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Comparison of Soil Biology Quality in Organically and Conventionally Managed Agro-Ecosystems Using Microarthropods

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Abstract: Since management practices profoundly influence soil characteristics, the adoption of sustainable agro-ecological practices is essential for soil health conservation. We compared soil health in organic and conventional fields in the Abruzzi region (central Italy) by using (1) the soil biology quality (QBS) index (which expresses the level of specialisation in soil environment shown by microarthropods) and (2) microarthropod diversity expressed by Hill numbers. QBS values were calculated using both the original formulation based on only presence/absence data and a new abundance-based version. We found that organic management improves soil biology quality, which encourages the use of organic farming to maintain soil health. Including arthropod abundance in QBS calculation does not change the main outcomes, which supports the use of its original, speedier formulation. We also found that agricultural fields included in protected areas had greater soil health, which shows the importance of the matrix in determining agricultural soil health and highlights the importance of land protection in preserving biodiversity even in managed soils. Finally, we found that soil biology quality and microarthropod community structure are distinctly influenced by certain physical and chemical characteristics of the soil, which supports the use of microarthropods as biological indicators.

Keywords: organic agriculture; soil properties; soil biological quality; soil health; arthropods; Hill numbers; land protection; soil biodiversity

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1. Introduction

Soils are a fundamental component of terrestrial ecosystems, for which they play many essential services [1–4]. Transformation of natural ecosystems into arable land leads to the loss of biodiversity associated with natural habitats and profoundly alters soil characteristics [5,6], with detrimental impacts on surrounding habitats (for instance, through soil erosion or pollution run-off) [7].

In agro-ecosystems, management practices influence many soil quality characteristics, such as biodiversity, stability, level of internal nutrients, and resilience to disturbance or stress [8]. Thus, the adoption of sustainable agro-ecological practices is essential for the conservation of soil health [9,10].

Soil biotas are of paramount importance for soil quality and vitality [11–13] and play several supporting and regulating ecosystem services [14,15]. Thus, preventing the decline in soil animal communities in agro-ecosystems is a key ecological strategy to effectively combine productive and sustainability goals [16]. In particular, comparative studies on biodiversity in conventional and organic fields indicated that organic farming exerts a beneficial effect on the biodiversity of agro-ecosystems [17–22] and, in particular, on their soil quality and biodiversity [23–26].

Within the soil biota, edaphic animals, i.e., those species that live below the soil surface, play a pivotal role in maintaining many soil characteristics (such as porosity, aeration, infiltration, and distribution of organic matter in soil horizons) and soil-related ecosystem services (such as plant nutrition and detoxification) through bioturbation, nutrient cycling, and organic matter decomposition and mineralisation [27–34]. In particular, using direct and indirect mechanisms, edaphic animals can release soil nitrogen and carbon, thereby modifying their availability [35]. Soil animals also provide organic matter to soil microorganisms, which, in turn, influence nutrients' availability for plant absorption and pest suppression [36,37]. Due to these multiple functions in maintaining soil characteristics, and especially in regulating soil nutrients essential for plant life, soil animal communities are frequently used to evaluate soil quality [16,38–52].

Arthropods are the most abundant and diversified group among soil faunas [53], and in agro-ecosystems they provide essential ecological services, including the decomposition of crop residues to form humus and the recycling of mineral nutrients for successive crops [54–56]. Owing to their ability to respond to variations in environmental conditions, soil properties, and changes in land management, soil arthropods are gaining increasing interest as effective indicators of soil biology quality [27,31,40,57–60], especially in agro-ecosystems or polluted or degraded sites [6,38,48,61–79].

The QBS-ar index (also known as SBQ-ar; soil biology quality based on arthropods) [40] has been introduced to expresses the biological quality of soil according to the degree of specialisation of the edaphic arthropods, because the most specialised forms are particularly sensitive to soil disturbance and might not survive to alterations due to, for example, agricultural cultivation and trampling [40,80–83].

More generally, since the taxonomic diversity and species abundance of the edaphic arthropods are highly dependent on species' tolerance limits to environmental conditions [84,85], the study of microarthropod community structure may add significant information on the soil status [6,16,26,41,78,79,86–90].

In general, soil arthropods are highly sensitive to the effects of agricultural management practices [91], and there are indications that organically managed fields contain a greater abundance and diversity of arthropods than conventionally managed fields [22,92–94]. However, relatively few works have explicitly evaluated the influence of management strategies on soil biology quality as expressed by the edaphic arthropod communities [11,26,48,72,76,95,96].

The aim of this study was to determine the effect of management practices (organic vs. conventional) on edaphic arthropods as indicators of soil biology quality. We used the QBS-ar index in its standard formulation, as well as a new formulation, proposed here for the first time, which takes into account the abundance of the various arthropod groups, and which we called QBS-ab.

We also considered the effect of management practices on the diversity of edaphic arthropods using Hill numbers, a mathematically unified family of indices that (1) combine information on species richness, species rarity, and species dominance and (2) are all expressed in the same units (i.e., the effective number of species), being therefore comparable between each other [97,98]. In addition to these indices, we also investigated the influence of management practices on total arthropod abundance (total numbers of individuals). In particular, we hypothesised that organic management may positively affect the abundance, diversity, and quality indices. Additionally, taking advantage of the presence of protected areas in the study area, we tested the influence of land protection on the soil health of agricultural fields.

