Collembola eco-morphological indices (EMI) and Soil Biological Quality Index (QBS-c): a review and practical guidelines for soil health assessment

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Abstract

Soil health assessments remain dominated by physicochemical indicators, largely due to limited functional understanding and a lack of practical tools for quantifying soil biodiversity in applied contexts. However, many soil functions are fundamentally driven by biotic components, highlighting the need for robust biological indicators. The Soil Biological Quality indices, QBS-ar and QBS-c (Parisi, 2001; Parisi et al., 2005), offer simple, direct approaches. While QBS-ar considers the entire soil (micro)arthropod community, QBS-c focuses on Collembola, assigning taxa eco-morphological index (EMI) scores based on their adaptation to soil. We reviewed 24 studies using Collembola-based QBS-c and EMI methods to evaluate their development and application over the past two decades. Our synthesis reveals substantial inconsistency in EMI assignment, with the widely cited framework of Vandewalle et al. (2010) both expanding EMI use beyond Italy and modifying Parisi’s original trait definitions and scoring schemes. We systematically compared trait selection, scoring approaches, and methods for aggregating species-level EMIs into community-level indices. Principal component analysis of Parisi’s genus–trait matrix showed strong correlations among antenna, furca, and leg traits, and among ommatidia, pigmentation, and cuticle traits, while body size was largely independent. To improve applicability in soil monitoring, we propose a standardized QBS-c protocol featuring: (i) a minimal trait set (body size, pigmentation, furca), (ii) EMI scoring schemes aligned with the original euedaphic gradient, and (iii) a flexible community-weighting framework incorporating both presence–absence and abundance data. These recommendations aim to enhance comparability across studies and usability for non-specialists, facilitating broader integration into soil monitoring programs.

Key words: QBS-ar; soil biodiversity; mesofauna; springtail; morphological trait; soil monitoring

1. Introduction

1.1 Soil quality assessment

A healthy soil is a vital living system that supports plants, animals and humans (Pankhurst et al., 1997). Key ecosystem functions, including organic matter decomposition, nutrient cycling and plant productivity, are largely mediated by the soil biota, which therefore play a central role for a healthy soil. Although often used interchangeably, ‘soil health’ and 'soil quality’ refer to distinct but related concepts. The term ‘soil health’ emphasises the importance of soil in meeting societal needs, such as food production, and is linked to environmental sustainability, which encompasses economic, social and environmental issues (Bünemann et al., 2018). In contrast, ‘soil quality’ refers to the extent to which soil properties fulfil expected functions for plants, animals and human well-being (Schjønning et al., 2004). To assess the ability of the soil to maintain its functions, soil quality is represented by a number of indicators. In addition to traditional agronomic parameters, it includes chemical, physical and biological properties of soils. The present study focuses on bioindicators of soil quality using functional groups of soil microarthropods, in particular Collembola (springtails), which exhibit a wide range of eco-morphological traits that indicate animal adaptations to soil microhabitats of different layers.

1.2 Soil biotic indicators

Biodiversity is increasingly recognised as a key component of soil health assessment. The European Commission has highlighted the importance of considering soil biodiversity as an indicator in the Soil Monitoring and Resilience Directive (Soil Monitoring Law) (Directive (EU) 2025/2360), which has been recently adopted by the

European Parliament and the Council (European Union, 2025; European Commission, 2025). It will serve as the first EU-wide soil protection legislation (i.e., the Soil Health Law; European Commission, 2023; Köninger et al., 2022). However, the assessment of soil health is still dominated by chemical-physical methods, due to difficulties in the taxonomic identification of soil biota, limited knowledge on functional traits affecting ecosystem functioning, and the lack of effective and standardised methods to collect or quantify responses and effects of soil biota (Lehmann, 2020). Even though soil organisms have been used to assess soil quality in managed ecosystems for about 60 years (Vandewalle et al., 2010), most biodiversity assessments and conservation measures at the legislation level still neglect soil bioindicators (Zeiss et al., 2022) and monitoring soil animal compartments are still optional in the European Soil Monitoring program (European Union, 2025).

1.3 Soil microarthropod indicator – QBS-ar

In addition to microbes, nematodes and earthworms microarthropods are widely recognised as sensitive and reliable bioindicators for assessing of soil quality and of the impact of anthropogenic disturbances, such as agricultural management, pollution, urbanisation and land-use change, (Parisi and Menta, 2008; Reis et al., 2016; Joimel et al., 2017; D’Alessandro et al., 2024; Coletta et al., 2025; Perinelli et al., 2025). They contribute to key soil functions and associated ecosystem processes (Parisi et al., 2005; Yin et al., 2020; Ashwood et al., 2023). However, the use of soil animals as bioindicators is hampered by the detailed taxonomic expertise required when collecting data and the limited knowledge of the roles played by different species in the ecosystem when inferring the consequence of changes. To overcome this difficulty, a simplified index based on the concept of functional groups using basic morphological traits of taxa has been introduced: the “Qualità Biologica del Suolo” (QBS), namely the biological quality of soil (Parisi, 2001). This measure calculates the eco-morphological index (EMI) of soil arthropod taxonomic groups (QBS-ar), which reflect their distribution and microhabitat preference in the soil profile (Gardi et al., 2002, Menta et al., 2018). When the QBS-ar was first introduced by Parisi (2001) in Italy, it was applied to soils from a wide range of ecosystems, including forests, pastures and different types of agricultural systems, distributed across lowlands, hills and mountainous areas. The QBS-ar pioneered the mapping of soil quality through quantitative measures of morphological traits of soil animals (Parisi et al., 2005). Recently, it has been included among the selectable soil health biological descriptors included in the Soil Monitoring Law (European Union, 2025).

The trait-based QBS-ar index does not require the classification of soil animals to species level, but rather the assignment of EMI values to different groups at a coarse taxonomic level using simple morphological traits. The rationale for biological quantification of soil quality is based on the morphological adaptation of different microarthropod taxa to microhabitats (Parisi, 1974). These morphological traits reflect the performance of organisms in the soil environment and their contribution to soil functions. It is assumed that the better the soil quality, the higher the number of microarthropod taxa that are well adapted to the soil (Parisi, 2001, Parisi et al., 2005; Menta et al., 2008). The QBS-ar index is calculated by summing the EMI values of different arthropod taxonomic groups present in soil samples according to their “biological forms” (BFs; Sacchi and Testard, 1971), which are assumed to be related to their functions in soil. The QBS-ar index therefore overcomes the challenges of species identification, which is time-consuming and requires specific taxonomic training (Parisi et al., 2005).

The main phases for obtaining QBS values of soil samples are (1) soil sampling (0–10 cm depth), (2) extraction of microarthropods, (3) preservation of collected specimens, (4) determination of BFs and assignment of EMI values to individuals and (5) calculation of the QBS-ar index for each soil sample (Parisi, 2001; Parisi et al., 2005). The operational phases for soil sampling and arthropod extraction are described in detail in Parisi (2001) and Parisi et al. (2005). Below we briefly outline the procedures for determining BF, assigning EMI and calculating the QBS-ar (Parisi, 2001; Parisi et al., 2005), and then describe in more detail the Collembola-specific QBS (QBS-c; Parisi, 2001).

