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Three-Year Monitoring of the Arthropod-Based Soil Biological Quality Index (QBS-ar) in Arable Fields of the Sentina Reserve: Spatial and Temporal Patterns and Environmental and Management Correlates

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ABSTRACT

Although the arthropod-based Biological Soil Quality Index (QBS-ar) is widely used to assess soil biological quality in agroecosystems, interpreting its variation under field conditions remains challenging. We characterised spatial and temporal patterns in QBS-ar and complementary arthropod-based indicators across four arable fields belonging to two farms within the Sentina Reserve (Central Italy): Fattoria Ferri (FE1 and FE2) and Selva Giurata (RL1 and RL2). Each field was sampled on six occasions, in June and October of each year from 2021 to 2023. Six exploratory multiple linear regression models examined associations between sub-sample level QBS-ar (partial QBS-ar) and six predictor groups: agricultural practices, soil chemistry, textural parameters, soil environmental factors, weather conditions and landscape composition. Across the 24 field-by-occasion assessments, total QBS-ar ranged from 102 to 209. Values were generally higher in the Selva Giurata fields, with RL2 and FE2 showing the highest and lowest mean values, respectively. The complementary biotic metrics followed a similar field-level pattern. At least one term in each predictor-group model met the significance threshold. These terms included exchangeable potassium, tillage for seedbed preparation, harvesting, very fine sand, temperature, relative humidity, soil moisture and the proportions of land classified as agricultural areas and of forest and semi-natural areas. Together, these results show the value of considering both management and environmental context when interpreting QBS-ar variation in field monitoring. The field-specific patterns identified here provide testable hypotheses for broader studies with independent farm-level replication.

1 | Introduction

The global food system is recognised as one of the main drivers of biodiversity loss across the planet (Benton et al. 2021). Intensive agriculture, characterised by monocropping, high chemical inputs, and intensive tillage, has been shown to significantly harm and reduce soil biodiversity particularly in

European agroecosystems (Tsiafouli et al. 2015). These impacts arise from both physical disturbances, such as soil compaction and erosion, and chemical disturbances, including the application of fertilisers and plant protection products (PPPs) (Chassain et al. 2023), particularly herbicides. Conversely, the adoption of sustainable farming practices, that focus on minimising disturbances to the soil, can significantly improve soil

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biodiversity (Bengtsson et al. 2005; Brussaard et al. 2007; Sharma et al. 2024). Techniques such as reduced or minimum tillage, crop rotation, and green manuring, help maintain a healthy soil ecosystem. As a result, soil organisms can thrive, leading to enhanced soil functionality, improving several soil processes, and the overall resilience of agricultural systems (Delgado-Baquerizo et al. 2020).

Among soil fauna, soil microarthropods represent a highly diverse and functionally important group of invertebrates that play a pivotal role in maintaining soil health. They promote soil health through contributions to organic matter decomposition, nutrient cycling, plant growth and overall ecosystem functioning (Lavelle et al. 2006). Their sensitivity to soil disturbance and management, makes them responsive and cost-effective indicators of soil quality (Parisi et al. 2005). One of the most widely used approaches based on soil microarthropod communities is the arthropod-based Soil Biological Quality Index (QBS-ar) (Parisi et al. 2001, 2005). The method is widely applied in Italy and is increasingly gaining international recognition (Menta et al. 2018). Recently, the proposed Standard Operating Procedures (SOPs) within the FAO Global Soil Laboratory Network (GLOSOLAN) further support its harmonised application (Gallese et al. 2025).

The QBS-ar index has been used to monitor and compare soil quality across different land uses (Menta et al. 2018; Machado et al. 2019; Hernández-Tirado et al. 2022), management systems (Ghiglieno et al. 2023; Fusco et al. 2023; Kurniawan et al. 2023), agroecosystems (Menta et al. 2011; Gallese et al. 2025; Coletta et al. 2025), cropping systems (e.g., strip cropping vs. pure stands) (Monticelli et al. 2026), and soil types (Fiorini et al. 2020; Leone et al. 2023). Moreover, it has been proven effective in detecting the effect of a wide range of soil disturbances, including PPPs application (D'Alessandro et al. 2024) photovoltaic installations (Menta et al. 2023), fire events (Mantoni et al. 2020; Memoli et al. 2022; Çakır et al. 2023) and urban pollution (Horváth et al. 2021; Tóth et al. 2023). Despite its widespread use, the relationships between QBS-ar and environmental and management conditions remain only partially understood. Soil chemical and physical properties are often measured alongside QBS-ar, but their direct associations with the index have rarely been assessed. Climatic variability (Ghiglieno et al. 2021; Tóth et al. 2025; Gallese et al. 2025) and landscape structure and composition (Szigeti et al. 2022) have received even less attention, limiting the contextual interpretation of QBS-ar index across heterogeneous agricultural settings.

To address this knowledge gap, a 3-year monitoring campaign was conducted in arable agroecosystems within the Sentina Natural Regional Reserve (Central Italy). Soil biological quality was assessed using total and partial QBS-ar, microarthropod abundance and number of biological (BFs) and euedaphic (EFs) forms (Parisi et al. 2005). Four arable fields (FE1, FE2, RL1 and RL2), belonging to two conventional farms (Fattoria Ferri and Selva Giurata) were monitored from 2021 to 2023. Sampling was conducted in June and October, representing spring and autumn periods, respectively, to capture seasonal variation in QBS-ar values and soil microarthropod communities under contrasting environmental conditions while maintaining a

consistent sampling design across years (D'Avino et al. 2023). The sampling dates were scheduled according to logistical constraints and agreements with farmers to ensure site accessibility and minimise interference with agricultural activities. Environmental and management data were systematically collected at each field, covering agricultural practices, soil chemical and textural properties, soil moisture and temperature at sampling, local weather conditions, and surrounding landscape composition.

The selected fields were described through a holistic and innovative approach that, to our knowledge, has not previously been applied to the QBS-ar index. We considered multiple variables to capture field-specific characteristics as comprehensively as possible.

The fields were close to one another and shared the same pedological origin (Agenzia Servizi Settore Agroalimentare delle Marche A.S.S.A.M. 2006) and local weather pattern, while differing in management history, soil characteristics and landscape context. This setting supported a detailed comparison of QBS-ar patterns and their potential environmental and management correlates under realistic field conditions. We consider this observational study an example of 'real-world' soil monitoring, which could serve as a benchmark in the context of the recent adoption of the EU Soil Monitoring and Resilience Law (Directive (EU) 2025/2360). Establishing trust in practical and integrative monitoring approaches will be crucial for the application of soil biological indicators.

By considering these variables within a common analytical framework, the study sought to enhance the contextual interpretation of the QBS-ar index and to explore how different groups of environmental and management variables were associated with the observed variation in the index. Based on the available literature, this is among the first-field based monitoring studies to examine QBS-ar variability within a common analytical framework.

The main aim of this study was to describe spatial and temporal variation in QBS-ar across four repeatedly monitored fields and to examine its associations with environmental and management variables. The analyses were exploratory, and were guided by the following directional expectations:

- i. We expected QBS-ar, microarthropod abundance, BFs and EFs to be higher in the Selva Giurata fields than in the Fattoria Ferri fields, consistent with the less intensive management documented at Selva Giurata. Based on previous evidence of soil arthropod responses to agricultural disturbance, we also expected these biotic metrics to be lower under more intensive management, particularly in association with tillage, harvesting and other field operations (Parisi, 2001; Parisi and Menta 2008; Sapkota et al. 2012; Fiorini et al. 2020; Pittarello et al. 2022; Kladvko 2001; Köninger et al. 2022).
- ii. Because the four fields were located close to one another and shared a common pedological origin (Agenzia Servizi Settore Agroalimentare delle Marche A.S.S.A.M. 2006), we expected soil texture to vary less among fields than soil nutrient status. Specifically, we expected fields with

higher N, P and K to show higher QBS-ar and associated biotic metrics (Fiorini et al. 2020; Di Giovanni et al. 2024).

