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Soil microarthropod communities from Mediterranean forest ecosystems in Central Italy under different disturbances

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Abstract The aim of this study is to assess soil quality in Mediterranean forests of Central Italy, from evergreen to deciduous, with different types of management (coppice vs. high forest vs. secondary old growth) and compaction impacts (machinery vs. recreational). Soil quality was evaluated studying soil microarthropod communities and applying a biological index (QBS-ar) based on the concept that the higher is the soil quality, the higher will be the number of microarthropod groups well adapted to the soil habitat. Our results confirm that hardwood soils are characterised by the highest biodiversity level among terrestrial communities and by a well-structured and mature microarthropod community, which is typical of stable ecosystems (QBS value, >200). While silvicultural practices and forest composition do not seem to influence QBS-ar values or microarthropod community structure, the index is very efficient in detecting soil impacts (soil compaction due to logging activities). Several taxa (Protura, Diplura, Coleoptera adults, Pauropoda, Diplopoda, Symphyla, Chilopoda, Diptera larvae and Opiliones) react negatively to soil compaction and degradation (QBS value, <150). In particular, Protura, Diplura, Symphyla and Pauropoda, are taxonomic groups linked to undisturbed soil. This index could also be a useful tool in monitoring soil biodiversity in protected areas and in urban forestry to prevent the negative effects of trampling. QBS-ar is a candidate index for biomonitoring of soil microarthropod biodiversity across the landscape to provide guidance for the sustainable management of renewable resource and nature conservation.

Keywords Soil fauna · Soil disturbance · Forest management · Biological index · Microarthropods · Soil monitoring

Introduction

Monitoring ecosystem components plays a key role in acquiring basic data to assess the impact of land management systems and to plan resource conservation.

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Maintaining soil quality is of the utmost importance to preserve biodiversity and sustainable management of renewable resources. However, the study of soil communities is still in an early stage and information on diversity of soil animals is actually very sparse with a few studies regarding the patterns of soil biodiversity across the landscape (Bardgett 2002; Callaham et al. 2006). There is a compelling need for establishing a set of bioindicators and indexes to understand proprieties and monitor changes in the soil organisms. The research challenge is to select biomonitors in situ for a wide range of environmental factors that respond to deteriorating or improving habitat quality linked to changing patterns of land use (Hodkinson and Jackson 2005; Ruf et al. 2003).

Soil properties determine ecosystem function and vegetation composition/structure, serve as a medium for root development, and provide moisture and nutrients for plant growth (Minnesota Forest Resources Council 1999). Disturbances linked to natural forces and to human activities can alter physical, chemical and biological properties of soils which can, in turn, impact long-term productivity (Burger and Zedaker 1993; Gupta and Malik 1996). Human activities alter the quantity and quality of detritus availability and the chemical–physical properties of microhabitats that influence microarthropods, most of which are sedentary and unable to respond spatially and temporally to soil property changes (Bird et al. 2000).

Soil quality is defined here as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation (Doran and Parkin 1994; Karlen et al. 1997). It can be evaluated through chemical–physical properties (e.g. granulometry, organic matter, heavy metals) and biological indicators. Biotic indices, based on invertebrate community studies, were recently developed as a promising tool in soil-quality monitoring (Cassagne et al. 2004; Deleporte 1981; Guinchard and Robert 1991; Menta et al. 2008; Paquin and Coderre 1997; Parisi 2001; Parisi et al. 2005). Soil invertebrates are a fundamental component of soil ecosystems, playing an important role in breaking down organic matter, regulating the recycling of nutrients, controlling the activity of microflora and developing soil structure (Lebrun 1987; Radea and Arianoutsou 2002; Rusek 1985; Toutain 1987). These organisms are highly sensitive to natural and human disturbances (Deleporte 1981; Hogervorst et al. 1993; Paoletti and Hassall 1999) and are increasingly being recognised as a useful tool for assessing soil quality.

Various studies have described the structure of soil invertebrate communities in relation to forest diversity, dynamics and management (Bird et al. 2000; Doblas-Miranda et al. 2007; Hedde et al. 2007; Jabin et al. 2004; Kaneko and Salamanca 1999; Paquin and Coderre 1997; Theenhaus and Schaefer 1995). Overexploitation generally results in dramatic and rapid changes in vegetation and soil quality that are likely to significantly affect soil invertebrate communities and, more in general, forest goods and services (Minnesota Forest Resources Council 1999).