Despite the increasing interest in the use of QBS-ar [99], virtually no study has attempted to investigate the influence of specific soil characteristics on the values of this index. In this paper, we tested the influence of soil physical and chemical characteristics on QBS-ar, QBS-ab, Hill numbers, and total abundance.

2. Materials and Methods

2.1. Study Area and Soil Characterisation

The study was conducted in the Abruzzi Region, central Italy. We used 12 agricultural fields (sites) randomly distributed through six major production areas in the region (Altopiano delle Cinque Miglia, Valle Peligna, Valle Subequana, Val Vomano, Montagna Aquilana, Fucino).

Then, each field was classified according to the form of management as organic (8 fields) or conventional (4 fields). Organic fields were cultivated without herbicide and synthetic pesticides. Except for a site cultivated with field beans and a site cultivated with carrots, ploughing, harrowing, and manure were absent in organically managed fields. Milling was also absent in most organically managed fields, and, when present, it was less than 20 cm. Conventionally managed fields were treated with fungicides, insecticides, and herbicides and were subjected to ploughing and harrowing (30–40 cm) and/or milling (20–25 cm). Fertilisation with agrochemicals was carried out in conventional fields, while organic fields were not fertilised, except for the two abovementioned fields fertilised with animal manure.

Abruzzi is an Italian region with the largest proportion of protected land (about a third of its territory is set aside as protected areas), with many agricultural areas included in protected areas. Thus, for each site, we also recorded if it was within (4 fields) or outside (8 fields) a protected area, in addition to the type of crop present during sampling (grain: 4 fields, carrots: 2 fields, fallow: 2 fields, field bean; 1 field, barley: 1 field, melons: 1 field, and soya: 1 field).

From each site, three soil samples were collected for routine physical and chemical analyses. Soil physical–chemical analyses were performed on soil samples dried at room temperature, crushed, and sieved to exclude particles >2 mm. Soil fractions smaller than 2 mm were analysed for texture; pH and electrical conductivity (EC); cation exchange capacity; calcium; total carbon (TC); total organic carbon (TOC) and inorganic carbon (IC); organic matter; total, ammoniacal, and nitric nitrogen; humic and fulvic acids; assimilable phosphorus; metals (Mg, K, and Na). Analyses were performed by Laboratori ISPA—Istituto Sperimentale Problematiche Ambientali Panetta S.r.l., Atina (Italy), mostly following Italian standards [100]. Soil texture was characterised using a volumetric cylinder and diluting soil samples with distilled water (1:4 ratio). The samples were mixed two times (after dilution and after 24 h) and left to stand 48 h until the three fractions (clay $\varnothing < 0.002$ mm; silt $\varnothing = 0.002$–0.05 mm; sand $\varnothing = 0.05$–2 mm) were clearly distinguishable and the volumes on the volumetric cylinder calculated. To measure soil pH and EC, soil samples were mixed with distilled water (1:5 ratio, 1 h at room temperature), and a HI2550 multiparameter pH metre (Hanna Instruments, Slovenia) was used. Cation exchange capacity was obtained by soil treatment with a pH-7 ammonium acetate solution (1:2 ratio, 1 h at room temperature and overnight standing) and inductively coupled plasma (ICP) determination. Calcium was determined by hydrochloric acid reaction (1:2.5 ratio until complete reaction at room temperature) and calcimeter estimation. The parameters TC, TOC, and IC (TC-TOC) were determined by high-temperature digestion of samples in an air/O_2 stream at 850 °C through a VARIO TOC cube analyser (Elementar Italia Srl, Lomazzo, Italy). With this method, the fully bonded carbon was converted into CO_2 and was quantitatively determined by a non-dispersive infrared sensor detector. Considering the average carbon content in soil organic matter to be 58%, organic matter (g/kg) was determined by multiplying the organic carbon values by 1.724. Total, ammoniacal, and nitric nitrogen contents were measured by potassium chloride reaction (1:10 ratio, 1 h at 20 °C) and ion chromatography. Humic and fulvic acids were analysed by alkaline extraction (0.1 M NaOH and 0.1 M $Na_4P_2O_7$, 1:25 ratio, 24 h), sample acidification ($pH < 2$), purification with Florsil$^{®}$ cartridges, dilution (1:20), and determination by VARIO TOC cube analyser (Elementar Italia Srl, Lomazzo, Italy). Assimilable phosphorus was determined by using the Olsen and Sommers method. Metals were determined by inductively coupled plasma–mass spectrometry (ICP-MS) determination.

Correlation analyses showed that many chemical variables were highly inter-correlated (Pearson $r > 0.75$) and were therefore omitted from statistical analyses. Retained variables were organic matter, pH, % sand, % silt, humic and fulvic acids, ammoniacal nitrogen, nitric nitrogen, assimilable phosphorus, calcium, magnesium, potassium, and sodium. Site location and characteristics are given in Tables S1 and S2.