- iii. Given the sensitivity of soil mesofauna to soil moisture (Parisi and Menta 2008; Menta et al. 2018; Coleman et al. 2024), we expected QBS-ar values, microarthropod abundance, BF_s and EF_s to be higher during wetter sampling periods, than during drier periods.
- iv. Among the four monitored fields, we expected those embedded in more heterogeneous landscapes, with a greater representation of semi-natural elements, to show higher QBS-ar and associated biotic metrics than fields surrounded predominantly by arable land (Pérez-Bote and Romero 2012; Franin et al. 2016) and neighbouring areas (Querner et al. 2018; Szigeti et al. 2022).

2 | Materials and Methods

2.1 | Study Area

The Sentina Natural Regional Reserve (Ascoli Piceno, Italy) is a complex system characterised by a homogeneous system of land, river, and lake areas; a landscape of water and sand covering an area of 177.55 ha, in the territory of the Municipality of San Benedetto del Tronto (<https://www.riservasentina.it/>). It was established by Regional Decree n. 156 of 14 December 2004. Two farms and two fields for each were selected for the study (FE1 and FE2 for Fattoria Ferri and RL1 and RL2 for Selva Giurata), resulting in a total of four sampling sites (Figure 1, Supporting Information Table S1, Figure S1). In agreement with the Reserve's Management Authority and the

Municipality of San Benedetto del Tronto, which financed the monitoring of the area, all the farms within the Reserve were contacted. As the participation in the project was entirely voluntary, site selection depended on farmers' willingness to collaborate. The sampling design was not pre-established for this study; it was adjusted according to the available sampling sites within the project's voluntary framework. The fields were monitored for 3 years 2021, 2022 and 2023, in spring and autumn. The sites were classified under the 'MS1 management system,' which refers to arable crop rotation excluding fodder, according to the Marche Region Monitoring System of Soils at Multi-Scale Project (Tiberi et al. 2014; Bharti et al. 2017).

2.2 | QBS-ar Index and Other Biotic Parameters

Soil microarthropods were sampled following the methodology described by Parisi (2001) and Parisi et al. (2005). At each field and during each of the six sampling occasions (June and October from 2021 to 2023), the standard QBS-ar protocol was applied by collecting three spatially distinct soil subsamples (A, B and C), each approximately 800 cm³ in volume (Coletta et al. 2025). Subsamples were collected using a cylindrical soil corer at 10 m intervals along a diagonal transect within the central, homogeneous part of each field (Coletta et al. 2025). Sampling effort was standardised across fields, with the number and volume of subsamples, spacing between subsamples, and within-field sampling layout kept constant regardless of field area. Areas affected by disturbance, such as flattened vegetation or tractor tracks, were avoided, and the herbaceous cover was removed before soil coring. According to the standard QBS-ar protocol, the three subsamples collected at each site contributed



FIGURE 1 | Aerial photograph of the Sentina Natural Regional Reserve (in green). The perimeter of the four monitored sites is shown in red, together with the central sampling points. Geographic coordinates are provided in Supporting Information Table S1.

to a single QBS-ar assessment for each sampling occasion. Individual subsamples were additionally considered separately to characterise within-site heterogeneity. Overall, 72 soil subsamples were collected (four fields $\times$ six sampling occasions $\times$ three subsamples). Arthropods were extracted from each subsample for 7 days using the Berlese-Tüllgren funnels, equipped with 25 W light bulbs and a 2-mm mesh sieve. Extracted specimens were preserved in a 75:25 (vol/vol) ethanol-glycerol solution. Microarthropod identification and assignment of eco-morphological index (EMI) values were performed according to Parisi (2001) and Parisi et al. (2005). Within the QBS-ar framework, taxa are classified into biological forms (BFs) based on morphological traits related to soil adaptation, such as reduction or loss of flight and visual adaptations, elongated body shape, reduced appendages, and depigmentation. Each BF is assigned an EMI value ranging from 1 to 20, reflecting its degree of adaptation to the soil environment. For each field-by-occasion assessment, total QBS-ar was calculated by retaining the highest EMI value recorded for each BF across the three subsamples and summing the resulting values. QBS-ar scores were also calculated for each subsample considered separately; these subsample-level scores are hereafter referred to as partial QBS-ar. Microarthropod abundance and the numbers of BFs and euedaphic forms (EFs; EMI = 20) were recorded for each subsample.

2.3 | Agricultural Practices Applied

Data related to management information and agricultural practices applied in each field, such as tillage depth, use of PPPs (herbicides) and fertilisers, and crop succession were collected through detailed questionnaires and interviews with farmers, which were developed as part of the monitoring project (Supporting Information Table S2, Figure S1). Information on the farming practices adopted in previous years was also gathered to obtain a complete picture. A numerical range from 0 (high impact/disturbance) to 100 (low impact/disturbance) was utilised to define the intensity of the various farming strategies employed at the different fields (Supporting Information Table S3). The agricultural practices considered were crop rotation; tillage for seedbed preparation (ploughing and harrowing), use of fertilisers and PPPs (herbicides), irrigation, false sowing, sowing, harvesting, shredding and burial of crop residues (Supporting Information Table S2).

2.4 | Soil Chemical and Textural Parameters

Soil samples for chemical-physical analyses were collected in accordance with the official methods for soil analysis of the Italian legislation DM 13/09/1999 SO No. 185 (*Approvazione dei Metodi Ufficiali di analisi chimica del suolo*). In each field, 10 soil subsamples were collected by using a pedological auger (Eijkelkamp, Giesbeek, The Netherlands) and then mixed and reduced to a single composite sample (1 kg). The samples were analysed by the laboratory of the Agenzia per l'Innovazione nel Settore Agroalimentare e della Pesca delle Marche (AMAP, Jesi, Italy). Soil analyses were performed according to DM 13/09/1999 SO No. 185, while soil texture was determined according to DM 01/08/1997. Soil texture fractions (coarse, fine, very fine

sand, silt, clay; g/kg) were determined by the pipette method after dispersion and sedimentation. Total organic carbon (TOC, g/kg) and total nitrogen (TN, g/kg) were determined by elemental analysis, and organic matter (OM, g/kg) was calculated from TOC using the Van Bemmelen factor. Soil pH was measured potentiometrically in water (1:2.5 soil/water ratio), and the C/N ratio was calculated accordingly. Available phosphorus (P, mg/kg) was determined by the Olsen method, exchangeable potassium (K, mg/kg) by BaCl₂-TEA extraction (barium chloride-triethanolamine, pH 8.1) as appropriate for calcareous soils, cation exchange capacity (CEC, meq/100 g), and electrical conductivity (EC, dS/m) on soil aqueous extracts. Samples for soil chemical-physical analyses were collected in spring 2021 (at the beginning of the study) and in autumn 2023 (at the end of the study) to evaluate any changes in the fertility status of the investigated soils.

2.5 | Weather and Soil Environmental Factors

The Sentina Reserve lies in the temperate climate zone, specifically in a transitional climate between the Mediterranean and European subcontinental sub-types. Summers are moderately hot and dry and winters are generally mild. Average annual temperature in coastal areas of the Marche region is 13–15°C, and average annual precipitation near the Reserve is approximately 550–650 mm (Sinatra 2014). Monthly mean temperature, precipitation and relative humidity for 2020–2023 were obtained from AMAP weather station at Spinetoli (Ascoli Piceno, Italy). Due to the limited extension of the study area, these weather observations were treated as common to all four fields and were used to explore temporal associations with QBS-ar across years and seasons (Supporting Information Figures S3, S4). Soil moisture (%) and temperature (°C), were also measured in triplicate on site, adjacent to each sampling point using portable probes: PMS-714 (Lutron, Taipei, Taiwan) soil moisture metre and a HI-98501 thermometer (Hanna Instruments, Milan, Italy) (Supporting Information Table S4). These measurements characterised the local conditions at sampling and were included in the exploratory analysis.