1.4 Eco-morphological index – EMI

To calculate QBS-ar, it is first necessary to identify microarthropod BFs by their basic morphology at a coarse taxonomic level (e.g. classes or orders), which implicitly reflects their ecological strategies; (Sacchi and Testard, 1971) for all specimens present in a soil sample. A specific EMI value is then assigned to each BF (Parisi, 2001 and Parisi et al., 2005). The QBS-ar of a soil sample is then calculated from the sum of the EMIs of all BFs. This procedure only involves the morphological classification of animals into coarse taxonomic groups and does not require quantification or estimation of abundance or density, but only the incidence (presence/absence) data of BFs with their specific EMIs, making it a quick and simple index for assessing soil quality.

The key to QBS-ar is the EMI assignment for each BF. The EMI can range from 1 to 20 (Parisi, 1974). Euedaphic forms generally receive an EMI of 20, indicating a high degree of adaptation to soil, while epigeic (epedaphic) forms receive an EMI of 1, indicating poor adaptation to soil. Hemiedaphic forms are assigned an EMI value proportional to their degree of soil specialisation (Parisi, 2001; Parisi et al., 2005). While most arthropod groups have specific single EMI values, others exhibit a range of EMI values where there are a large number of species that differ in microhabitat adaptations along the soil profile. For example, Collembola, which are very abundant and diverse among soil microarthropods, may exhibit different levels of adaptation to different soil layers (Parisi, 2001; Menta, 2008). In the following sections, we specifically address the promises and problems of using Collembola-related indices.

1.5 Collembola EMIs in QBS-ar

In the QBS-ar calculation there are seven EMI values for Collembola BFs: EMI = 1, epigeic form associated with arboreal vegetation; EMI = 2, epigeic form not associated with arboreal vegetation; EMI = 4, small epigeic form not associated with arboreal vegetation; EMI = 6, hemiedaphic form with well developed visual apparatus; EMI = 8, hemiedaphic; EMI = 10, euedaphic; EMI = 20, euedaphic completely unpigmented (Parisi et al., 2005). A single EMI value is assigned to each Collembola specimen following an overall morphological assessment. It does not consider each individual morphological trait separately, but the “life-form” together, which includes body size, pigmentation, hairs, ommatidia, post-antennal organ (PAO), appendages and furca development, with three possible options, epigeic (or epedaphic), hemiedaphic and euedaphic (Parisi, 2001; Parisi et al., 2005; Menta 2008). Moreover, for the calculation of QBS-ar, only one EMI value can be assigned to all Collembola individuals as a group, regardless of what other species or morphology may be present in the same soil sample. If more than one morpho-type occurs in Collembola, e.g. one with an EMI of 2 (epigeic) and one of 10 (euedaphic), the highest value (i.e., EMI = 10) is used for determining the EMI value for the whole Collembola group (Gardi et al., 2002; Parisi et al., 2005; Menta, 2008). Although this reduction is justified by the objective of QBS-ar, which is to identify the most soil-adapted ‘form’ (i.e., morpho-type) for each BF, it does not capture the diversity of strategies through which different Collembola species adapt across soil layers. It also misses the proportional distribution of Collembola individuals with different densities along the soil profile. The single value assigned to Collembola is therefore usually that of a high EMI, even if only a single euedaphic individual is stochastically present and occasionally found in a given sample. It is evident that the discrimination is rather coarse and generic. It should be noted, however, that this assessment is not exclusive to a specific taxon. Indeed, the QBS-ar approach allows for the consideration of the entire soil microarthropod community, which compensates for the more generic measurement of individual species.

1.6 Collembola-specific QBS – QBS-c

Considering Collembola as one of the most abundant and morphologically diverse groups of soil mesofauna, Parisi (2001) implemented the QBS method with a version based exclusively on Collembola: the Collembola-based Soil Biological Quality Index (QBS-c) for assessing soil quality. The QBS-c is conceptually and practically the same as the QBS-ar, but it takes into account variation between different life-forms at a finer taxonomic level (e.g., species or genus) and their soil microhabitat adaptations. In addition, the morphological traits used for QBS-c are described in more detail than those used for QBS-ar. Each morphological trait is considered individually, and each Collembola species can have a specific EMI value for each of the traits, resulting in a range of 1 to 40 for the EMI for each species. The EMIs of all Collembola species are then scaled to the community (per sample) by summing the EMI values of all species, sometimes taking into account the relative abundances (densities) of the “forms” (as described in the Results section). It has been proposed that the QBC-c is more useful for studies on hydric balance of soil than QBS-ar (Parisi and Menta, 2008).

1.7 Aims of the study

This study synthesises the current use of QBS-c in soil ecology, with a particular focus on how EMIs are assigned to Collembola. Despite its increasing use in recent years, no consensus currently exists on EMI assignment for Collembola, limiting comparability across studies. We analyse the development of Collembola EMIs since Parisi's original proposal and evaluate how different researchers have adapted the index. Finally, we also provide practical recommendations for the use of Collembola EMIs in community ecology and soil quality studies, with the explicit goal of harmonising EMI assignment and QBS-c computation for applied soil monitoring.

2. Methods

2.1 Literature review

We conducted a literature search using the Scopus and Web of Science databases to identify studies addressing eco-morphological indices (EMIs) and the Collembola-based Soil Biological Quality index (QBS-c). The search was performed using the following query applied to titles, abstracts and keywords: ((EMI OR EMIs OR ecological morphological indices OR ecological morphological index OR ecomorphological indices OR ecomorphological index OR ecomorphology indices OR ecomorphology index OR QBS-c) AND (Collembola OR springtail)). The search result was deposited at https://www.webofscience.com/wos/woscc/summary/356de728-39b9-4ac2-a07f-3d84b3733815-cda92dcf/date-descending/1. The search retrieved 15 studies as of 19 November 2025. Additional relevant studies were identified through screening of the reference lists of the retrieved articles. We also included Collembola trait studies which used methods essentially analogous to the QBS-c and EMI. In total, we compiled 24 references on Collembola EMI or QBS-c and compared how different researchers assigned the EMI and quantified QBS-c (Table S1).

2.2 Principal component analysis of Collembola traits

We used the trait data reported in the appendix 1 of Menta (2008), which documented the original trait values of Italian Collembola species used by Parisi (2001). Congeneric species sharing the same combinations of trait values were treated as the same unit, thereby compiling a genus-trait code matrix (available on request). With this matrix, we conducted a principal component analysis (PCA) on numeric variables after centring (zero mean) and scaling (unit variance) using the *rda* function in the vegan package in R (Oksanen et al., 2022). The analysis was conducted to examine correlations among morphological traits and to assess whether EMI values (calculated as the sum of the seven traits proposed by Parisi) are aligned with the main PCA gradients representing adaptation to soil conditions. Based on the PCA results, we identified a reduced set of informative traits by considering both their contribution to trait variation and the practical feasibility of their assessment. This selection was used to support recommendations for trait choice in future QBS-c applications.