The aim of this study is to assess soil quality in various Mediterranean forests of Central Italy, from evergreen to deciduous, with different types of management (e.g. coppice vs. high forest). Soil quality was analysed through a biological index, the QBS-ar, based on the concept that the higher the soil quality, the higher will be the number of microarthropod groups adapted to the soil habitat (Gardi et al. 2008; Menta et al. 2008; Parisi et al. 2005). Particular attention was focused on stands with different levels of soil compaction, due to harvesting methods, grazing and recreation. In cases of multiple use forests (e.g. wood, pasture and recreation), such as the Mediterranean landscape, soil compaction can deeply alter edaphic fauna microhabitat and vegetation productivity. Since compaction produces a decrease in soil porosity and water retention, it is a target impact that needs to be monitored and managed in Mediterranean resource planning.

Materials and methods

Study area description

A total of 11 forest areas of Central Italy (Regions—Lazio, Toscana; Provinces—Viterbo, Roma and Grosseto; Fig. 1) were selected along an altitudinal gradient from 3 to 1,045 m above sea level (Fig. 2). They are referred to as five compositional type (coenosis), and each one is dominated by *Fagus sylvatica* (beech); *Castanea sativa* (chestnut); *Quercus cerris* (Turkey oak) and *Quercus pubescens* (downy oak); *Quercus ilex*

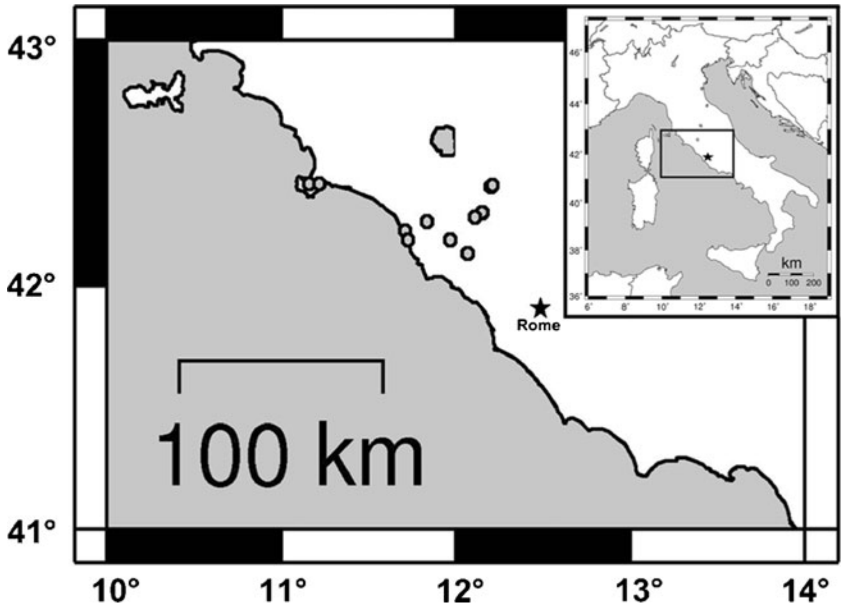


Fig. 1 Map showing the locations of soil sampling sites

(holm oak); and *Pinus pinea* (umbrella pine). Apart from vegetation composition/successional stages, the forest stands differ by forest management and type of disturbance (Table 1; detailed site description in the Electronic supplementary material (ESM)). In every forest stand, a variable number of sampling plots were chosen in relation to the specific disturbance studied; soil plots were considered impacted by tractor (with either tires or tracks), tourists (recreational use or tourist trampling) or animals when heavy marks of soil disturbance were present at the time of sampling.

Soil sampling, microarthropods extraction and QBS-ar index application

Each plot consisted of a square (10 × 10 m) with homogeneous forest cover, slope, exposure and pedology. Along the plot diagonals, three 1,000-cm^3 soil samples were taken. Microarthropods were extracted from each sample with a Berlese–Tüllgren funnel (for detailed explanation, see the ESM). The microarthropod community was identified to order level using a stereo microscope. Soil biological quality was expressed using the QBS-ar index (Parisi et al.