2.6 | Landscape

To characterise the surrounding landscape and explore its association with QBS-ar, land use and land cover classes were mapped in a Geographic Information System (GIS) software, running on QGIS v. 3.34.12-Prizren. The Sentina Nature Reserve map from Santolini et al. (2016) was digitised in the QGIS software based on the land use map (Carta dell'uso del suolo CUS 2007) and the vegetation map (Carta della Vegetazione 2009). Data on railways, waterways and roads were retrieved from OpenStreetMap (OSM 2026) and subsequently processed in QGIS. The map was then updated through visual interpretation of Google's 2023 satellite image, available via the Quick Map Services QGIS plugin. A fixed 500-m-radius buffer centred on each plot centroid (approximately 78.5 ha) was used for all fields, following Le Provost et al. (2021). Because the focal fields represented only 0.9%–3.7% of their respective buffers, variation in field area had only a minor effect on the estimated proportion of agricultural land. Twenty land-use and land-cover

types were identified within the four buffers (arable land, continuous buildings, salt marsh vegetation, paved roads, olive groves, unpaved roads, halophytes, scattered buildings, hedges and shrubs, railway, reedbed, pond and small lakes, riparian woodland, gardens and parks, watercourse, grassland, vineyards, psammophilous or arenophilous vegetation, sea, shoreline), and the percentage of each type was calculated for each field (Figure 2; Supporting Information Table S5).

2.7 | Statistical Analysis

Total QBS-ar was calculated for each field and sampling occasion, yielding 24 field-by-occasion assessments (four fields $\times$ six occasions). Partial QBS-ar, microarthropod abundance, BFs and EFs were calculated for each of the 72 subsamples (four fields $\times$ six occasions $\times$ three subsamples) to characterise within-field variation. The data were first checked for normality of distribution (Shapiro-Wilk test) and homoscedasticity (Levene's or Bartlett's test, depending on the distribution). Between-farm comparisons were performed separately for each sampling occasion using Student's *t*-test or the Wilcoxon rank-sum test, as appropriate. Comparisons among fields and years, and seasons were performed using one-way ANOVA or the Kruskal-Wallis test, followed by Tukey's honestly significant

difference or Dunn's post hoc test when applicable. The analyses did not include site-level clustering or repeated-measure terms and were used to describe patterns and associations within the four monitored fields. Six separate exploratory multiple linear regression (MLR) models (*lm*, package 'stats') were fitted with partial QBS-ar as the response variable, one for each predictor group: agricultural practices, soil chemical properties and soil textural properties, landscape, weather and soil environmental factors (Supporting Information Table S3). The weather, landscape, agricultural-practice, soil-texture and soil-environmental models used all 72 subsample-level scores. For the soil-chemical model, the three partial QBS-ar values from each field were linked to the corresponding field-level soil chemical data obtained from the composite sample collected in spring 2021 and autumn 2023, yielding 24 records (four fields $\times$ two sampling occasions $\times$ three subsamples). Models were fitted with all candidate predictors when the number of QBS-ar observations allowed an adequate observation-to-predictor ratio. Multicollinearity was assessed using pairwise Pearson correlations and variance inflation factors (VIFs). A conservative correlation threshold of $|r| > 0.90$ was used to identify highly redundant predictors, while VIF values < 7 were considered acceptable. When predictor reduction was required because of highly correlated variables, alternative predictor sets were compared using root mean square

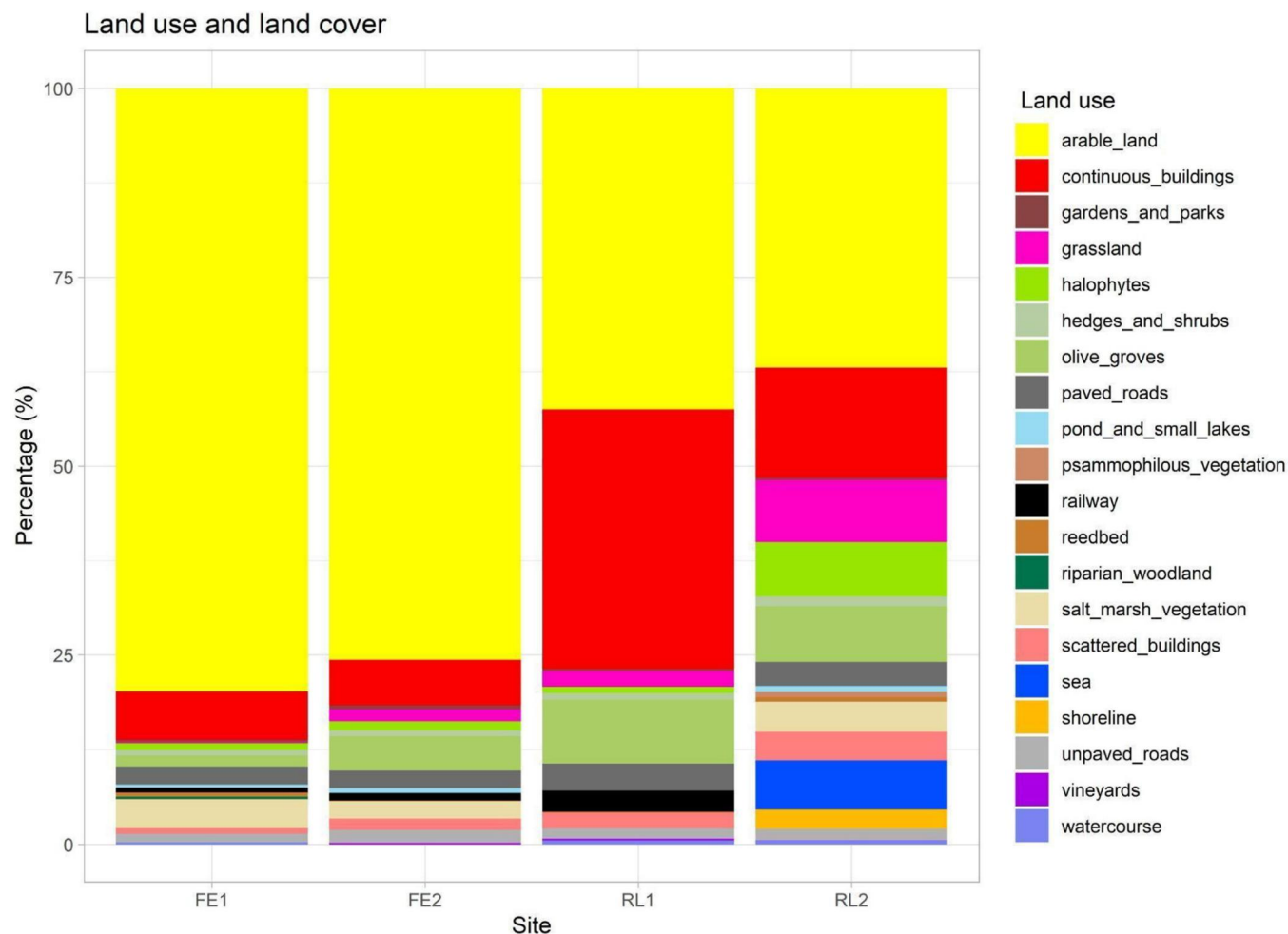


FIGURE 2 | Barplot of land-use and land-cover types present in each site (FE1, FE2, RL1 and RL2) considering a landscape-level spatial scale (i.e. 500 m radii from plot centroids).

error (RMSE), mean absolute error (MAE), and Akaike information criterion (AIC), and the most appropriate combination was retained. For the soil-chemical model, where nine candidate predictors were evaluated against 24 QBS-ar observations, predictor reduction was required due to the limited observation-to-predictor ratio. Correlated predictors were therefore screened before model fitting, and alternative predictor sets were evaluated based on collinearity diagnostics and model performance metrics. Where further reduction was required, final terms were retained by backward elimination based on AIC.

Residuals were examined for normality, heteroscedasticity using the Breusch-Pagan test and autocorrelation using the Durbin-Watson test. Candidate predictors are listed in Supporting Information Table S3 and retained terms in Table 3. R^2 values summarised within-dataset model fit, while p -values < 0.05 identified associations for further interpretation. All regression results were interpreted as exploratory associations rather than causal effects. Analyses were performed in R version 4.4.0 (R Development Core Team 2021).