3. Results – EMI and QBS-c application trajectory

3.1 The original QBS-c and Collembola EMI assignments

As originally proposed by Parisi (2001), seven traits were considered for index determination and each was assigned an EMI value within a defined range: (1) Body size (large, > 3 mm, EMI = 0; medium, 2 - 3 mm, EMI = 2; small, < 2 mm, EMI = 4),

(2) pigmentation/pattern (complex pattern, EMI = 0; simple pattern, EMI = 1; with colour, EMI = 3; absent, EMI = 6), (3) cuticular structure such as the presence of macrochaetae, scales, trichobothria, sensilla and PAO (EMI = 0, 1, 3 or 6), (4) number of ommatidia (8 + 8, EMI = 0; 6 + 6, EMI = 2, from 1 + 1 to 5 + 5, EMI = 3; 0 + 0, EMI = 6), (5) antenna length (longer than head diagonal, EMI = 0; approximately equal to head, EMI = 2; shorter than head, EMI = 3; strongly reduced, EMI = 6), (6) leg length (strongly developed, EMI = 0; moderately developed, EMI = 2; short, EMI = 3; reduced, or empodium absent or reduced, EMI = 6) and (7) furca development (highly developed, EMI = 0; average development, EMI = 2; little developed, EMI = 3; mucro absent, alternative form in manubrium and dens, EMI = 5; completely absent or rudimentary, EMI = 6; Parisi and Menta, 2008). This approach takes into account all identified morphotypes, not just those with the highest EMI as the QBS-ar does, and the EMI of a species for the calculation of the QBS-c of a community can range from 1 to 40 (Parisi, 2001). To facilitate the determination of the EMI, Parisi (2001) evaluated the EMI values for the traits of Collembola species in Italy and the data were published as a list for a total of 171 Collembola species in the book by Menta (2008). The QBS-c can be used without specialists-level taxonomic expertise (e.g. chaetotaxy), but it still requires at least basic knowledge of Collembola morphology (Menta, 2008).

3.2 QBS-c empirical studies

The QBS-c has been used less frequently than the QBS-ar. We found only 24 papers and one book that applied QBS-c or EMI for Collembola between 2001 and 2025. In contrast, Menta et al. (2018) reported that the QBS-ar was applied in 41 studies until 2017. The lower use of QBS-c may reflect the fact that Collembola determination is more time-consuming and requires more taxonomic expertise, morphological or biological knowledge of the group and instrumentation to assign EMI to species than QBS-ar.

Despite its complexity, the QBS-c has proven to be an effective tool for distinguishing agroecosystems with different water content, organic matter and mechanical treatments, and between grasslands and vineyards with different management intensities (Gardi et al., 2002). Menta (2008) showed negative effects of agricultural practices such as deep ploughing on soil quality by applying the QBS-c to a few Collembola studies in Italy (Sabatini et al., 1997). The author was able to quantify empirical QBS-c values for riparian meadows (QBS-c = ca. 90) and forests (QBS-c = ca. 200) (Migliorini et al., 2003). Menta et al. (2014) also found that the QBS-c was able to differentiate the inside and outside of *Tuber aestivum* Brûlé in Italian and Spanish truffle cultures. The index was higher outside the brûlé, although the differences were not statistically significant. Twardowski et al. (2016) applied the QBS-c to assess differences in potato cultivation in monoculture and rotation, and found that QBS-c was about 50% higher in rotation than in monoculture. Using the QBS-c, Gruss et al. (2019) evaluated the effect of biochar in arable fields and found that the index was higher in treatments where biochar was applied. While Mutyambai et al. (2024) compared monoculture to push-pull soils, finding higher QBS-c index values in the latter. On the contrary, Remelli et al. (2025) evaluated the effect of different agricultural systems and soil management strategies, finding higher QBS-c values in vineyards under integrated management compared to organic management, as well as in arable land, orchards and meadows, regardless of management type.

Except for Twardowski et al. (2016), Gruss et al. (2019) and Mutyambai et al. (2024), the QBS-c was applied in agroecosystems mainly in Italy, the country where the index has been developed. The QBS-c and EMI of Collembola were then adopted not only by a number of other European researchers, but also by researchers from Brazil, China, Japan and Kenya. However, different researchers used the EMI differently for calculating QBS-c. In the following, we will present the main commonalities and discrepancies between the studies.

3.3 Parisi-alike EMI changed after the original

Over time, several Collembola studies have adopted the idea of the EMI, but quantified it in different ways, either with different combinations of morphological traits or with different values assigned to species (see Table S1 for an overview of trait combinations, scoring schemes and study contexts). It appears that there is still no consensus on how to score traits and how to assign EMI to species particularly with respect to trait selection, scoring schemes and aggregation procedures (Table S1). Although the initial EMI assignment was proposed by Parisi (2001), Menta (2008) and Parisi and Menta (2008) for Collembola species in Italy, the functional trait paper by Vandewalle et al. (2010) has significantly changed the later use of the EMI for Collembola traits. Using data from Sousa et al. (1997, 2000), Vandewalle et al. (2010) considered five morphological traits instead of the seven traits proposed by Parisi and Menta (2008). They determined a range of EMI values for each trait as follows: (1) antenna-to-body length ratio (> 1, EMI= 0; between 0.5 and 1, EMI = 2; ≤ 0.5, EMI = 4), (2) furca development (fully developed, EMI = 0; reduced/short, EMI = 2; absent, EMI = 4), (3) number of ommatidia (7 + 7 or 8 + 8, EMI = 0; 5 + 5 or 6 + 6, EMI = 1; 3

+ 3 or 4 + 4, EMI = 2; 1 + 1 or 2 + 2, EMI = 3; 0 + 0, EMI = 4), (4) scale/hairs (present, EMI = 0; absent, EMI = 2) and (5) pigmentation (coloured and with pattern, EMI = 0; coloured but without pattern, EMI = 2; absent, EMI = 4). The five individual traits were then combined to represent the 'life-form' trait (LFT) as the sum of the EMI of all individual traits, ranging from 2 (indicating adaptation to the soil surface) to 18 (indicating adaptation to soil), making Collembola life-form scaled as a continuous gradient. Vandewalle et al. (2010) demonstrated how the LFT can be applied to Collembola species composition, to assess the effects of replacing native forest with exotic *Eucalypus globulus* plantations on the functional composition of Collembola. Compared to the EMI for QBS-c originally proposed by Parisi (2001), Vandewalle et al. (2010) assigned different EMI values to the traits. They simplified the EMI for cuticular structures and excluded body size and leg length from the evaluation. The ideas of Vandewalle et al. (2010) were soon applied to broader studies of Collembola communities (Table S1).

Following Vandewalle et al. (2010), Martins da Silva et al. (2016) used the same five traits but modified the EMI assignments for the two: ommatidia (present, EMI = 0; absent, EMI = 4) and scales/hairs (present, EMI = 0; absent, EMI = 4). The authors did not include body length and leg length, as originally proposed by Parisi and Menta (2008). In addition, they standardized the EMI of species by dividing it by 20, which is the maximum EMI obtained from the sum of the EMIs of the five traits. The final LFT therefore varies between 0 and 1, indicating lower and higher soil adaptation, respectively. Using several functional diversity metrics, the authors studied Collembola communities inhabiting different land-use systems (forest, grassland and arable land) along an European transect. However, Joimel et al. (2017) did not use morphological traits to assign Collembola EMI, but rather based on Gisin's (1943) life-form information and expert knowledge, quantifying it as 1, 2 and 3. They took into account the relative abundance of species, to derive a Collembola “ecomorphological index” for each sample (i.e., community; not for species as in most of other studies). They found that arable land was most detrimental to soil biodiversity, but urban and industrial land provided the same level of soil biological quality as forests.