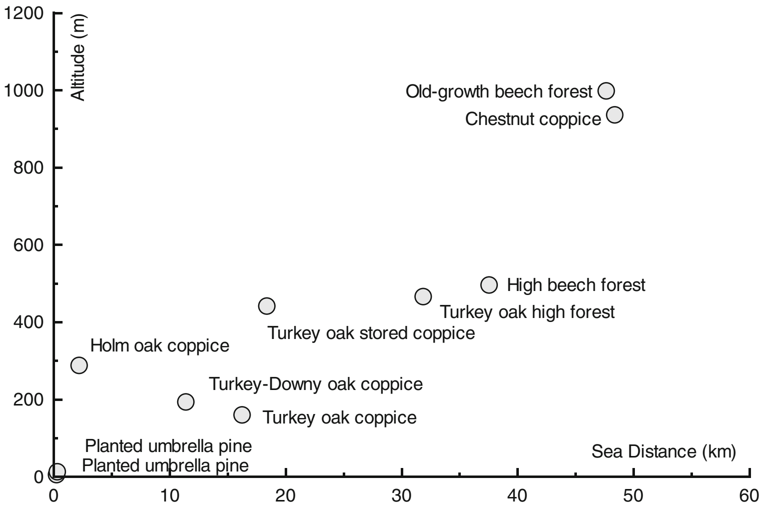


Fig. 2 Distribution of sample plots along an altitudinal gradient from the coast to the mountains

Table 1 Geographical and stand characteristics of sample plots

Forest type	Municipality	Latitude (N)	Longitude (E)	Sampling dates	Sampling plots	Soil disturbance[a]	Maximum tree height (m)	Tree age (years)	Litter thickness (cm)	Bedrocks
Old-growth beech forest	Soriano nel Cimino (VT)	42°24′24″	12°12′10″	28/04/08 and 16/09/08	9[b]	Tractor (1), natural gap (2)	35–47	>200	1–7	Volcanic
Beech high forest	Ronciglione (VT)	42°18′13″	12°08′59″	15/04/08	2		25–30	~150	4–8	Volcanic
Chestnut coppice with standards	Soriano nel Cimino (VT)	42°24′51″	12°12′13″	08/05/08 and 16/09/08	6[b]	Recently coppiced (3)	25	2–25	1–8	Volcanic
Turkey oak stored coppice	Tolfa (RM)	42°11′12″	11°57′52″	02/03/07, 12/03/07, 16/03/07 and 07/11/07	13[b]	Tractor (3), recently coppiced (6)	18	36	4–7	Volcanic
Turkey oak high forest	Vetralla (VT)	42°17′01″	12°06′16″	15/04/08	2[b]		30–35	~150	2–5	Volcanic
Turkey oak coppice with standards	Canale Monterano (RM)	42°08′05″	12°04′14″	16/05/08, 22/10/07 and 24/10/07	11[b]	Over grazing (1), recently coppiced (8)	10	3–22	3–6	Volcanic
Turkey–downy oak coppice with standards	Tarquinia (VT)	42°15′41″	11°49′57″	04/06/08	2[b]		15–20	22	5–7	Sedimentary
Holm oak coppice	Orbetello (GR)	42°24′55″	11°09′30″	11/12/07	1		15	~15	4	Sedimentary
Planted umbrella pine	Orbetello (GR)	42°25′03″	11°13′12″	11/12/07	3	Recreational use (3) and sea effect (1)	25	84	2–4	Sedimentary (sand)
Planted umbrella pine	Tarquinia Lido (VT)	42°13′28″	11°42′21″	04/06/08 and 16/06/08	3[b]	Recreational use (1)	10–25	~50	1–3	Sedimentary
Planted umbrella pine	San Giorgio, Tarquinia (VT)	42°11′20″	11°43′22″	04/06/08 and 16/06/08	3[b]	Recreational use (2) and sea effect (2)	10	24–35	1–3	Sedimentary (sand)

Every stand is identified by the average of geographic coordinates of sampling plots