2.2. Calculation of Soil Biological Quality Index

Investigated fields were very small, being in the range of 0.2–3.5 hectares, with an average of about 1 hectare (average ± standard deviation: 0.95 ± 0.89 hectares). In each site, we collected three soil samples (10 cm × 10 cm × 10 cm). Soil microarthropods were extracted by using Berlese–Tullgren extractors [101], equipped with a mesh screen of 2 mm and an incandescent lamp (60 W), for one week. Extracted microarthropods were placed in ethanol 95%. Microarthropods were classified into main groups, and each group received a score reflecting its specialisation in soil life, following Parisi et al. [40]. For groups including organisms with different levels of soil adaptation, the highest score was taken to reflect the most highly adapted microarthropods belonging to that group. The QBS-ar index for a soil sample was calculated as the sum of the scores recorded for each taxon.

In addition to this already established protocol, we applied a new approach that takes into consideration the abundance of the groups used in the QBS-ar calculation. To this end, we multiplied the score of a given group by its abundance, expressed as the number of collected individuals. Prior to calculations, the number of individual was $\log_{10}(x + 1$-transformed to reduce the impact of extremely abundant groups (Acarina and Collembola), which are typically present with hundreds or even thousands of individuals in most samples. For groups which included species with different levels of soil adaptation, and which had a range of scores, we made separate calculations for the different levels of specialisation, to reflect the actual composition of the arthropod assemblage. As in this new formulation of the QBS index the scores were weighted by the abundance of each group, we termed the new index “QBS-ab” (abundance-based QBS-ar). Data on arthropods are given in Tables S3–S14.

We used generalised linear mixed models using the glmmTMB R package to test the effects of agricultural management, land protection, and type of cultivation on QBS-ar and QBS-ab values, with sites nested into geographical areas as a random factor. Data were checked for normality (Shapiro–Wilk test and Q-Q plot) and homoscedasticity (Bartlett test) before analyses. The r.squaredGLMM function of the MuMIn R package was used to calculate the R2 explained by fixed and random factors in generalised linear mixed models. Potential spatial autocorrelation in the residuals of generalised linear mixed models was checked using Moran’s I test as implemented in the moran.test function of the spdep R package. We correlated QBS-ar and QBS-ab values with soil characteristics using a Pearson correlation coefficient. All statistical analyses were performed using R 4.0.3 software [102].

2.3. Arthropod Diversity

Previous research attempted to express the arthropod biodiversity of soil samples using diversity indices at the level of class (Diplopoda, Chilopoda, Symphyla, Pauropoda) or order (insects, chelicerates, and crustaceans) [16,26,89]. Indeed, there are a plethora of proposed measures of diversity that combine richness and abundance into a single metric [103,104] and different authors used different indices [6,16,26,48,76,86,89]. Among the vast multitude of available diversity measures, Hill numbers ${}^{q}D$ are increasingly used [97,105,106]. Hill numbers, which differ among themselves only by the exponent q, include three widely used species diversity measures as special cases: species richness (when $q = 0$), exponential Shannon diversity (when $q = 1$ as the limiting case, since the equation for Hill numbers is undefined for $q = 1$) and Simpson diversity ($q = 2$) [97,98]. As the diversity order q can assume any value, it is possible to construct, for any given species assemblage, a diversity profile plotting ${}^{q}D$ versus q [105]. Here, we used Hill numbers to compare diversity profiles of soil samples from biological and conventional fields. Calculations of Hill numbers were carried out using PAST 3 [107].

We tested differences in species richness ($q = 0$), Shannon diversity ($q = 1$) and Simpson diversity ($q = 2$), and total abundance values using, in all cases, generalised linear mixed models as described above. A Poisson distribution was applied for count data (richness and abundance). We correlated richness (log-transformed), Shannon diversity, Simpson diversity, and total abundance (log-transformed) values with soil characteristics using Pearson correlation coefficients.

2.4. Influence of Soil Characteristics on Variation in Soil Arthropod Composition

We investigated variability in arthropod community structure and composition using a non-metric multidimensional scaling with Bray–Curtis dissimilarity calculated on abundance data. Then, we calculated the correlation between soil characteristics and the first two dimensions extracted by the non-metric multidimensional scaling. Calculations were carried out using PAST 3 [107].

3. Results

We assigned soil arthropods to ecomorphological groups, belonging to five subphyla: Chelicerata, including Acarina, Pseudoscorpionida, and Araneae; Hexapoda, including Collembola, Protura, Diplura and nine insect orders; Crustacea, only represented by Isopoda; Myriapoda, including Diplopoda, Chilopoda, Pauropoda, and Symphyla (Tables S3–S14). Acarina were present in all samples; Collembola were present in all samples except one; Pauropoda, Diptera, and Coleoptera were recorded in more than 50% of samples; Symphila, Diplura, Hemiptera, Hymenoptera (including Formicidae), and Thysanoptera were found in 30–50% of samples; the other groups were less frequent (<20% and of samples). Values of QBS-ar, QBS-ab, taxon richness, Shannon diversity, Simpson diversity, and abundance are given in Table S2. Values of QBS-ar, QBS-ab, and taxon richness were significantly higher in organic than conventional fields (Table 1, Figure 1). The position of sites within or outside a protected area had a significant effect on QBS-ar, QBS-ab, Shannon diversity, and Simpson diversity (Table 1, Figure 1). In all these measures, sites within protected areas showed, on average, significantly higher values than those outside protected areas. All diversity measures and abundance varied according to the type of cultivation (Table 1). In all cases, most of the variance was explained by fixed factors (Table 1). The residuals did not show any significant spatial autocorrelation (Table 1). The use of diversity profiles indicates that most of the sites with organic management had higher diversity than those with conventional management (Figure 2).