3 | Results

3.1 | QBS-ar Results

Across the 24 field-by-occasion assessments, total QBS-ar ranged from 102 to 209 (Table 1). The descriptive mean total QBS-ar was higher for the Selva Giurata fields than for the Fattoria Ferri fields (168 vs 148), although field-level means overlapped: FE2 had the lowest mean (130), RL2 the highest (178), and FE1 and RL1 had intermediate values (166 and 158, respectively). Exploratory comparisons of partial QBS-ar distributions detected a difference between the two farms only in spring 2022; all other occasion-specific comparisons were not significant (Figure 3A).

3.2 | Soil Microarthropod Abundance

Mean subsample-level microarthropod abundance was higher in the Selva Giurata fields than in the Fattoria Ferri fields (2306 vs 767 individuals; Figure 3B). Exploratory comparisons between the two farm contexts detected differences in spring and autumn 2021 and in spring 2022, but not at the other sampling occasions. Abundance was highest overall in 2021 and varied markedly among fields and occasions. Field-by-occasion

means ranged from 70 individuals at FE2 in spring 2022 to 8316 at RL2 in spring 2021; in autumn 2022, RL1 had the highest abundance (2208), whereas abundance at RL2 declined to 395 individuals (Table 2).

3.3 | Biological (BFs) and Euedaphic Forms (EFs)

The numbers of BFs and EFs broadly followed the QBS-ar pattern. Both metrics were lower overall in 2022 than in 2021 and 2023, although only EFs showed a significant among-year difference (Table 2). Values were generally higher in the Selva Giurata fields. Exploratory comparisons between the two farm contexts detected higher numbers of BFs at Selva Giurata in spring 2021, spring 2022 and autumn 2023, whereas EFs were higher at Selva Giurata only in autumn 2022 (Figure 3C,D). Across the four fields, FE2 most often had the lowest BF and EF values, while RL2 frequently had the highest values (Table 2).

3.4 | Agricultural Practices Applied

Management practices differed most clearly in tillage and crop sequence. At Fattoria Ferri, seedbed preparation involved medium tillage (35 cm) followed by post-tillage harrowing (< 15 cm), whereas shallow tillage (< 15 cm) was more frequently used at Selva Giurata. An exception occurred in autumn 2022, when deep tillage (50 cm) followed by harrowing (< 15 cm) was applied at both RL1 and RL2. RL1 included field bean and horseradish as cover crops, which were subsequently incorporated as green manure. Wheat predominated in most other field-by-occasion combinations, although leek and maize were also grown at FE2 (Supporting Information Table S2; Figure S1). Fertiliser and herbicide (PPPs) applications, harvesting, sowing, crop-residue management and irrigation varied among fields and sampling occasions and did not consistently distinguish the two farm contexts. Overall, the clearest management contrasts concerned tillage depth and the use of cover crops and green manuring. The complete chronology of field operations is provided in Supporting Information Table S2.

3.5 | Soil Chemical and Textural Properties

The four fields spanned three USDA soil-texture classes: FE1 was classified as silt loam, RL1 as loam, and FE2 and RL2 as sandy loam (Supporting Information Table S6; Figure S2).

TABLE 1 | Total QBS-ar values obtained in each farm and site in the 3 years and the average total QBS-ar values across the two farms, the four sites, and according to the season.

Farm	Site	2021		2022		2023		Average total QBS-ar values per site	Average total QBS-ar values per farm
		Spring	Autumn	Spring	Autumn	Spring	Autumn		
Fattoria Ferri	FE1	138	168	154	159	207	172	166	148
	FE2	174	120	102	113	136	132	130	
Selva Giurata	RL1	158	175	165	125	153	172	158	168
	RL2	194	163	153	149	209	202	178	
Average total QBS-ar values per season		166	157	144	137	176	170		

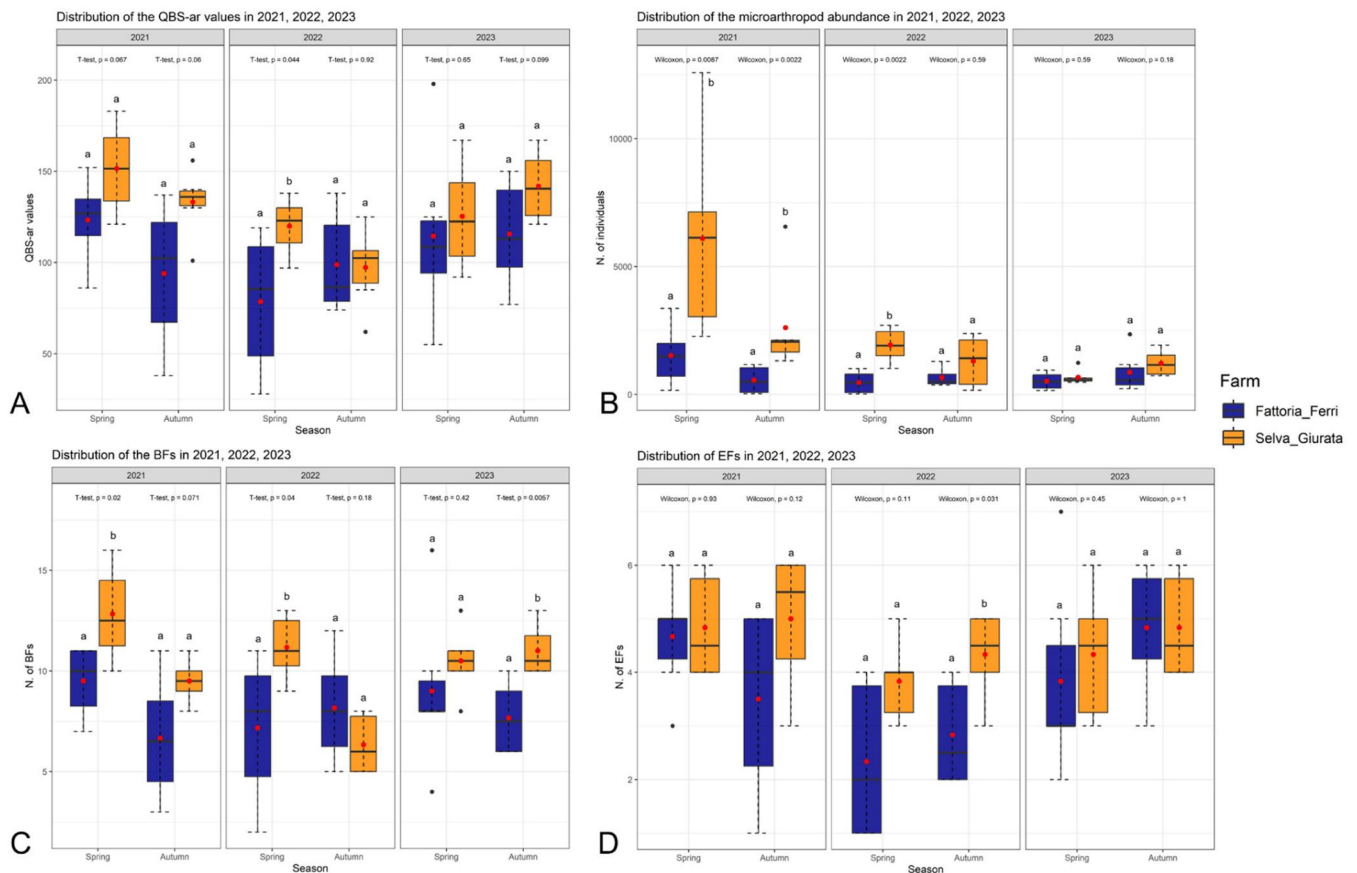


FIGURE 3 | The boxplots show the distribution of the partial QBS-ar values (A), average microarthropod abundance (B), number of Biological forms (BFs) (C) and Euedaphic forms (EFs) (D) in the two monitored farms (blue: Fattoria Ferri; orange: Selva Giurata) by year and season. The horizontal line is the median, the red dot is the mean, whiskers show the boxplot range and isolated black dots are outliers. Lowercase letters represent significant differences between farms by Student's t-test or Wilcoxon test at p -value < 0.05.