De Oliveira Filho et al. (2016) studied Collembola community structure using the same EMI as Martins da Silva et al. (2016), but applied it to arable systems with different tillage practices. They further defined life-forms as epigeic (epedaphic) with EMI 0 - 6, hemiedaphic 8 - 12 and (eu)edaphic 14 - 20 and indicated that Collembola eco-morphological groups were better predictors of ecosystem functioning than Collembola density. Also, Reis et al. (2016) assigned the same EMI as Martins da Silva et al. (2016) and de Oliveira Filho et al. (2016), to assess whether the identification of Collembola species to morpho-types could be used as a surrogate for species richness in an extensive monitoring scheme. They concluded that the EMI approach and genus-level determination were sufficient for a cost-effective assessment of species richness. Alexandre et al. (2025), using the same EMI assignment as de Oliveira Filho et al. (2016), focused on the impact of landscape fragmentation on Collembola communities in Brazil. The study found that edaphic morphotypes dominated across all levels of fragmentation. The densities of hemiedaphic and epigeic morphotypes were observed to be lower, with the former being particularly prevalent in less fragmented landscapes. Similarly, Dos Santos et al. (2018) adopted the same EMI assignment as de Oliveira Filho et al. (2016). However, the authors calculated QBS-c with the abundance of Collembola species to obtain the abundance-weighted QBS-c, which summed all individuals, but not the presence of species, of their EMIs in a community. Like de Oliveira Filho et al. (2016), Machado et al. (2019) defined life-forms and proposed a variant of QBS-c: the QBS-adapt index. The traits assigned with EMI were the Collembola morphological traits considered by Martins da Silva et al. (2016). However, to determine the QBS-adapt, the abundance of the Collembola morpho-type was multiplied by the corresponding EMI. The previous multiplied values were then summed for all morpho-types found in a sample, essentially the same as in dos Santos et al. (2018) but termed differently. The QBS-adapt index of Machado et al. (2019) was used to determine the soil quality in Brazil, showing its efficiency and sensitivity in distinguishing different land-use systems and seasons. The four studies, de Oliveira Filho et al. (2016), dos Santos et al. (2018), Machado et al. (2019) and Alexandre et al. (2025), all applied the EMI to Collembola community studies in Brazil, where information on local species taxonomy is limited, but the EMI overcomes the difficulty of species-based identification, making Collembola as soil quality indicator more applicable to land management and valuation than traditional taxonomic work (see Table S1 for study details).

The approach of Martins da Silva et al. (2016) was further used by Moss et al. (2020) and Llovet et al. (2021). Moss et al. (2020) investigated the influence of different long-term organic crop rotations and the short-term two-year effects of different tillage systems on Collembola communities. They compiled the life-form assignment for Collembola species in Germany from different studies (Chauvat et al. 2007, Sticht et al. 2008, Stierhof, 2003, Salamon et al. 2011) and found that euedaphic Collembola increased with organic matter availability in stable habitats. Similarly, Llovet et al. (2021) used Collembola LFT as Martins da Silva et al. (2016) to assess the effects of biochar on soil ecosystem functioning in a barley field in Spain. In addition, their comprehensive study also included QBS-ar, along with the other soil quality indices.

Different from the original seven traits (Parisi, 2001) or the five traits (Vandewalle et al., 2010), Yin et al. (2020) considered nine traits for EMI attribution to Collembola species, although the authors termed the species EMI as ‘QBS for Collembola species’. The EMI scores attributed to Collembola traits generally followed those of Vandewalle et al. (2010) and Martins da Silva et al. (2016), but were ordered in the opposite direction, with higher scores indicating “surface-adaptive” rather than soil adaptation. The scores for furca, pigmentation and scale/hairs are in the opposite direction to that of Martins da Silva et al. (2016) and ommatidia in the opposite order to that of Vandewalle et al. (2010) with five levels. However, Yin et al. (2020) included body length with four levels: > 3 mm (score = 4), 2 - 3 mm (score = 3), 1 - 2 mm (score = 2) and 0 - 1 mm (score = 1), and assigned different scores for antenna-to-body length ratio with two levels: 0 - 0.5 (score = 0) and > 0.5 (score = 4). They did not include leg length, but rather considered “habitat” (i.e., life-form; epedaphic, hemiedaphic or euedaphic), reproductive mode (sexual or parthenogenetic) and dispersal ability (fast or slow) following Malmström (2012) in the index calculation. Yin et al. (2020) investigated the effects of climate and land-use change at the Global Change Experimental Facility in Germany and found that the index decreased significantly with intensive land-use, with a decrease from grassland to cropland across climate change scenarios.

Qiao et al. (2022) calculated the QBS-c index differently from the original method (Parisi 2001). They considered seven traits, with furca, ommatidia, pigmentation and scale/hairs within the range of EMIs described by Martins da Silva et al. (2016). However, the direction of the trait orders followed Yin et al. (2020), with surface-adapted species having higher values and deep soil species having lower values. When comparing the studies of Qiao et al. (2022) and Yin et al. (2020) with the QBS-c results of other studies, readers should notice the different way that the authors used to define soil- or surface-adaptation of Collembola. Contrary to Martins da Silva et al. (2016), body size was included in Qiao et al. (2022) but antennal-to-body length ratio was excluded. The EMI of body length followed the range described in Yin et al. (2020). In contrast to Parisi (2001) and Parisi and Menta (2008), Qiao et al. (2022) also considered life-form and dispersal ability, but did not include leg length. They applied the QBS-c in southern China to assess differences in urbanisation and green space types. The index was found to be sensitive to vegetation complexity and effective in distinguishing between urban and suburban areas. The authors also calculated several trait-based functional diversity metrics, such as community weighted mean and functional richness, evenness and divergence (Mason et al. 2005, Villéger et al., 2008).

Hishi et al. (2022) developed the Edaphic Adaptation Score (EAS), a numerical index ranging from 0 to 20. However, the EAS is essentially the same as the EMI but termed differently. They used the traits mentioned in Martins da Silva et al. (2016), with the exception of ommatidia, which was scored differently: 0 + 0 (EAS = 4), from 1 + 1 to 4 + 4 (EAS = 2) and from 5 + 5 to 8 + 8 (EAS = 0). Compared to the original EMI proposed by Parisi (2001), leg length was not included and body size (ranging from 0.4 to 4.0 mm) was calculated separately from the EAS. The authors also used the EAS values to define the life-forms, but with different cut-off values than that in de Oliveira Filho et al. (2016). They defined epedaphic (EAS 5 - 9), hemiedaphic (EAS 10-14) and euedaphic (EAS 15 - 20). The EAS was applied to Collembola species in Japan to investigate the effects of topography and forest types on the functional composition of Collembola.

Unlike the other QBS-c studies that used five, seven or ten traits, Ferrín et al. (2023) used a total of 22 traits, although many belong to the same morphological characters, from the ColTrait database (Salmon et al. 2014) to test the adaptation of Collembola to different soil layers in a standardised climate manipulation experiment across six European countries. This represents the upper extreme of trait inclusion among reviewed studies. The rationale for including many traits is that different traits cover different niche dimensions, including life history (as represented by e.g., reproductive strategy), dispersal ability (leg length) and biotic interaction (sensory organs and defensive structures). They also used the EMI as originally proposed by Parisi et al. (2005). However, how the values of the 22 traits in the ColTrait database were harmonised with the Parisi et al. (2005) EMI assigned to each of the species they collected was not clearly documented. Another recent paper by Ashwood et al. (2023) used the same five traits as Machado et al. (2019), rooted in Vandewalle et al. (2010), and the same EMI methodology as Parisi et al. (2005) in their QBS-c analysis to assess the influence of reclamation practices of a restored landfill and compared it with the surrounding arable land and woodland in the United Kingdom. Although they were able to show the sensitive responses of QBS-c to different levels of disturbance (with a low QBS-c value of ca. 20 in reclaimed soils and high QBS-c values of 74 and 92 in woodland and grass margins, respectively), it is unclear how the authors assigned the EMI values for each trait and species, given the discrepancies between Parisi et al. (2001) and Vandewalle et al. (2010) listed above, e.g. for the number of ommatidia. Taken together, these findings reveal substantial methodological variability in EMI assignment and QBS-c computation across studies, highlighting the need for a more standardized framework, as outlined in the following section.

