notion was observed in our results; for example, decomposition of organic matter, soil organic carbon, soil biodiversity and fauna, biological activity, and basal respiration are shown as indicators with high applicability but also have the ability to integrate all organisms and their functions. This classification is close to the framework of the United States Department of Agriculture, which proposes and incorporates organic matter (soil color)—potential mineralizable N, activated carbon, respiration, microbial analysis, earthworms, and fungi (USDA, 2015)—as a base of biological indicators for soil monitoring.

In our results, we also observed the application of specific biological indicators to a taxonomic group, such as earthworms, nematodes, or springtails; these are also associated with soil macrofauna and microfauna and the functions they fulfill in the ecosystem. It is evident and we

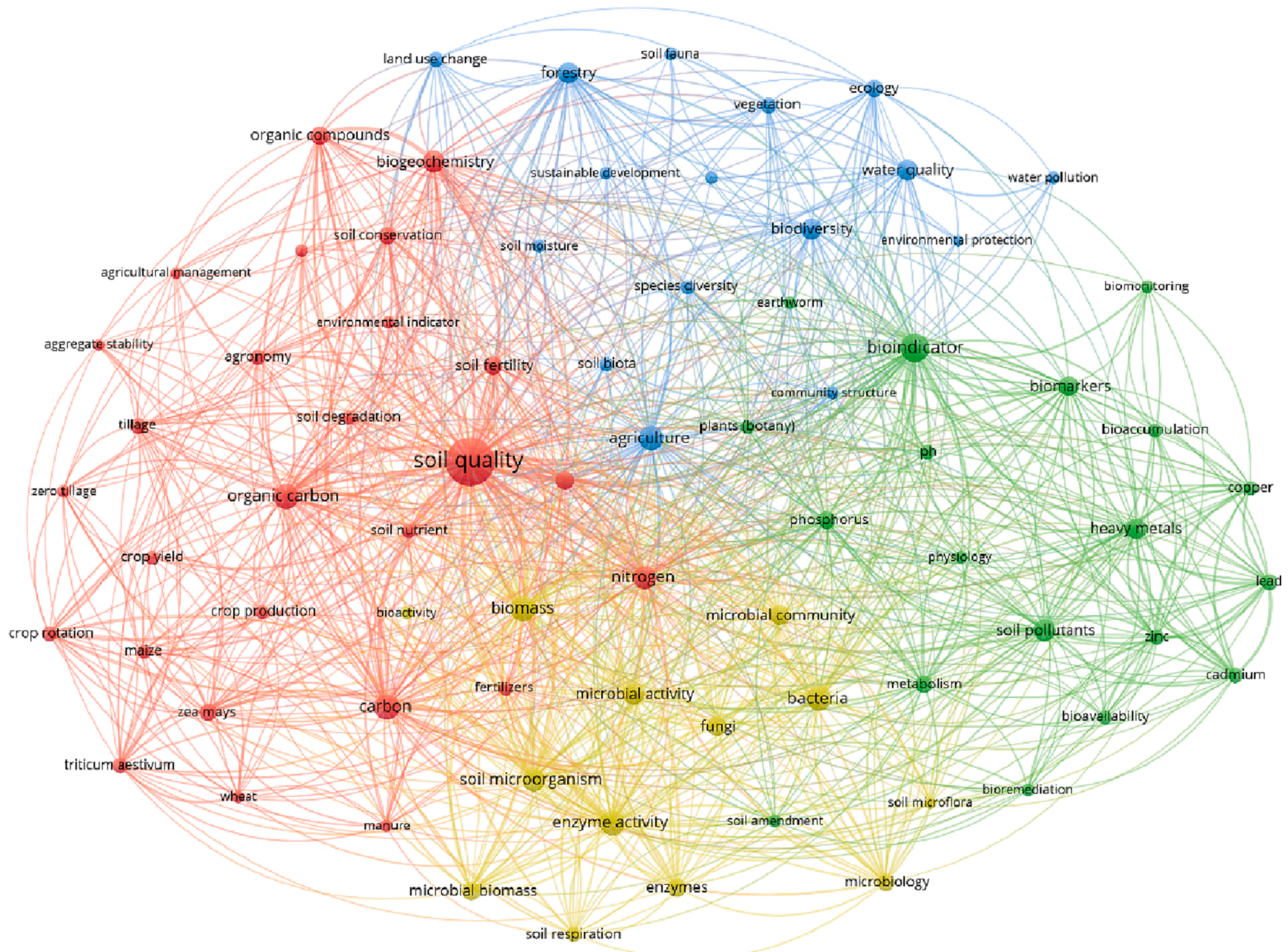

Fig. 9. Network visualization map of keyword co-occurrence in soil quality biological indicators research. The size of the circle represents the frequency of occurrence of the keyword, the lines between each circular node represent the co-occurrence relationship, and the nodes with the same color represent the same attribute clustering.

agree with Barrios' (2007) and Darby and Nehher's (2016) argument that the application of this type of indicator, despite fulfilling a fundamental role in soil nutrient cycles, is lagging behind in terms of research, taxonomy, and conservation (Barrios, 2007; Darby & Neher, 2016). Further, several studies have suggested that some soil quality indicators should be derived from soil microbial responses to different disturbance processes (Van Bruggen & Semenov, 2000; Stone et al., 2016). Our results visualize this trend and agree with Stone et al. (2016), who, by applying a logical filter based on published data and expert surveys, present several biological indicators for soil monitoring. Among these, four biodiversity indicators (three microbial and one mesofaunal) by various measurement methods, and three ecological function indicators (multiple enzyme assay, multiple substrate-induced respiration profiles, and functional genes by molecular biological means) are observed. It should be noted that seven of the top 10 indicators reported by these authors use molecular methods for their action.

5. Conclusion

Scientific advances aimed at the generation of biological indicators of soil quality have yielded several proposals for criteria and indicators, initially aimed at monitoring biodiversity and later on the ecosystem functions that depend on this biodiversity. In much of the developed world and also in emerging regions, the development, application, and monitoring of these parameters show two clearly differentiated approaches: on the one hand, the development, application, and monitoring of powerful initiatives at the regional scale as a response aimed at a policy of conservation, management, and restoration of soil, in the medium and long term, as a vital and non-renewable resource; and, on the other hand, the application and monitoring of indicators accessible to many users and aimed at linking science to practice, ensuring the productive activities that sustain these soils.

We surmise that these two approaches can be integrated into a global strategy for the conservation, restoration, and management of soil resources for a sustainable world. The next few decades will show the results of the monitoring strategies applied in different world regions and habitats, providing inputs for land management strategies. Furthermore, this information will generate new challenges for soil monitoring in the transition to global sustainability.

Finally, the 25 biological indicators presented in this review are a basis for the development of land use management and soil monitoring policies in regions where the scientific gap and, therefore, the development of soil management policies remains limited but emergently necessary. In these regions, the development of national and international policies on soil quality requires data on the current situation to create a range of performance that can be managed through new policies that must necessarily be monitored from the indicators presented here.

Thus, the implementation of soil quality monitoring strategies represents a major challenge for the global conservation of soil resources, the transition to a sustainable agricultural production model, the management of ecosystem services, and adaptation to climate change. To this end, both international scientific collaboration and the development of policies aimed at soil management, restoration, and use require alliances between leading countries, institutions, and countries whose scientific, political, productive, and technological developments are emerging. Notably, these countries represent regions where the phenomena of agricultural expansion, urban growth, forest loss, and degradation have been concentrated in recent decades.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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