TABLE 2 | Mean partial QBS-ar values, microarthropod abundance, number of BFs and EFs by site, year and season. Partial values were calculated for the three spatial subsamples within each site-specific sampling event and describe within-site variation.

Farm	Site	2021		2022		2023		Biotic parameters
		Spring	Autumn	Spring	Autumn	Spring	Autumn	
Fattoria Ferri	FE1	116	119	101	120	135	139	QBS-ar index
	FE2	130	69	56	78	94	92	
Selva Giurata	RL1	130	122	123	103	101	128	
	RL2	173	144	117	91	150	156	
Fattoria Ferri	FE1	2291	1047	867	907	654	1057	Soil micro-arthropod abundance
	FE2	751	76	70	410	392	679	
Selva Giurata	RL1	3883	1849	1787	2208	542	1365	
	RL2	8316	3370	2073	395	805	1073	
Fattoria Ferri	FE1	9	9	10	10	11	9	BFs
	FE2	10	4	4	6	7	6	
Selva Giurata	RL1	11	9	12	6	9	10	
	RL2	14	10	10	7	12	12	
Fattoria Ferri	FE1	4	4	3	4	4	6	EFs
	FE2	5	3	2	2	3	4	
Selva Giurata	RL1	4	4	4	5	3	4	
	RL2	6	6	4	4	5	5	

Between the spring 2021 and autumn 2023 chemical surveys, exchangeable K showed the clearest among-field contrast. At RL2, it decreased from 314 to 228 mg/kg but remained well above the values recorded at the other fields (77–126 mg/kg). Available P decreased at all four fields, most markedly at RL2 (from 40.0 to 13.8 mg/kg). At RL2, soil organic matter, total organic carbon and total N also decreased, from 17.6 to 10.2, 10.2 to 5.9 and 1.4 to 0.7 g/kg, respectively. Complete soil-chemical profiles are reported in Supporting Information Table S7.

3.6 | Weather and Soil Environmental Factors

Autumn weather conditions were broadly similar among years, with a recurrent October water deficit (Supporting Information Figure S3). Spring conditions differed more clearly: 2021 and 2022 were relatively dry, whereas spring 2023 was markedly wetter, and RL1 flooded before sampling. Relative humidity in the sampling months was higher in October than in June in 2021 and 2022, whereas the reverse pattern occurred in 2023 (Supporting Information Figure S4). Across the four fields, soil moisture at sampling averaged 16.9% in spring and 16.4% in autumn, while the corresponding mean soil temperatures were 23.7°C and 19.5°C. Mean soil moisture was highest in spring 2023 (28.3%) and lowest in spring 2021 (10.5%); mean soil temperature was highest in spring 2022 (26.8°C) and lowest in autumn 2023 (18.2°C) (Supporting Information Table S4).

3.7 | Landscape Context

Within the fixed 500-radius buffers, the Fattoria Ferri fields were strongly dominated by arable land, which accounted for 79.8% around FE1% and 75.6% around FE2, compared with 42.6% around RL1% and 36.9% around RL2 (Figure 2; Supporting Information Table S5). RL1 was distinguished by the highest proportion of continuous buildings (34.4%). RL2 combined the lowest arable cover with the greatest representation of forest and semi-natural areas, wetlands and water bodies and was the only buffer containing psammophilous vegetation, sea and shoreline. The complete distribution of the 20 land-use and land-cover classes is reported in Supporting Information Table S5.

3.8 | Exploratory Multiple Linear Regression (MLR) Models

The exploratory MLR models were fitted separately for the six predictor groups and described associations with partial QBS-ar within the analysed observations (Table 3). The agricultural-practice model showed evidence of an overall association with partial QBS-ar ($R^2 = 0.2954$, model $p = 0.001542$). Among the retained predictors, tillage ($p = 0.02088$) and harvesting ($p = 0.00228$) met the significance threshold, whereas the remaining management variables did not. The soil-chemical model also showed an overall association with partial QBS-ar ($R^2 = 0.5415$, model $p = 0.0002778$). Exchangeable K was the only retained chemical predictor that met the significance threshold ($p = 0.000379$), while total N did not ($p = 0.090472$). The soil-texture model showed an overall association

($R^2 = 0.2105$, model $p = 0.0002877$), with very fine sand emerging as the only significant retained predictor ($p = 0.00443$), whereas coarse sand did not ($p = 0.42722$).

The landscape, weather and soil-environmental models also showed overall associations with partial QBS-ar. In the landscape model ($R^2 = 0.2046$, model $p = 0.0003714$), both agricultural areas ($p = 0.0207$) and forest and semi-natural areas ($p = 0.0183$) were retained as significant predictors. In the weather model ($R^2 = 0.1112$, model $p = 0.04447$), temperature ($p = 0.012761$) and relative humidity ($p = 0.006408$) met the threshold, whereas precipitation did not ($p = 0.73889$). In the soil-environmental model ($R^2 = 0.1021$, model $p = 0.02433$), soil moisture met the threshold ($p = 0.00675$), whereas soil temperature did not ($p = 0.55826$). All retained predictors and the corresponding model statistics are reported in Table 3. Because each predictor group was analysed using a separate model, the R^2 values describe the fit of individual models and were not intended for formal comparison among predictor groups.

4 | Discussion

Across the four monitored fields, all 24 total QBS-ar values exceeded the tentative threshold of 93.7 proposed by Menta et al. (2018) to distinguish agricultural soils with high biological quality from values typical of poor quality soils. Mean total QBS-ar was 162 in spring and 155 in autumn (Table 1), within the broad range reported for agricultural areas in the Marche region (Perinelli et al. 2025; D'Alessandro et al. 2024; Coletta et al. 2025).

4.1 | Agricultural Practices and Soil Microarthropod Metrics

Among the four fields, FE2 had the lowest mean total QBS-ar (130) and generally the lowest partial QBS-ar, microarthropod abundance and numbers of BF and EFs (Tables 1 and 2). Its management history combined repeated medium tillage (35 cm) followed by post-tillage harrowing (< 15 cm) herbicide applications during four sampling occasions and the most varied crop sequence, from soft wheat to leek, maize and durum wheat (Supporting Information Table S2). Neither Fattoria Ferri fields included legumes or cover crops in the recorded crop sequence.

At Selva Giurata, shallow tillage (< 15 cm) was used at both fields until the deep tillage applied in autumn 2022, while cover cropping and green manuring were recorded at RL1. Notably, RL2 had the highest mean total QBS-ar (178) and frequently showed high values for the complementary biotic metrics, particularly in 2021 and 2023. In spring 2021, RL2 had the highest total and partial QBS-ar, microarthropod abundance and numbers of BF and EFs among the four fields (Tables 1 and 2). This sampling occasion coincided with two fertilisation applications during soft-wheat cultivation and with the highest available P and exchangeable K concentrations recorded in the 2021 chemical survey (Supporting Information Tables S2 and S7). Soil-fauna responses to fertilisation depend on fertiliser type, application regime, functional group and environmental conditions (Di Giovanni et al. 2024). The recorded applications

TABLE 3 | Exploratory multiple linear regression models relating partial QBS-ar values to the six predictor groups. Candidate predictors are listed in Supporting Information Table S3. Predictor reduction considered the observation-to-predictor ratio, pairwise correlations ($|r| > 0.90$ indicating high redundancy), VIFs (values < 7 considered acceptable), and comparisons of alternative predictor sets using AIC, RMSE and MAE, as described in Section 2.7. R^2 values are reported as model-specific summaries of fit.