4. Discussion

4.1 Recommendation for unification of the EMI assignment and QBS-c quantification

From an applied perspective, the key question is how to use Collembola traits to derive robust, cost-effective indicators of soil quality that can be implemented in monitoring schemes. The QBS-c method offers such a possibility because it avoids full species determination and can be applied by non-specialists. However, our review shows that despite a strong conceptual basis, methodological differences currently hamper wider use and cross-study comparison, particularly regarding which traits to include, how to score them and how to aggregate EMIs of species to community-level indices. To support future applications of QBS-c in soil quality assessment and trait-based ecology, we recommend harmonising data acquisition procedures from species-level EMI assignment to community-level QBS-c computation. Based on these findings, we outline guidelines that can be readily adopted and adapted by soil ecologists, consultants and agencies (Table 1).

Table 1. Current practices and suggested recommendations for the future use of the Collembola eco-morphological index (EMI) and the Collembola-based Soil Biological Quality Index (QBS-c) in applied soil monitoring. (Mean Trait Value, mT; Community Weighted Mean, CWM; Edaphic Adaptation Score; EAS; Life-Form Trait, LFT).

Aspect	Current practice in literature	Recommendation
Number of traits	5 – 22 traits used; 5 most common	Select 3 core traits: body size (3 – 4 classes), furca (presence/degree of reduction), pigmentation; can be extended to 3 – 6 traits depending on resources

Trait types	Mix of morphological and non-morphological	Restrict to morphological traits for QBS-c/EMI; avoid using habitat, life-form, dispersal ability and reproductive mode as EMI components
EMI direction	Some use high score for soil adaptation; others do the opposite	Following Parisi (2001), assign EMI so that higher scores always reflect deeper soil adaptation (euedaphic)
Trait scores	E.g., ommatidia, 0 – 3 or 0 – 4	Use ordinal discrete classes with clear cut-offs; provide thresholds in a table; for each species, sum standardized trait scores to obtain species EMI, e.g., use four classes for ommatidia as in Parisi (2001): 8 + 8, 6 + 6, from 5 + 5 to 1 + 1 and 0 + 0; alternatively, balance species number in each class to standardize across traits so each contributes equally
Community metric	QBS-c, mT, CWM, EAS, LFT	Use QBS-c as umbrella term; clearly specify whether presence/absence or abundance-weighted; report both presence–absence QBS-c and abundance-weighted QBS-c when possible

4.1.1 How many traits?

The main discrepancy in species-level EMI assignment concerns the number of traits used. Most studies use five traits, whereas the original implementation by Parisi (2001) used seven traits (body size, pigmentation, cuticular structure, ommatidia, antenna length, furca and leg length). Vandewalle et al. (2010) reduced this to five traits (pigmentation, scales/hairs, ommatidia, antenna-to-body length and furca), and subsequent authors often followed this scheme with minor modifications to scoring (Martins da Silva et al. 2016, Oliveira Filho et al. 2016, Reis et al. 2016, dos Santos et al. 2018, Machado et al. 2019, Hishi et al. 2022, Qiao et al. 2022). For example, Hishi et al. (2022) used the same five traits but changed the EMI values for ommatidia and scales/hairs and Qiao et al. (2022) replaced antennae with body size, but Ferrín et al.

(2023) used considerably more (up to 22) traits, resulting in a wide methodological spectrum of trait complexity.

To maintain operational simplicity and still capture the main gradient of edaphic adaptation, we advocate a compromise between labour (time, equipment and expertise) and performance (sensitivity and robustness). For routine soil monitoring and broad-scale comparisons, a minimal set of three traits—body size, furca and pigmentation—is sufficient, while more detailed functional studies may extend this to six morphological traits (body size, pigmentation, ommatidia, antenna length, scales/hairs and furca). This tiered trait design allows managers and monitoring agencies to choose a level of complexity that matches their resources, while still producing QBS-c values that are comparable across sites and studies.

4.1.2 Which traits?

Researchers have used different criteria for trait selection and value assignment, making across-study comparison difficult, if not impossible (Yin et al. 2020, Qiao et al. 2022, Ferrín et al. 2023). For example, Joimel et al. (2017) used pigmentation, scales/hairs, ommatidia, antenna length, furca and legs, but not body size. Similarly, Yin et al. (2020) used body size, pigmentation, scales/hairs, ommatidia, antenna length and furca, but not leg; instead, they added life history. Conversely, Ferrín et al. (2023) considered several additional morphological traits, such as body shape, minimum and maximum body length and antenna-head ratio, leg-body ratio, minimum and maximum number of pseudocelli, ommatidia, post-antennal organ (PAO) and trichobothria. However, such a determination for many traits—in their case up to 22—requires specialised instruments or comprehensive databases. We propose to retain the most commonly used six morphological traits to ensure comparability with existing literature: body size, pigmentation, ommatidia, antenna, scales/hairs and furca (Yin et al. 2020). However, for ease of application, this set can be reduced to three key traits: body size, furca and pigmentation.

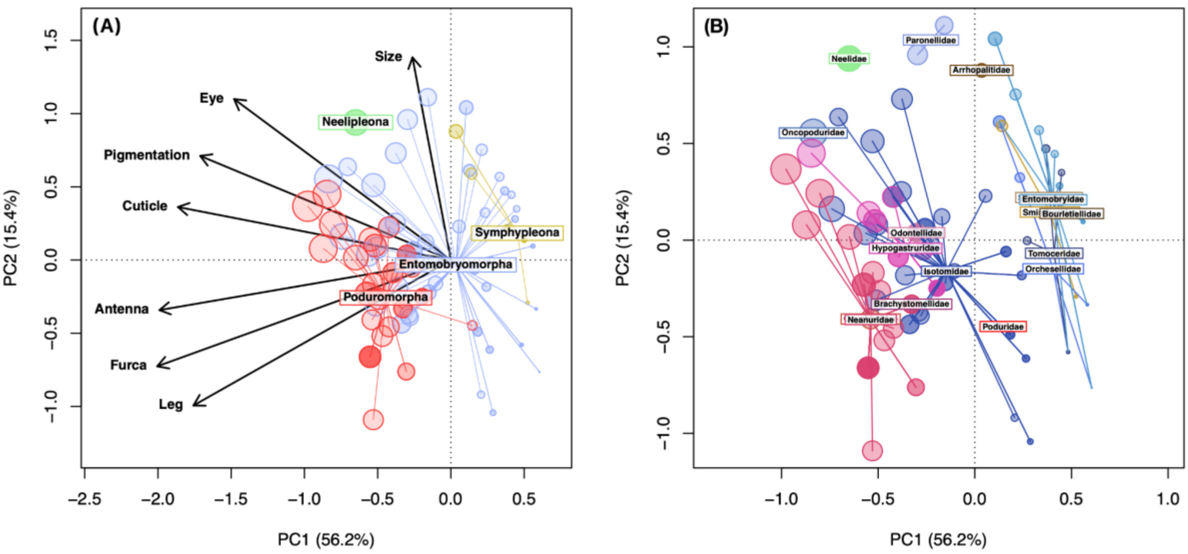

Figure 1. Principal Component Analysis for the seven traits (black arrows) proposed by Parisi (2001) for EMI calculation (values ranging from 0 to 40) in Italian Collembola genera. Congeneric species with different trait value assignments were treated as separate analytical units. In total, 177 genus-trait units were analysed. EMI values are represented by circle size, taxonomy by colour (order, A; family, B), and number of genus-trait units overlap by colour intensity of circles. Positions of rectangles with taxonomic nomenclature are centroid positions for the genera of the respective taxa.