Table 1. Results of generalised linear mixed models for soil biology quality (QBS-ar), soil biology quality weighted by abundance (QBS-ab), total arthropod abundance, arthropod richness, Shannon diversity, and Simpson diversity in organic and conventional fields in central Italy with different crops. Park indicates whether the field was inside or outside a protected area: Df = degrees of freedom; P = probability. Goodness-of-fit (R^2) values were calculated including the random effect (sites nested into geographical areas; R^2c) and for the fixed factors (R^2m). Values of Moran's I and respective P-values testing for occurrence of significantly spatially autocorrelated residuals are also provided.

	QBS-ar			QBS-ab		
	χ^2	Df	p	χ^2	Df	p
Management	5.506	1	0.019	7.539	1	0.006
Park	12.024	1	<0.0001	11.735	1	<0.001
Crop	40.260	6	<0.0001	28.749	6	<0.0001
	R^2c = 0.80 R^2m = 0.740; $I = -0.082$, $p = 0.839$			R^2c = 0.83 R^2m = 0.700; $I = -0.051$, $p = 0.666$		

Table 1. *Cont.*

	Abundance			**Richness**		
	χ^2	Df	p	χ^2	Df	p
Management	5.506	1	0.019	7.539	1	0.006
Park	12.024	1	<0.0001	11.735	1	<0.001
Crop	40.260	6	<0.0001	28.749	6	<0.0001
	R^2c = 0.999, R^2m = 0.890; $I = -0.100$, $p = 0.911$			R^2c = 0.519, R^2m = 0.519; $I = -0.077$, $p = 0.811$		
	Shannon Index			**Simpson Index**		
	χ^2	Df	p	χ^2	Df	p
Management	2.275	1	0.132	4.804	1	0.028
Park	2.601	1	0.107	2.448	1	0.115
Crop	61.129	6	<0.0001	23.469	6	<0.001
	R^2c = 0.810, R^2m = 0.540; $I = -0.095$, $p = 0.887$			R^2c = 0.770, R^2m = 0.560; I = -0.085, $p = 0.851$		

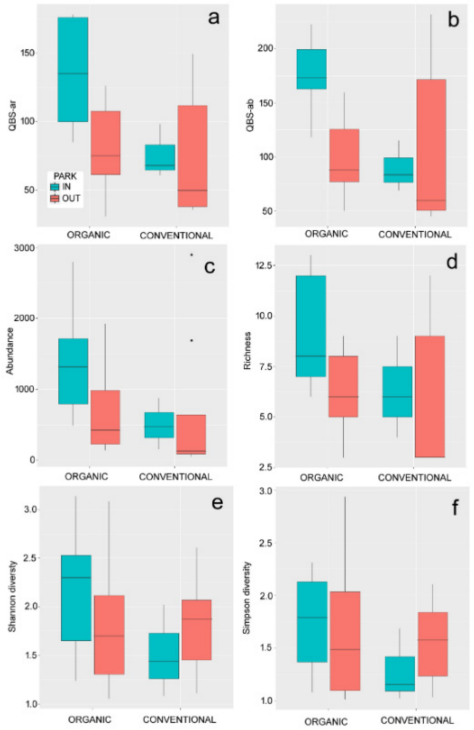

Figure 1. Box plots (median, quartiles, ranges and outliers) comparing values of (**a**) soil biology quality (QBS-ar), (**b**) soil biology quality weighted by abundance (QBS-ab), (**c**) total arthropod abundance, (**d**) arthropod richness, (**e**) Shannon diversity, and (**f**) Simpson diversity between biological and conventional fields in central Italy. Park indicates whether the field was inside (in) or outside (out) a protected area. Differences between organic and conventional fields were significant in all cases except for the Shannon index; differences between parks within and outside protected areas were significant for QBS-ar, QBS-ab, abundance, and richness but not for Shannon and Simpson indices (see Table 1).