Weather	Landscape	Agricultural practices	Soil chemical properties	Soil textural properties	Soil environmental factors
Temperature ($^{\circ}\text{C}$), $p\text{-value} = 0.012761$	Agricultural areas (%), $p\text{-value} = 0.0207$	Tillage for seed bed preparation, $p\text{-value} = 0.02088$	Total nitrogen (TN) (g/kg), $p\text{-value} = 0.090472$	Coarse sand (g/kg), $p\text{-value} = 0.42722$	Soil moisture (%), $p\text{-value} = 0.00675$
Relative humidity (%), $p\text{-value} = 0.006408$	Forest and semi natural areas (%), $p\text{-value} = 0.0183$	Harvesting, $p\text{-value} = 0.00228$	Exchangeable potassium (mg/kg), $p\text{-value} = 0.000379$	Very fine sand (g/kg), $p\text{-value} = 0.00443$	Soil temperature ($^{\circ}\text{C}$), $p\text{-value} = 0.55826$
Precipitation (mm), $p\text{-value} = 0.073889$	Residual standard error: 30.47 on 69 degrees of freedom	Irrigation, $p\text{-value} = 0.50490$	Residual standard error: 19.01 on 21 degrees of freedom	Residual standard error: 30.36 on 69 degrees of freedom	Residual standard error: 32.37 on 69 degrees of freedom
Residual standard error: 32.44 on 68 degrees of freedom	Multiple R^2 : 0.2046 Adjusted R^2 : 0.1816	Sowing, $p\text{-value} = 0.08176$	Multiple R^2 : 0.5415 Adjusted R^2 : 0.4979	Multiple R^2 : 0.2105 Adjusted R^2 : 0.1876	Multiple R^2 : 0.1021 Adjusted R^2 : 0.07608
Multiple R^2 : 0.1112	F-statistic: 8.875 on 2 and 69 DF, $p\text{-value}$: 0.0003714	False sowing, $p\text{-value} = 0.78390$	F-statistic: 12.4 on 2 and 21 DF, $p\text{-value}$: 0.0002778	F-statistic: 9.198 on 2 and 69 DF, $p\text{-value}$: 0.0002877	F-statistic: 3.923 on 2 and 69 DF, $p\text{-value}$: 0.02433
Adjusted R^2 : 0.07201		Use of herbicides and fertilisers, $p\text{-value} = 0.47282$			
		Shredding and burial of crop residues, $p\text{-value} = 0.20223$			
F-statistic: 2.837 on 3 and 68 DF, $p\text{-value}$: 0.04447		Residual standard error: 29.78 on 64 degrees of freedom			
		Multiple R^2 : 0.2954 Adjusted R^2 : 0.2184			
		F-statistic: 3.833 on 7 and 64 DF, $p\text{-value}$: 0.001542			

therefore formed one component of the broader fertility, management and environmental context in which the high biotic values at RL2 were observed.

In 2022, RL1 had higher partial QBS-ar and microarthropod abundance than RL2 in both sampling periods. Total QBS-ar was also higher at RL1 in spring, whereas RL2 had the higher value in autumn; BF and EF patterns differed between metrics and occasions. This partial RL1 advantage followed the incorporation of the field-bean and horseradish cover crop, shallow tillage and false sowing recorded at RL1 in autumn 2021. These practices may have contributed to better soil nutrient management and structure improvement, which facilitated nutrients uptake (Xing et al. 2025). During autumn 2022, when deep tillage was applied at both Selva Giurata fields, total and partial QBS-ar were lower than in spring at both RL1 and RL2. BF also declined at both fields, while abundance declined markedly at RL2 but increased at RL1 and EF remained unchanged or increased slightly (Tables 1 and 2). The autumn management sequence at RL1 differed among years. In 2021, residue incorporation was followed by shallow tillage, false sowing, fertilisation and sowing. In 2022, harvesting and residue incorporation were followed by deep tillage, harrowing, fertilisation, false sowing and sowing. In 2023, harvesting and residue incorporation were the only recorded operations (Supporting Information Table S2). Corresponding autumn total and partial QBS-ar values were 175 and 122 in 2021, 125 and 103 in 2022, and 172 and 128 in 2023 (Tables 1 and 2). Each autumn observation thus represented a distinct combination of field operations. Tillage for seedbed preparation and harvesting were also the only management terms meeting the significance threshold in the exploratory model for partial QBS-ar (Table 3), identifying them as the clearest management correlates within the analysed dataset.

Taken together, the results were broadly consistent with expectation (i). The QBS-ar and the complementary biotic metrics were generally higher in the Selva Giurata context than in the Fattoria Ferri context. Support for this expectation was strongest in the field means and complementary metrics. In this regard, among the partial distributions of the QBS-ar for specific sampling occasions, a difference between the two farm contexts was detected in spring 2022 (Figure 3A). Within the four monitored fields, higher values were most often observed alongside shallower tillage and, at RL1, cover-crop incorporation and green manuring. This pattern is consistent with studies reporting higher QBS-ar under reduced tillage or conservation management (Parisi and Menta 2008; Sapkota et al. 2012; Fiorini et al. 2020; Pittarello et al. 2022) and with broader evidence concerning soil-arthropod responses to agricultural management (Gonçalves et al. 2021).

4.2 | Soil Chemical and Textural Properties and Soil Microarthropod Metrics

Soil chemical parameters explained a significant portion of the variance of the exploratory model for partial QBS-ar index ($R^2 = 0.5415$, model $p < 0.001$; Table 3). K was the only retained parameter that met the significance threshold ($p < 0.001$), exhibiting the greatest variation between fields and being consistently higher in RL2 (Supporting Information Table S7). Although exchangeable K decreased at RL2 from 314 mg/kg in 2021 to 228 mg/kg in 2023, both values remained substantially

higher than those recorded at the other fields. This field-level contrast coincided with high total and partial QBS-ar and several complementary biotic metrics at RL2, particularly in spring 2021 and during 2023 (Tables 1 and 2). Relationships between K and soil fauna appear to vary among study systems and response variables. Inkotte et al. (2024) identified K among the soil properties associated with several mesofauna groups across dry and rainy seasons, particularly Collembola during the rainy season. Fiera et al. (2020) also examined K in relation to springtail communities, although its association with species richness did not meet the significance threshold. Conversely, Mantoni et al. (2021) reported weak negative relationships between K and QBS-ar, richness and abundance. Together, these studies place the association observed here within a broader, context-dependent relationship between soil fertility and arthropod communities. At RL2, the high exchangeable K formed part of a wider field context that included repeated fertilisation during wheat cultivation (Supporting Information Tables S7 and S2). The other primary macronutrients did not show the same pattern as K. Available P decreased between the two chemical surveys at all four fields, most markedly at RL2, from 40.0 to 13.8 mg/kg. The particularly high P concentration at RL2 in spring 2021 coincided with the highest biotic values recorded during that sampling occasion. Ghiglieno et al. (2023) identified exchangeable P among the soil variables related to QBS-ar variation, whereas Mantoni et al. (2021) found a significant negative association. Total N varied within a relatively narrow range in 2021 but decreased from 1.4 to 0.7 g/kg at RL2 by 2023. In the exploratory chemical model, total N was retained but did not meet the term-level significance threshold, while P was not retained in the final model (Table 3).

Soil texture was also associated with partial QBS-ar in the exploratory analysis ($R^2 = 0.2105$, model $p < 0.001$; Table 3). Very fine sand was the only textural parameter meeting the significance threshold ($p = 0.0044$), whereas coarse sand was retained but showed no evidence of association. This result is consistent with previous research linking soil texture to soil mesofauna activity and distribution (Ruf and Beck 2005; Wolfarth et al. 2013; Van Capelle et al. 2012; Domene et al. 2011; Vanolli et al. 2024; Leone et al. 2023; Coletta Martina, Innangi Michele, Marinsalti Silvia, Kumar Santosh, Bharti Daizy, Insom Emilio, Ciabocco Giovanni, Tiberi Mauro, La Terza Antonietta, manuscript in preparation). The association with very fine sand was therefore detected within a relatively restricted range of loam-related textures, and its broader applicability could be evaluated across a wider textural gradient. Overall, these findings were partly consistent with expectation (ii). The fields occupied a relatively restricted range of soil textures, although they were distributed among three USDA classes rather than being texturally uniform (Supporting Information Table S6; Figure S2). Among the expected macronutrients, exchangeable K was the only one showing clear model-level evidence of association with partial QBS-ar, whereas the results did not provide comparable evidence for N or P.