As shown in Figure 1, the PCA results indicated that the first two principal components together explain 71.6% of the total trait variation, with antenna, furca and leg length forming one correlated group and ommatidia, pigmentation and cuticle forming another, while body size defined an almost independent axis. This redundancy suggests that a smaller, carefully selected subset of traits can capture most of the relevant variation for edaphic adaptation. Collembola species with high EMI values are positioned on the left side along PC1, reflecting the general “euedaphic” trend of EMIs in different Collembola.

To balance information content and feasibility, we recommend using body size, pigmentation and furca as a default minimal trait set for EMI assignment in applied QBS-c studies. Size contributes unique information and is straightforward to measure; pigmentation is easier to score consistently than ommatidia or cuticle structures; and furca is robust to handling and strongly related to microhabitat use. In routine soil surveys this minimal trait set can be implemented without specialised taxonomic expertise, making Collembola-based QBS-c feasible for applied soil health monitoring. We elaborate these points below.

4.1.2.1 Body size

Body size (or length) was not directly used for EMI by Vandewalle et al. (2010) but as the base for judging antenna relative length. However, in the original Parisi (2001), body length was assigned as a discrete ordinal trait with three levels and added into species EMIs, and 10 out of the 21 studies considered body size. As our trait PCA has indicated, body size is a relatively independent trait from the other traits and it contributed the least to the EMI. However, body size can be rendered as the second dimension of the Collembola morphological trait space, apart from the other traits indicating the life-form. In Collembola trait-based ecology, body size has proven to be an effective functional trait which is widely used (Bonfanti *et al*., 2018; Hishi *et al*., 2024).

4.1.2.2 Other morphological traits in Parisi EMI

The other traits considered by Parisi (2001) are rather correlated with each other and aligned in the same direction in the EMI trait space, suggesting using them together is good to represent Collembola trait syndrome which, in the original idea, is to indicate adaptation to soil life (i.e., life-form). Due to the dominance of these positive correlated traits, the EMI is inevitably weighted more by these morphological traits than by body size. However, we do not consider it necessary to include all these traits in the EMI calculation, but rather to select a subset, as some are rather difficult to acquire. For example, as compared to furca, legs and antennae are more fragile and prone to damage. Pairs of legs and antennae would also increase measurement variations of different researchers as compared to a single or absence of furca for each species. However, furca, legs and antenna could provide different functions for Collembola: furca for locomotion and antenna for sensation; nevertheless, these traits may be needed when Collembola encounters predators. Due to redundancy (high correlation) with furca, leg and antenna can be excluded from but furca retained in the EMI calculation.

Determination of ommatidia number and scales/hairs may require specific instrumentation or comprehensive descriptions such as the Collembola synopsis series (Zimdars & Dunger, 1994; Bretfeld, 1999; Potapov, 2001; Thibaud et al., 2004). For a less experienced researcher (e.g., students) in the beginning it could be difficult to empirically observe such features from field-collected specimens, as ommatidia are transparent and usually confusing with the pigment beneath them. It may be challenging for beginners who only rely on a basic stereoscope. However, an advantage of having the ommatidia number in the EMI is due to its taxonomic conservatism thereby the values for species can be inferred from taxonomy at a higher level than species (i.e., families or genera) from literature. However, for some difficult taxa such as Isotomidae, genera are divergent across the EMI trait space **(**Fig. 1B**).** Therefore, the ommatidia number of them should be confirmed by microscopy. Pigmentation is rather easy to observe and its value to define. However, pigmentation may vary between juvenile and adults, and it is often not a reliable character in species determination, as intraspecific color variations are documented for some genera (e.g., Isotoma, Entomobrya) (Fjellberg, 2003; Burkhardt & Filser, 2004; Baquero & Jordana, 2008; Katz et al., 2015a). As ommatidia and pigmentation are highly correlated (R2 = 0.75), we recommend having either ommatidia or pigmentation is sufficient.

Collecting data of Collembola cuticle structures, hairs and scales, remains difficult, even if these two traits are documented as presence or absence for species. Empirically, the presence of hairs can vary depending on life stages; juveniles may show different characteristics than adults. It is advisable to consider only the adult trait state when assessing EMI; however, it may not reflect reality, as most field populations could be dominated by juveniles or sub-adults. There would also be significant intraspecific variation in the presence or amounts of hairs, which might arise from several factors, including genetic diversity, environmental influences, or developmental conditions (Katz et al., 2015a; Katz et al., 2015b; Tully & Potapov, 2015; Palacios-Vargas et al., 2019). In practice, determination of hairs is often subjective and strongly dependent on the observer’s experience. Compared to hairs, scales are even more difficult to observe, as they require good magnification instruments and some training for researchers for finding the feature under microscopes. Scales are hardly visible on scanned images when many specimens are processed at once. In the EMI trait space, cuticle structures (i.e., hairs/scales) are highly correlated with antennal length, as indicated by the similar loadings along the PC1. Along the PC2, the cuticle trait is grouped with pigmentation and ommatidia number. We therefore recommend excluding cuticle structure from the EMI.

For the EMI trait space, the first three PCs represented 88% of the total variation, suggesting the seven traits are rather redundant. We recommend minimising effort by focusing on a reduced set of traits and measuring the three following traits of each species: body size, furca and pigmentation (or ommatidia number). Nonetheless, authors may adjust which traits according to their need and capacity, as long as the procedures are well documented, but this tiered trait design allows land managers and monitoring agencies to select a level of complexity that matches their resources while still producing QBS-c values that are comparable across sites and studies.

4.1.2.3 Non-morphological variables

In some EMI and QBS-c studies, researchers incorporated non-morphological variables for indicating life history, behaviour and microhabitat preferences such as habitat, reproductive mode, dispersal ability and life-form. They claimed that these “traits” can reflect certain soil habitat adaptations (Yin et al., 2020; Qiao et al., 2022; Hishi et al., 2022; Ferrín et al., 2023). However, to avoid ambiguity and make future studies comparable, we recommend not using traits beyond the morphological ones proposed by Parisi (2001) and Parisi et al. (2005), when the research aim is for biomonitoring with Collembola EMI concept and QBS-c index (Parisi 2001, Parisi et al. 2005). However, these traits may be useful for some fundamental ecological questions.

Reproductive mode has been applied for studies on QBS-c and Collembola trait ecology, but it has never been included in Parisi et al (2005) or Vandewelle et al. (2010). However, reproductive mode could be used as a proxy for environmental resource availability, which further suggests some quality criteria of the soil habitat. As predicted by the Structured Resource Theory of Sex suggests, sexual reproduction is predominated in spatially structured habitats where resources are structured and renewed at low rates (Scheu and Drossel, 2007). However, empirically for researchers, without certain training, it is difficult to assign reproductive mode to field-collected individuals (Chahartaghi et al., 2006). Reproductive mode, therefore, should not be used as a regular trait for EMI or QBS-c.