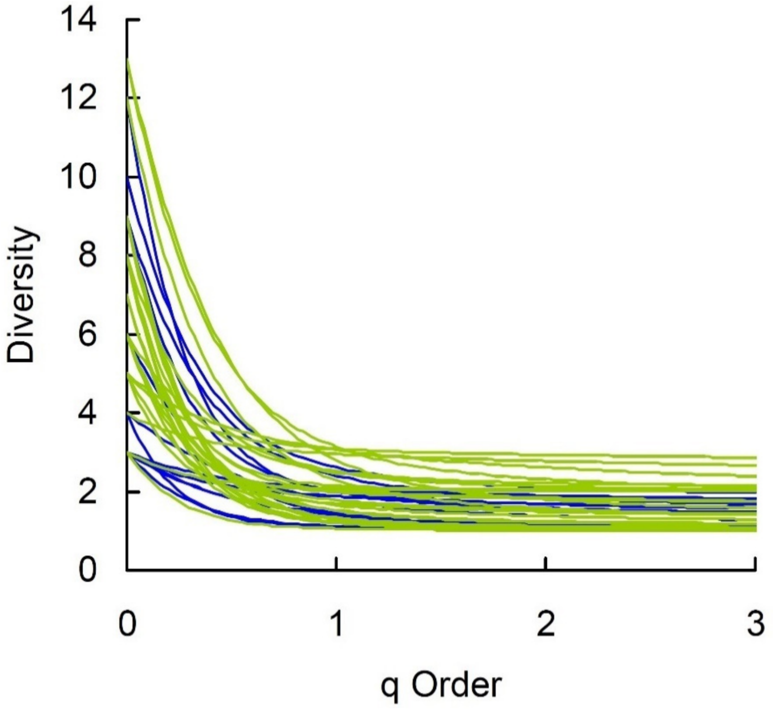

Figure 2. Soil arthropod diversity profiles for organically (green) and conventionally (blue) managed fields in central Italy obtained by using Hill numbers.

Correlations between QBS indices, diversity indices, abundance, and soil characteristics are given in Table 2. The two QBS indices (QBS-ar and QBS-ab) were strongly correlated. Both QBS-ar and QBS-ab were correlated with total arthropod abundance, taxon richness, and Shannon diversity but not with Simpson diversity.

Table 2. Correlations between QBS indices, diversity indices, abundance, and soil characteristics. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. In all correlations, $n = 36$.

	QBS-ar	QBS-ab	Shannon Index	Simpson Index	Richness	Abundance
QBS-ar		0.919 ***	0.387 *	0.173	0.924 ***	0.721 ***
QBS-ab			0.452 **	0.260	0.843 ***	0.817 ***
Shannon index				0.943 ***	0.305	0.072
Simpson index						−0.029
Richness						0.769 ***
Organic substance	−0.300	−0.101	−0.028	0.109	−0.352 *	−0.023
pH	0.188	0.025	−0.110	−0.207	0.254	−0.015
Sand	0.338 *	0.419 *	0.187	0.206	0.463 **	0.552 ***
Silt	−0.119	−0.139	0.248	0.298	−0.188	−0.169
Humic acids	0.033	0.194	0.016	0.092	0.006	0.264
Ammoniac nitrogen	−0.249	−0.303	−0.101	−0.075	−0.286	−0.297
Nitric nitrogen	−0.429 **	−0.326	0.023	0.084	−0.420 *	−0.364 *
Phosphorus	−0.438 **	−0.400 *	0.426 **	0.533 ***	−0.472 ***	−0.572 ***
Calcium	0.079	0.083	−0.230	−0.287	0.171	0.172
Magnesium	−0.563 ***	−0.576 ***	−0.372 *	−0.350 *	−0.604 ***	−0.644 ***
Potassium	−0.441 **	−0.423 **	−0.244	−0.152	−0.449 **	−0.350 *
Sodium	−0.174	−0.172	−0.004	−0.027	−0.335 *	−0.371 *

Organic matter was negatively correlated with richness. Percent of sand was positively correlated with QBS-ar, QBS-ab, richness, and abundance. Nitric nitrogen was negatively correlated with QBS-ar, QBS-ab, richness, and abundance. Phosphorus was negatively correlated with QBS-ar, QBS-ab, richness, and abundance but positively with Shannon diversity and Simpson diversity. Magnesium was negatively correlated with

QBS-ar, QBS-ab, richness, abundance, Shannon diversity, and Simpson diversity. Potassium was negatively correlated with QBS-ar, QBS-ab, richness, and abundance. Sodium was negatively correlated with richness and abundance.

Results of non-metric multidimensional scaling (Figure 3) show that sites do not form clearly distinguishable groups on the basis of their arthropod composition. However, samples from the same sites tend to be grouped closely, thus showing high similarities in arthropod community structure. Moreover, high concentrations of magnesium, potassium, sodium, assimilable phosphorus, nitric, and ammoniac nitrogen seem to be associated with sites from conventional fields, whereas a high percentage of silt influences the microarthropod composition of a site organically managed.