4.3 | Soil Microarthropods Responses to Weather and Soil Environmental Conditions Across Years and Seasons

The temporal patterns were only partly consistent with expectation (iii), which predicted higher QBS-ar and associated

biotic metrics during wetter sampling periods than during drier periods. Spring 2023 had the highest rainfall (Supporting Information Figure S3), and heavy rain in May flooded RL1 before spring sampling. At sampling, RL1 also had the highest soil-moisture reading recorded during the study (40.6%; Supporting Information Table S4). Nevertheless, its total QBS-ar (153), partial QBS-ar (101), microarthropod abundance (542) and numbers of BF (9) and EF (3) were all lower than in the two preceding spring samplings (Tables 1 and 2). Across the four fields, mean total QBS-ar was highest in spring 2023 (176), but partial QBS-ar and the complementary metrics did not increase uniformly. This contrast is consistent with the different biological implications of adequate soil moisture and short-term waterlogging, the latter potentially restricting soil aeration and microarthropod activity. Responses to combined drought and flooding can also differ between QBS-ar and microarthropod abundance (Lakshmi et al. 2021). The autumn pattern provided clearer, although incomplete, support for expectation (iii). In autumn 2023, total and partial QBS-ar and the number of BF were higher than in autumn 2021 and 2022 (Figure 3A, C; Tables 1 and 2). The 2023 autumn sampling followed a summer with only one dry month, whereas the 2021 and 2022 autumn samplings followed dry periods lasting approximately 3 months (Supporting Information Figure S3). EFs were also numerically higher in autumn 2023, while microarthropod abundance remained below the value recorded in autumn 2021. Thus, the wetter preceding conditions coincided with higher QBS-ar and functional-form metrics, but not with a uniform increase in all biotic parameters.

During the spring sampling, 2021 showed the highest microarthropod abundance, while the numbers of BF and EF were also higher than in the dry spring of 2022, and the very wet spring of 2023 (Figure 3C, D; Table 2). This occurred despite spring 2021 having the lowest mean soil-moisture reading at the time of sampling (10.5%; Supporting Information Table S4). The weather record and the probe measurements therefore represented complementary temporal scales, the former described conditions during the months preceding sampling, whereas the latter characterised soil conditions at the sampling occasion. Rainfall in late winter 2020 and early 2021 formed part of the preceding weather context associated with the high spring 2021 abundance (Supporting Information Figure S3). Overall spring–autumn contrasts were limited: no seasonal difference was detected for QBS-ar, microarthropod abundance or EFs, whereas BF were higher in spring. In 2022, annual total and partial QBS-ar and the mean numbers of BF and EF were the lowest of the three monitoring years; abundance was lower than in 2021 but not than in 2023. This temporal pattern coincided with the prolonged water-stress period shown in Supporting Information Figure S3 and with the 2022 management sequence discussed in Section 4.1. Considering soil environmental conditions, the descriptive correspondence with QBS-ar depended on season and analytical scale.

Seasonally averaged total QBS-ar tended to be higher at sampling occasions characterised by higher soil moisture and lower soil temperature. Autumn partial QBS-ar showed a similar pattern, whereas no consistent relationship emerged for the spring partial values. At the individual field-by-occasion level, soil moisture and temperature were often inversely related, but

their correspondence with partial QBS-ar varied among fields and sampling occasions.

In the exploratory analyses, the weather model had $R^2 = 0.1112$ (model $p = 0.0445$), with temperature and relative humidity meeting the term-level significance threshold, whereas precipitation did not. The soil-environmental model had $R^2 = 0.1021$ (model $p = 0.0243$), with soil moisture, but not soil temperature, showing evidence of association with partial QBS-ar (Table 3). The weather-station data characterised the temporal context shared by the four fields, while the probe measurements captured local soil conditions at sampling. Their combined use can therefore strengthen the interpretation of longitudinal QBS-ar monitoring, particularly when cumulative precipitation and extreme events are considered alongside sampling-time conditions (Lakshmi et al. 2021; Gallese et al. 2025). According to Parisi et al. (2005), QBS-ar samples should be collected when soil moisture is between 40% and 80% of field capacity. Expressing future field measurements relative to site-specific field capacity would allow this sampling criterion to be evaluated directly.

4.4 | Landscape Context and Soil Microarthropod Biotic Metrics

The landscape surrounding Fattoria Ferri fields was predominantly characterised by arable land. Within the fixed 500-m buffers, arable land represented 79.8% of the area surrounding FE1 and 75.6% around FE2 (Figures 1 and 2; Supporting Information Table S5). FE2 had slightly lower arable cover and greater representation of grassland and olive groves than FE1, but it did not have a greater overall proportion of forest and semi-natural elements. Nevertheless, mean total and partial QBS-ar were lower at FE2 than at FE1 (Tables 1 and 2). Thus, the modest difference in land-cover composition between the two Fattoria Ferri buffers was not accompanied by higher biotic values at FE2. In contrast, the Selva Giurata fields were embedded in landscape with substantially less arable land, which represented 42.6% of the RL1 buffer and 36.9% of the RL2 buffer. The composition of these two buffers, however, differed markedly. RL1 had the highest proportion of continuous buildings (34.4%), whereas RL2 combined a lower proportion of continuous buildings (14.6%) with the greatest representation of grassland (8.2%), halophytes (7.2%), salt-marsh vegetation (4.0%), hedges and shrubs (1.3%), ponds and small lakes (0.8%), psammophilous vegetation (0.7%), shoreline (2.6%) and sea (6.5%) (Figure 2; Supporting Information Table S5). Landscape heterogeneity therefore represented different ecological compositions at RL1 and RL2: at RL1 it largely reflected the combination of agricultural and built-up land, whereas at RL2 it included a broader mixture of semi-natural, wetland and coastal elements. The greater proportion of continuous buildings within the RL1 buffer (34.4%, compared with 14.6% around RL2) coincided with a lower representation of several semi-natural, wetland and coastal land-cover types (Figure 2; Supporting Information Table S5). This compositional contrast may be ecologically relevant because field margins and other non-cultivated habitats can support abundant and diverse arthropod assemblages (Franin et al. 2016; Pérez-Bote and Romero 2012), while agricultural fields embedded within protected areas may

show higher soil biological quality, highlighting the relevance of the surrounding landscape matrix (Mantoni et al. 2021). Such habitats may therefore act as potential source areas contributing to the recolonisation of cultivated soils following disturbance. The connection between surrounding habitats and field communities depends, however, on taxon-specific dispersal pathways and spatial scales. Olejniczak (2004) documented differences in soil-microarthropod communities between a shelterbelt and an adjacent wheat field sampled at distances of 0.5–50 m, whereas Cameron et al. (2013) showed in microcosms that soil corridors facilitated active belowground movement over centimetre scales. At the landscape level, Querner et al. (2018) discussed associations between Collembola richness and landscape variables at 250–1000 and 1000–1750 m, interpreting the smaller- and larger-scale relationships as potentially reflecting active migration from bordering habitats and passive wind dispersal, respectively. Haque et al. (2024) directly documented taxon-dependent colonisation of experimental coastal islands located 500 m from source habitats, primarily through passive dispersal, while Le Provost et al. (2021) detected responses of belowground biodiversity to landscape composition across 500-, 1000- and 2000-m radii. Thus, the fixed 500-m buffers used here captured an ecologically plausible landscape context for interpreting the contrasting biotic patterns, although the processes represented by this scale may differ among microarthropod groups.