Traits in terms of “habitat”, dispersal ability and life-form, when used in EMI or QBS-c context, are less defined. Therefore, we recommend not to use them. Theoretically the distribution “traits” (occurrence or occupancy) have to be empirically collected from fields, but in practice researchers usually derive the distribution variables (e.g. life-form) from databases or simply inferred by the morphological traits. Empirical microhabitat distribution of Collembola species would vary across studies or ecological contexts. Dispersal ability is generally assigned to species based on morphology (Qiao et al., 2022; Yin et al., 2020), which is already redundant with the information provided by morphological variables. Habitat is an ambiguous term as a trait and strictly speaking it refers to the vertical stratification of Collembola in the soil profile, thus ecological preference, and so does the life-form, which, in principle, refers to Collembola spatial niches in soil horizons. It is a real physical distribution of Collembola species in soil profile and is an outcome of adaptation, which is usually informed by the morphological traits discussed in the previous sections. As these variables are derived from other variables, the habitat preference, dispersal ability and life-form are secondary variables and redundant to the other morphological traits. They may have problems of logical circularity and therefore are not suitable for soil quality assessment. Although they have been used in studies of community functional diversity, we propose that such non-morphological traits should not be included in EMIs and QBS-c when the aim is soil quality assessment.

4.1.3 What type of variable and which values to assign?

4.1.3.1 Continuous or ordinal discrete variables

For the traits from the studies we have reviewed, only body size and antennal length are continuous variables. Measuring a quantitative continuous variable across thousands of individuals is laborious. The problem may even be more serious for measuring antenna length (or the ratio of antennae length to body length), as antennae are easily being lost during handling of specimens. Therefore, when exact measurements are not feasible, ordinal discrete variables provide a practical alternative for continuous traits in EMI assignment, even if some statistical power is lost.

For ordinal discrete variables, it is essential to define adequate intervals for the whole range of values. However, there appears to be no consensus on the number of intervals and the range for each interval for Collembola body size. Collembola body size can vary widely from 0.18 - 6.5 mm (Ferrín et al., 2022). Parisi (2001) defined three intervals of measurements for body size (>3 mm; 2 - 3 mm; <2 mm), while Yin et al. (2020) defined four intervals (> 3 mm; 2 - 3 mm; 1 - 2 mm; 0 - 1 mm). It seems appropriate to consider the full range of size spectrum of the species collected and let each interval have a similar number of species belonging to it, and then, to have three or four levels in the end for the ordinal discrete variable, where each species has a specific category for size class. However, empirically, researchers may find many juveniles from the collection, which are much smaller than the adults. In this case, the assignment of size by the adult class may not reflect real size distribution in the community. By contrast, traits such as furca and ommatidia (but not pigmentation) are assumed to be consistent between adult and juvenile and to show limited intraspecific variation, and therefore omit the juvenile problem. The furca is usually coded as a presence/absence binary variable, while ommatidia are ordinal discrete integers.

4.1.3.2 Levels and scoring orders for discrete traits

Even if a discrete ordinal variable like ommatidia is relatively easy to assign scores to Collembola species, discrepancy exists between studies. Researchers divided the number of ommatidia into different scoring classes. In Parisi (2001), there are four possible EMI scores: “0” (8 + 8 ommatidia), “2” (6 + 6 ommatidia), “3” (from 5 + 5 to 1 + 1 ommatidia) and “6” (0 + 0 ommatidia). In Vandewalle et al. (2010), there are five possible EMI scores: “0” (7 + 7 and 8 + 8 ommatidia), “1” (5 + 5 and 6 + 6 ommatidia), “2” (3 + 3 and 4 + 4 ommatidia), “3” (1 + 1 and 2 + 2 ommatidia) and “4” (0 + 0 ommatidia). In Yin et al. (2020), the same range is used as Vandewalle et al. (2010), but the EMI values are in ascending order with ommatidia number. In Hishi et al. (2022), there are three possible EMI scores: “0” (from 5 + 5 to 8 + 8 ommatidia), “2” (from 1 + 1 to 4 + 4) and “4” (0 + 0 ommatidia). In other studies, including Martins da Silva et al. (2016), Oliveira Filho et al. (2016), Reis et al. (2016), dos Santos et al. (2018) and Machado et al. (2019), the values attributed to ommatidia is simplified to: “0” (present) and “4” (absent), whereas in Qiao et al. (2022) it is in the opposite direction: “4” (present) and “0” (absent). How researchers divided ommatidia numbers, which range from 0 + 0 to 8 + 8, into classes vary. We recommend the most straightforward approach proposed by Parisi (2001) with four classes of ommatidia numbers. Adopting a common ommatidia scoring system and direction across studies will greatly facilitate cross-site comparisons and the use of QBS-c in multi-site monitoring programmes.

In Qiao et al. (2022), not only for the scoring of ommatidia number different from the other studies, the researchers also ordered the life-form differently from Yin et al. (2020) by assigning a higher EMI value to more surface-adaptive (i.e. epiedaphic) species. We recommend synchronising the value assignment in line with the original proposal of Parisi (2001), i.e., a higher value indicating more soil-habitat (i.e. euedaphic) adaptation. Moreover, we call for an open and comprehensive clarification of the process of trait score assignment in research studies. We have noticed that, in many cases, it is rather difficult to understand the methods used by authors to extract or determine these scores. Clear guidance on this issue would greatly improve transparency and facilitate better comparison between studies.

4.1.3.3 Standardization and sources for species traits

When multiple traits are summed into species EMI, it is recommended to standardize values across trait variables, thereby to give the same weights for different traits. Currently for Italian Collembola species, Menta (2008) provided a list, to which a fixed EMI value has been assigned to each species. This list serves as the only species-level EMI reference available, while the occurrences of the species in the list are not limited to Italy. For species not included in such lists, although values may be derived from taxonomic literature, we recommend using empirical measurements from field-collected specimens as primary data sources. Establishing regional Collembola trait databases is currently needed, albeit the process would be lengthy and some databases have achieved this goal (e.g., BETSI; Joimel et al., 2021). In addition, for the existing Collembola database, it would be a mutual benefit if chances are allowed to integrate the EMI in addition to the existing trait variables. The creation of a more extensive regional species trait list or global trait database with EMI being included could serve as a standardized database for future Collembola ecological research, making taxonomic determination work more ecological and even applicable for monitoring by QBS-c.

4.1.4 Scaling species EMIs to community-level QBS-c

4.1.4.1 Terminology for community-weighted metrics

At the community level, studies have used a variety of terms and metrics (QBS-c, mT, CWM, EAS, life-form indices), although the underlying principle is the same: aggregating species-level adaptation scores into a single community value. To reduce confusion, we suggest using the term “EMI” for species-level soil adaptation values and reserving “QBS-c” for the community-level Collembola soil quality index. Other community-weighted means of EMI scores can be described explicitly as presence–absence-based QBS-c or abundance-weighted QBS-c, rather than introducing additional acronyms.