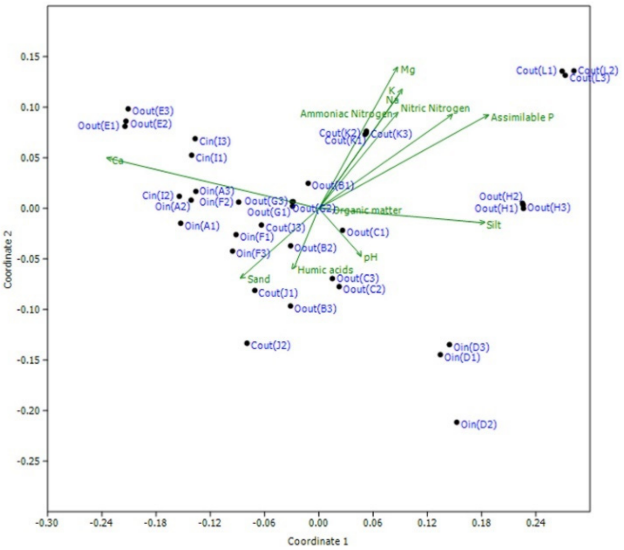

Figure 3. Ordination of soil samples by non-metric multidimensional scaling with Bray–Curtis dissimilarity index based on arthropod abundances. Stress = 0.078. Cin = conventional sites within protected areas; Cout = conventional sites outside protected areas; Oin = organic sites within protected areas; Out = organic sites outside protected areas. Codes in parentheses identify samples as in Table S2. Arrows indicate correlations with soil characteristics: organic matter, pH, % sand, % silt, humic and fulvic acids, ammoniacal nitrogen, nitric nitrogen, assimilable phosphorus, calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na).

4. Discussion

Our study demonstrated that (1) organic management improves soil biology quality (as expressed by the soil biology quality index based on microarthropods) and microarthropod richness; (2) including arthropod abundance in QBS-ar calculation does not change the main outcomes; (3) fields that are included in protected areas have better soil health (higher values of soil biology quality, Shannon diversity, and Simpson diversity), even under conventional management; (4) values of soil biology quality and community structure are distinctly influenced by certain physical and chemical characteristics of the soil, which supports the use of microarthropods as biological indicators.

Research studies on the effects of different management practices on soil arthropods in agro-ecosystems produced variable results [11,40,90,95,96,108,109]. Although some studies have shown no significant positive effect of organic farming on certain soil arthropods [110], in general, organic farming increases species richness and abundance of soil organisms, compared with conventional systems [78,94,111–113]. As regards the QBS-ar, Tóth et al. [109] found no significant positive effect of organic and integrated management on QBS-ar index, and Mazzoncini et al. [95] observed higher QBS-ar values in conventional fields than in the organic ones because of the unique presence of few rare individuals of Protura and Chilopoda in the conventional system. However, most research indicated that organic farming increases soil biology quality as expressed by the QBS-ar index (see [40,90]).

Our results are, therefore, in line with previous studies and support the use of organic management to preserve soil health.

The beneficial effect of organic management on soil health can be due to the reduced use of both tillage and chemicals. Tillage negatively affects soil arthropods both directly, by crushing their soft bodies, and indirectly, by destroying the channels they use to move around in [16,114,115]. In general, fields that are not subject to intensive tillage have higher values of arthropod abundance and diversity [39,48,76,116–122]. For example, House and Parmelee [116] and Hendrix et al. [117] reported higher abundance and biomass of microarthropods in no-tillage than in conventional tillage systems. Cortet et al. [121] found that the mites were more abundant in no-tillage than in conventional tillage conditions. Ferraro and Ghersa [122] similarly reported higher values of mite density in association with a decrease in tillage impact. Tabaglio et al. [48] also observed that mites were more abundant in no-tillage, compared with traditional tillage, although results on total microarthropods were equivocal and no effect was detected for QBS-ar. Sapkota et al. [76] reported that no-tillage affected positively microarthropod richness and Simpson diversity, as well as QBS-ar values (no effect was deduced for evenness).

As regards the influence of chemicals, it is known that their application can negatively affect the soil fauna community [123,124], and thus, organic management may assist the preservation of soil arthropod communities. In our study, the organically managed fields were characterised by no-tillage (or very reduced tillage) and no use of synthetic pesticides and fertilisers, whereas all conventionally managed fields were subject to repeated tillage and use of chemicals, so we could not disentangle the possible different contribution of these two factors (tillage and chemicals) in improving soil health in organic fields.

Another key result of our study is the positive influence of land protection on the soil health of agricultural fields. The influence of landscape characteristics on soil microarthropods has been investigated in relatively few studies involving mites [125,126], collembolans [127–129], or both [130–132]. The current opinion is that soil-dwelling animals are more affected by local factors than landscape features, mostly because of their limited home ranges and dispersal ability [111,113,128,133,134]. However, recent research demonstrated the influence of landscape characteristics on soil fauna community structure [129], for example, by constraining habitat conditions at finer spatial scales [127,135].

We found that fields within protected areas had higher soil health than those outside protected areas, as demonstrated by higher values of QBS-ar, QBS-ab, Shannon index, and Simpson index, which indicates a beneficial role exerted by the conservation status of the areas surrounding the fields. This beneficial effect may have two non-mutually exclusive explanations.

First, in protected areas, even conventional agriculture follows more sustainable practices, because (1) some chemicals are always prohibited, (2) some chemicals are allowed but with more restrictions than in non-protected areas, and (3) the reduction in the use of chemicals is incentivised. As a result, the use of agrochemicals is strongly limited in park territories [136].