Within this landscape context, RL2 had the lowest proportion of arable land and the highest proportions of grasslands, halophytes, hedges and shrubs, shoreline, psammophilous vegetation, ponds and small lakes the four field landscapes (Figure 2, Supporting Information Table S5). This distinctive landscape composition corresponded to the strongest overall biological profile recorded during the monitoring. RL2 had the highest mean total QBS-ar (178) and, across the six sampling occasions, the highest mean partial QBS-ar, microarthropod abundance and numbers of BF and EF (Tables 1 and 2). RL2 was also the only study field located within the protection zone of the Reserve, whereas FE1, FE2 and RL1 were situated in the economic and social promotion zone, where human activities predominate (Figure 1). The highest soil biological quality values therefore occurred where protected-area zoning coincided with the greatest representation of semi-natural, wetland and coastal habitats. By comparison, RL1 had a lower mean total QBS-ar (158) and lower overall values for partial QBS-ar and the complementary biotic metrics, despite the comparatively less intensive agricultural practices described in Section 4.1. The biological contrast between RL1 and RL2 consequently highlights the relevance of landscape composition and protected-area context alongside field management and soil properties.

These findings supported expectation (iv) most clearly for the Selva Giurata fields: the landscape with the greatest representation of semi-natural elements was associated with the highest QBS-ar and complementary biological metrics. The same pattern did not emerge at Fattoria Ferri, where FE2 was slightly less dominated by arable land than FE1 but showed lower total and partial QBS-ar, microarthropod abundance, BF and EF. This contrast indicates that the biological response was related not simply to a minor reduction in arable cover, but to the extent and ecological composition of the surrounding non-

cultivated habitats. The exploratory landscape model further supported the relevance of the surrounding matrix for partial QBS-ar ($R^2 = 0.2046$, model $p = 0.0003714$), with agricultural areas ($p = 0.0207$) and forest and semi-natural areas ($p = 0.0183$) retained as significant landscape terms (Table 3). Together with the field-level patterns, this result identifies the cultivated matrix and the surrounding semi-natural habitats as biologically relevant components of QBS-ar variation within the 500-m buffers. For modelling, the 20 mapped land-use and land-cover types were consolidated into four broad categories (Supporting Information Table S3), while the original high-resolution classes remain available in Supporting Information Table S5. The detailed cartography makes it possible to identify the specific habitat components associated with the distinctive biological profile of RL2, including grasslands, halophytic and salt-marsh vegetation, hedges, ponds and coastal habitats, which would otherwise be concealed within the broader model categories. This integration of QBS-ar monitoring with fine-scale landscape characterisation represents an innovative component of the study, particularly for agricultural systems located within protected areas. Overall, the results emphasise that soil biological quality monitoring in these systems should integrate agricultural management with the composition and conservation status of the surrounding landscape.

4.5 | Integrated Environmental and Management Context

Across the four monitored fields, agricultural practices, soil chemical and textural properties, soil environmental factors, weather and landscape composition, were associated with variation in the QBS-ar index. All six exploratory predictor-group models showed evidence of association with partial QBS-ar (Table 3), with each describing a different ecological dimension of the monitored system. Agricultural practices represented direct disturbance and changes in vegetation cover and residue inputs; soil chemical and textural properties characterised resource availability and the physical habitat; weather and sampling-time soil conditions described temporal variation in the soil microenvironment; and landscape composition characterised the surrounding matrix. Their biological relevance emerged from the convergence of these dimensions in the QBS-ar pattern and in the complementary biotic metrics. This convergence was clearest in the contrasting biological profiles of RL2 and FE2: RL2 showed the highest overall values for QBS-ar, abundance, BF and EF, whereas FE2 showed the lowest (Tables 1 and 2). These concordant indicators revealed differences in both microarthropod abundance and the representation of soil-adapted forms. Management and soil fertility were interconnected components of this pattern. Partial QBS-ar values were associated with exchangeable K, tillage and harvesting, in line with previous evidence relating soil fertility and physical disturbance to soil-fauna patterns (Fiera et al. 2020; Kladvko 2001; Van Capelle et al. 2012). The soil-texture, soil-environmental and landscape models provided additional evidence of association. Temporal variation indicated no simple response to soil moisture, while RL2's location in the Reserve's protection zone and its surrounding semi-natural, wetland and coastal habitats may have favoured community persistence and recolonisation after disturbance (Mantoni et al. 2021; Querner

et al. 2018; Le Provost et al. 2021). The lower biological quality of RL1, despite several comparatively sustainable practices, reinforces the conclusion that QBS-ar reflected the combined field-scale and landscape context rather than any single factor.

The study originated from a voluntary monitoring initiative promoted by the Municipality of San Benedetto del Tronto and the Reserve's Management Authority. Farmer participation made it possible to monitor soil-microarthropod communities under real-farm conditions, across actual crop sequences, management operations and contrasting weather conditions. Integrating repeated QBS-ar assessments with abundance, BFs, EFs and detailed environmental information helped distinguish persistent differences in soil biological quality from more transient population responses. This integrated, field-based approach provides a practical framework for interpreting QBS-ar variability in operational soil monitoring and for identifying the environmental and management information that should accompany biological assessments in agricultural systems.

5 | Conclusion

The promotion of sustainable soil management is a key target of the EU Biodiversity Strategy for 2030 and an essential component of the European Green Deal. In this context, QBS-ar can support soil biomonitoring by providing an arthropod-based assessment of edaphic biological quality, consistent with the objectives of the EU Soil Monitoring Law.

Across 3 years of monitoring, all total QBS-ar values exceeded the proposed reference value for agricultural soils but varied markedly among fields and sampling periods. The Selva Giurata fields generally showed higher biological quality than those at Fattoria Ferri, with RL2 and FE2 displaying the strongest and weakest overall profiles, respectively. The concordant variation in QBS-ar, microarthropod abundance, BFs and EFs revealed differences in both community abundance and the representation of soil-adapted forms.

Overall, QBS-ar variation reflected the combined effects of management, soil properties, hydroclimatic conditions and landscape context operating across different spatial and temporal scales. The incorporation of landscape-related variables represents an innovative aspect of this study, especially in the context of protected agricultural systems. The surrounding landscape may have contributed to sustaining high soil biological quality despite recurrent field disturbances.

Voluntary farmer participation enabled repeated monitoring under real-farm conditions, encompassing actual crop sequences, management operations and contrasting weather. Integrating QBS-ar with complementary biological metrics and detailed environmental information helped distinguish persistent field differences from transient community responses and identify the contextual data needed for operational soil monitoring.

Future research should test the relationships identified here across a broader and independently replicated network of farms

and landscape settings, combining repeated biological assessments with harmonised management, soil and high-resolution landscape information. This would support the development of context-aware interpretative ranges for different agroecosystems. Preserving soil biodiversity is essential due to its intrinsic value and the vital ecosystem services it provides. Therefore, it is important to implement biodiversity-friendly practices and monitor soil conditions over time, rather than relying solely on a one-time survey. Longitudinal QBS-ar monitoring, interpreted alongside complementary biological and environmental information, can provide timely evidence of changes in edaphic biodiversity and support practice-oriented agricultural management.

Author Contributions

Martina Coletta: conceptualisation, methodology, investigation, formal analysis, data curation, writing – original draft, writing – review and editing, validation, visualisation. **Aurora Torresi:** methodology, investigation, formal analysis, data curation, visualisation, writing – review and editing. **Aldo D'Alessandro:** investigation, writing – review and editing. **Marco Monticelli:** investigation, writing – review and editing. **Daizy Bharti:** investigation, writing – review and editing. **Santosh Kumar:** investigation, writing – review and editing. **Stefano Chelli:** resources, writing – review and editing. **Antonietta La Terza:** conceptualisation, methodology, validation, formal analysis, writing – review and editing, visualisation, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the article.

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Ethics Statement

Ethical review and approval were not required for this study, as it involved soil invertebrates (microarthropods), which are not subject to animal welfare regulations or institutional review board (IRB) requirements. Sampling was conducted following standard soil ecological protocols, minimising disturbance to the environment.

Conflicts of Interest

ALT has received research support from the San Benedetto del Tronto Municipality, Italy. Other authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

The authors will make the data underlying this study available upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: sae270213-sup-0001-Supplementary_material_Coletta_et_al.docx.