4.1.4.2 Presence–absence versus abundance-weighted approaches

QBS-c was originally defined as the sum of species (or morphotype) EMI values based on presence–absence data. Several recent studies have extended this to abundance-weighted versions by multiplying each species’ EMI by its abundance and summing across the community. Both approaches have merits:

- Presence–absence QBS-c is simpler, less sensitive to sampling effort, and more suitable for large-scale comparisons or monitoring networks.
- Abundance-weighted QBS-c captures the dominance of specific life-forms and may be more sensitive to local habitat quality and management effects.

We recommend that, where abundance data are available, both metrics are reported. Presence–absence QBS-c allows comparability with the original method, while abundance-weighted QBS-c provides additional ecological resolution, particularly in small-scale or experimental studies. In applied contexts, presence–absence QBS-c can be prioritised when resources are limited, while abundance-weighted QBS-c is particularly useful in experimental or long-term observatories where more detailed information on dominance patterns is desirable. Reporting both presence–absence and abundance-weighted QBS-c will support integration of Collembola-based indicators into broader soil health frameworks, including national or continent-wide monitoring schemes, where consistency and cost-effectiveness are essential. In both cases, the treatment of juveniles should be described clearly, and, where possible, restricted to adults for EMI assignment.

4.1.5 Good practice in implementation and reporting

Transparent reporting of data types, trait sources and computational steps is essential for making EMI- and QBS-c-based studies comparable and reusable. We recommend the following minimum reporting standards:

1. Provide a supplementary table listing all traits used, their type (continuous or ordinal), scoring scheme, and the direction of scores (e.g., higher EMI = more euedaphic).

2. For each species or morphotype, report the trait values and resulting EMI, along with the source of information (empirical measurement vs literature/database).
3. Explicitly describe how species EMIs were aggregated to the community level (presence–absence vs abundance-weighted, treatment of juveniles, handling of unidentified morphotypes).
4. If deviations from the original Parisi or Vandewalle schemes were necessary (e.g., different trait sets, different scoring thresholds), clearly justify these choices and document them so that other studies can reproduce or adjust the procedure.

Adopting these reporting practices will facilitate meta-analysis, cross-site comparisons and integration of QBS-c with other soil quality and functional diversity metrics. It will also help bridge taxonomic trait compilations and applied biomonitoring, making Collembola EMI-based indices more broadly usable in both ecological research and land management.

4.2 Two different paths leading to the same destination for Collembola functional index

Regarding the future application of QBS-c, according to the current techniques, two scenarios are envisioned for future EMI index determination:

- The taxonomic way, which involves the assistance of specialised taxonomists to determine the species for each individual analysed. This approach requires compiling a list of known Collembola species and associating an EMI index with each of them. Once the species are identified, their EMI values are assigned using this list. An important advantage for standardisation is that users can rely directly on published EMI values associated with species names in Parisi-based lists.

- The morphological functional way, which involves measuring morphological traits using image acquisition techniques, and then determining the EMI index through trait measurements, followed by determining a less detailed taxonomic level (family). This approach is time-saving and better reflects empirical conditions.

The choice between the two ways for the index determination will depend on the researcher's expertise. Without measures to train new personnel, support from experienced taxonomists is likely to decrease over the coming years. Therefore, we believe that the second method will become the more popular one, especially for regions where taxonomists are limited. However, for a long-term monitoring of a locality, having taxonomic expertise would be needed, in order to find actual Collembola diversity. The Global Collembola Initiative may provide scientific support not just for connecting researchers of different expertise across the globe together but also training young scientists.

4.3 Bridging QBS-c to Collembola functional ecology

Bioindication applications typically rely on combinations of different trait sets, whereas fundamental community trait ecology tends to focus on the examination of individual traits. In the following section, we will delve into fundamental community ecology within the context of functional traits.

Comparing the efficacy of the QBS-c method to other existing methods, such as the community weighted mean (CWM) and functional diversity (FD) indices, in addressing fundamental ecological questions regarding soil animal at community level is not straightforward (Hishi et al., 2022; Martins da Silva et al., 2016; Moss et al., 2020; Yin et al., 2020; Qiao et al., 2022). This complexity arises because the QBS index is derived from summing values based on multiple trait assessments.

In Parisi (1974, 2005) the morphological characters of edaphic microarthropods that reveal adaptation to soil environments are described as: reduction or loss of pigmentation and visual apparatus; streamlined body form, with reduced and more compact appendages (hairs, antennae, legs); reduction or loss of flying, jumping or running adaptations; reduced water-retention capacity—e.g. thinner cuticle, lack of hydrophobic compounds on the outer surface. The conceptual basis of EMI is to assign higher values to traits associated with greater soil adaptation, and consequently to attribute higher soil quality values to environments with a higher number of euedaphic forms. In this sense, adaptations of morphological traits are considered functional 'responses' to soil microhabitats. These morphological traits have been shown to respond to land use changes and agricultural practices (Martins da Silva et al., 2016; dos Santos et al., 2018; Yin et al., 2020; Chassain et al., 2023). Further studies are required to gain a deeper understanding of the influence of local environmental variables e.g. soil pH, moisture and nutrients on these traits as well as other morphological traits of Collembola.

However, Parisi's framework did not explicitly link these traits to ecosystem services. (Parisi, 1974, 2001, 2005). On the contrary, Vandewalle et al. (2010) showed that trait-based metrics can be linked to ecosystem functions, providing a bridge between biodiversity and ecosystem service provision Furthermore, trait-based metrics can serve as proxies for the rate or relative importance of specific processes and can assist in predicting ecosystem services (Bonfanti et al., 2018).

4.4 Future perspectives

The main future challenge is to standardise the application of QBS-c across countries, to encourage wider adoption of the index and generate comparable datasets for upcoming soil biodiversity and soil health syntheses. We call for a coordinated effort to develop regional and global Collembola EMI databases, ideally by integrating EMI values into existing trait repositories such as ColTrait and BETSI.

In the short term, a global trait list could be built by extending the Italian EMI compilation of Menta (2008) with additional species lists under the supervision of experienced taxonomists. In the medium term, these trait values should be validated using empirical specimens collected through large-scale and standardised sampling campaigns, for example within the Soil BON Foodweb initiative (https://soilbonfoodweb.org/) and other soil biodiversity monitoring projects. In the longer term, integrating automated image analysis (Oriol et al., 2024) and metabarcoding pipelines will allow the development of models for semi-automatic QBS-c implementation in large-scale biomonitoring.

Several technical and conceptual questions remain, particularly regarding how to account for juveniles in QBS-c. Potential solutions include using head-to-body length ratios or assigning different EMIs to juveniles and adults, acknowledging that they may differ in their degree of soil adaptation. Future research should also explore correlations between QBS-c, other soil biological quality indices (such as QBS-e based on earthworms; Paoletti et al., 2013; Fusaro et al., 2018; Ashwood et al., 2023) and standard chemical, physical and microbiological soil properties, as well as links between Collembola morphological traits, soil functions and ecosystem services. Moreover, QBS-c needs to be tested in a wider range of environments beyond forests, pastures and arable fields, including urban areas, green roofs, solar parks, and post-industrial sites. The recent availability of global Collembola community data (Potapov et al., 2024) provides an opportunity to address many of these questions.

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Data availability

Data will be made available on request.

Author contributions

MC and TWC conceived the idea, compiled literature, analysed the data and wrote the manuscript with significant improvement from ALT and SS. All authors contributed critically to the study and approved the final version of the manuscript.

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Conflicts of interest/Competing interests

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

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