Second, fields within protected areas may benefit from the good environmental quality of the surrounding matrix. In contrast to fields outside the protected areas, which are typically embedded into matrices with comparable or even lower environmental quality (such as other fields, urbanised areas, or semi-natural landscapes often subject to high disturbance), agricultural fields located within natural parks are embedded into a high-quality matrix. This may allow microarthropods of agricultural fields in protected areas to benefit more from rescue effects, i.e., the maintenance of viable populations owing to immigration from adjacent areas [137–139]. To the best of our knowledge, our study is the first that highlights the positive effect of land protection on soil health in agricultural fields. Since farmers are frequently hostile to land protection, as it is perceived as a limit to the agricultural exploitation of a territory [130], our results may have important implications in promoting the importance of land protection in sustainable farming.

We also found that crop type may have a role in determining soil biology health, as already observed in other agricultural contexts [79]. However, because of unbalanced sampling, we cannot disentangle the possible effect of crop type from those of management and land protection, and further research is needed to explore the role of crop type.

Various studies attempted to use diversity measures in conjunction with QBS index, including number of observed taxa [16,26,88,89], Menhinick diversity [6,88], Margalef diversity [26,88], Shannon diversity [6,16,26,48,88,89], Simpson diversity [76], Pielou evenness [6,16,26,48,89], Buzas and Gibson evenness [26], Simpson dominance [6,26,88], and Berger and Parker dominance [26]. Surprisingly enough, possible correlations between QBS-ar and measures of community structure have been almost completely unexplored. Exceptions are a study by Galli et al. [89], who found that QBS-ar was positively correlated with Shannon index but not with Pielou evenness, and one by Blasi et al. [88], who reported a positive relationship between QBS-ar values and the number of taxonomic groups.

We found that QBS-ar (and its variant based on abundances) was strongly correlated with total abundance and taxon richness and, less strongly, with Shannon diversity but not with Simpson diversity. Since in the QBS-ar the various taxa are weighted according to their ecomorphological specialisation, the positive correlation between QBS-ar and taxon richness indicates that weighting by specialisation in soil life has a secondary role and that most of the information is given simply by the number of taxa. In Hill number, the importance of species abundances increases with the q-order: thus, Simpson index ($q = 2$) places more weight on the frequencies of abundant species than Shannon index ($q = 1$), and the contribution of rare species is emphasised by richness ($q = 0$) [97,140]. The positive correlation of QBS-ar with Shannon index and its lack of correlation with Simpson index are, therefore, consequences of the strong dependence of QBS-ar on richness.

Given the correlation of QBS-ar with richness, it is not surprising that QBS-ar and richness produced parallel results in highlighting the importance of management. By contrast, using Shannon and Simpson indices, the generalised linear mixed models showed no significant influence of management, but the importance of land protection appeared to be significant. This suggests that land protection profoundly affects community diversity possibly through rescue effects. Elia et al. [88] found that QBS-ar was able to show significant differences in soil quality when indices of community diversity (Shannon, Menhinhick, Margalef) or dominance (Simpson) failed. Our results confirm that QBS-ar is sensitive to more factors than diversity measures such as Shannon and Simpson diversity. However, it should be noted that in all these studies (including our own), diversity indices were calculated using the level of class or order, which is a very low taxonomic resolution; it would be interesting, in the future, to investigate the relationship between QBS-ar and diversity indices calculated using identification to species.

An important point of merit of the QBS-ar index is that it does not require abundance data, being based on only the presence/absence of all groups found in the sample. The underlying assumption is that the presence of an animal belonging to a group means the possibility of this group to live in that soil, independently from its abundance [44,73]. This characteristic makes QBS-ar calculation very fast because the researcher does not have to spend time counting, for the various groups, the number of individuals arthropods, which, even in a single sample, may amount to hundreds or thousands. On the other hand, discounting abundances may be considered a potential limit of the QBS-ar; thus, one objective of our research was to test if considering abundances would lead to different results. We found that the results obtained with abundances paralleled those achieved with only presence/absence. This is a positive result, as indicates that the original, easier formulation of the QBS-ar is effective, and there is no need to spend time counting arthropod individuals.

Research on the influence of soil characteristics on edaphic arthropod communities is still limited and mostly focused on the influence of soil texture, soil organic matter content, and pH (e.g., [38,74,80,87,111,141–146]). In general, however, such types of studies produced contradictory results, depending on the study area and the taxa [78]. For example, Andrén and Lagerlöf [141], Kautz et al. [143], and Salmon et al. [144] found that the amount of organic material in the soil increases the abundance of soil microarthropods, and Tóth et al. [109] reported that soil organic matter content had a significant positive correlation with QBS index. However, Moço et al. [78] found a negative influence of organic carbon on the richness of fauna, and Begum et al. [147] and Santorufo et al. [6] reported no correlation of QBS-ar values with soil organic carbon and organic matter content, respectively. In our study, organic matter was correlated (negatively) only with richness, and correlation was weak (albeit significant), which suggests that organic matter was not a limiting factor in the studied systems and that an excess of it may have a negative effect on soil arthropods.

Salmon et al. [144] found a positive correlation between pH and diversity (Shannon index) of zoological groups, and Moço et al. [87] observed a positive effect of soil pH on the richness of fauna, but Begum et al. [147], Santorufo et al. [6] and Tóth et al. [109] reported no correlation between QBS-ar values and pH. We also found no effect of pH on either QBS-ar or diversity indices and total abundances.

Moço et al. [87] reported a negative effect of clay content on the richness of fauna, but Tóth et al. [109] reported no effect of clay percentage on QBS-ar values. We did not make correlations with clay, as it was strongly negatively correlated with sand and humic acids, and we preferred to retain sand, as it was not correlated with humic acids. We found a positive effect of sand content on QBS-ar, richness, and total abundance, although correlations were not very strong. Sandy soils are generally characterised by a high macroporosity and lower capacity of water storage than those with a heavier texture [148]. Thus, these positive correlations can be explained by the fact that a higher sand content makes the soil more penetrable and hence more favourable to edaphic microarthropods [149]. This hypothesis is in line with Müller and Rauhe [150], who also described a higher level of collembolan density in sandy soils than loamy ones. Although silt did not affect soil quality, a high silt percentage was associated with the arthropod composition of an organically managed field. In highly silty conditions, organic management might influence profoundly arthropod composition due to the increase in organic matter provided by the use of manure in this field.

Negative (albeit not very strong) correlations of nitric nitrogen and potassium with QBS-ar, richness, and abundance, as well as their importance in characterising assemblage similarity of sites from conventionally managed fields, can be explained by the fact that the excessive application of these substances creates a stratification of inorganic forms unavailable for plant absorption, representing a pollution source of immobilised forms with negative effects on biodiversity and species trophic interactions [151,152]. Moço et al. [87] already reported a negative indirect effect of total nitrogen on the richness of fauna, and Tabaglio et al. [48] observed a negative effect of nitrogen on mite and collembolan abundance but not on Shannon diversity, evenness, and QBS-ar values.

Sodium was slightly negatively correlated with richness and abundance and was important in characterising assemblage similarity of sites from conventionally managed fields, which is an expected result, as saline soils are more hostile environments for most organisms [153]. However, we found no significant effects of sodium on QBS-ar and Shannon or Simpson indices, which suggests that an increase in sodium (at least until a certain value) affects more richness and total abundances than the relative abundance of the taxa, and affects them irrespective of their specialisation towards the edaphic life. On the other hand, an increase in magnesium, which is also a form of salinisation, negatively influences richness and abundance, QBS-ar, Shannon diversity, and Simpson diversity, and characterises assemblage similarity of sites from conventionally managed fields. This suggests that magnesium has a general negative influence on soil microarthropods and also affects more specifically those less common and more specialised. Magnesium induces both accumulations of sodium in soil and soil aggregate destabilisation by increasing clay dispersion [154,155]. These indirect and direct impacts on soil structure create more hostile environments and may have a negative effect on edaphic animals.

Phosphorus was negatively correlated with QBS-ar, richness, and abundance but positively with Shannon and Simpson diversity (albeit not strongly) and characterises assemblage similarity of sites from conventionally managed fields. In general, the amount of phosphorus may be considered an indication of the intensity of the use of fertilisers, as it is one of the main three nutrients most found in fertilisers, that is, nitrogen, phosphorus, and potassium [156]. Thus, these negative correlations may reflect, more generally, the impact of management (in our case, conventionally managed fields have a higher phosphorus content than those organically managed; median values: 10 mg × Kg^{-1} in organic fields against 72.5 mg × Kg^{-1} in conventional fields; Mann–Whitney U-test: $U = 54.0$, $p = 0.002$). Surprisingly, increasing values of phosphorus increase Shannon and Simpson diversity values. This situation paralleled the effect of soil metal pollution, which seemed to cause an increase in invertebrate diversity and evenness in urban soils [6]. A possibility is that by reducing the abundance of the most abundant taxa, pollution increases equitability and hence increases diversity but after wiping out the most sensitive species. Thus, caution should be paid in using arthropod diversity metrics to evaluate soil health.

5. Conclusions

We found that organic management improves soil biology quality, as indicated by the QBS-ar index, a widely used index which expresses the level of specialisation of microarthropods to the soil environment. This should encourage the use of organic farming to maintain soil health. QBS-ar is based only on the presence/absence of taxa, with no reference to their abundances. We demonstrated that including arthropod abundance in QBS-ar calculation does not change the main outcomes, which supports the use of its original, more user-friendly formulation. We also found that agricultural fields included in protected areas had greater soil health, which shows the importance of the matrix in determining agricultural soil health and highlights the importance of land protection in preserving biodiversity even in managed soils. Finally, we found that soil biology quality and microarthropod community structure are distinctly influenced by certain physical and chemical characteristics of the soil, which supports the use of microarthropods as biological indicators.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agriculture11101022/s1: Table S1: Site location (coordinates), Table S2: Site characteristics. Area codes: ACM = Altopiano delle Cinque Miglia, MA = Montagna Aquilana, FUC = Fucino, VP = Valle Peligna, VS = Valle Subequana, VV = Val Vomano. For each replicate, values of QBS-ar, QBS-ab, richness, Shannon diversity, Simpson diversity, and abundance are provided, Tables S3–14: Scores reflecting specialisation (ecomorphological index, EMI) and abundance of arthropods sampled in each replicate used for calculating QBS-ab. For groups with variable EMI scores, the highest value was used in QBS-ar calculation. Replicates have the same codes as in Table S2.

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