VT Viterbo, *RM* Roma, *GR* Grosseto

[a] A sampling plot can be affected by more than one type of disturbance

[b] The site was sampled for physical–chemical soil analyses

2005). Soil organisms are separated into biological forms according to their morphological adaptation to soil environments; each of these forms is associated with a score named eco-morphological index (EMI), which ranges from 1 to 20 in proportion to the degree of adaptation (Tab. S1 in the ESM). The QBS-ar index value is obtained from the sum of the EMI of all collected groups. If in a group, biological forms with different EMI scores are present, the higher value (more adapted to the soil form) is selected to represent the group in the QBS-ar calculation. This index was applied in very different studies, primarily in Italy, where it was conceived (see previous QBS-ar application in the ESM), but this study is the first example of a systematic forest monitoring across an entire region.

Physical–chemical analyses (dry weight, per cent of water, bulk density, texture, pH and organic matter) were carried out on a subsample of plots representative of the network (Table 1) to investigate the effect of such factors on microarthropods biodiversity.

Statistical analysis

Data were analysed using a combination of univariate and multivariate techniques. Statistical analyses were performed using the PAST program, ver. 1.34 (Hammer et al. 2001).

In order to identify community gradients, a principal component analysis (PCA) (Davis 1986; Harper 1999) was carried out on a rectangular matrix (samples plot × taxa) of EMI data. A bootstrap resampling technique with 1,000 replicates was employed to evaluate the number of informative axes (Jackson 1993). The significance of eigenvector coefficients was evaluated by determining whether their 95 % confidence limits—extracted from bootstrap analysis—overlapped zero. Eigenvectors were then considered informative if at least two variables were significant on that axis. Before carrying out the analysis, we removed the taxa Acari and Collembola, which were present in all samples and represented by the maximum EMI value (20). In order to eliminate redundant data, PCA was performed on a matrix of EMI data excluding taxa, as Dermaptera and Blattaria, with frequency of <5 %, and taxa, as Thysanoptera, Hemiptera, Psocoptera and Diptera (adults), contributing less than 2 % to QBS-ar value.

To verify differences of soil quality and of microarthropod community structure among disturbed/undisturbed areas, dry season, types of forest management, forest composition and localities, a Kruskal–Wallis test (K-W; Zar 1996) and a non-parametric MANOVA (Anderson 2001) was carried out on QBS-ar index values and on the EMI data matrix respectively. The K-W statistic is corrected for ties. The Non-Parametric MANOVA (NPMANOVA) is based on a Bray–Curtis distance applied on EMI data matrix. When differences in community structure were significant ($p < 0.05$), a post hoc test was used to compare two by two the different group of samples; the significance level of this comparison was corrected according to Bonferroni (1935, 1936). The taxa contributing most to dissimilarity among group of samples were checked using the similarity percentage procedure SIMPER (cut off, ≈70 %, Clarke 1993) adopting the Bray–Curtis measure.

Results

Microarthropod communities

A total of 26 microarthropod groups belonging to the Chelicerata and Mandibolata subphyla were recovered. The Chelicerata subphylum was represented by: Araneae, Pseudoscorpiones, Palpigrada, Opiliones and Acari. The Mandibolata subphylum included Isopoda (1 taxon) and Tracheata (20 taxa). The Acari and the Collembola were gathered in every sampling plot with an EMI value equal to 20. Chilopoda, Hymenoptera and Coleoptera (larvae and adults) showed a frequency in the samples plots of >90 %. Araneae, Diplopoda, Symphyla, Pauropoda, Protura, Diplura and Diptera larvae were present in more than 50 % of forest plots investigated. Palpigrada, Isoptera, Embioptera, Dermaptera and Blattaria were uncommon (<10 % of sampling plots).

In 56 % of the forest plots investigated, the number of eco-morphological taxa collected ranged from 10 to 15. It was higher than 15 in about a third of sampling plots and lower than 10 in the 13 % of sampling plots. A positive relationship exists ($r=0.87$, $p<0.001$, $n=55$) between QBS-ar values and the number of taxonomic groups gathered in each sampling plot (Fig. 3).

The highest number of taxa (19), linked to the maximum QBS-ar value (267), was observed in the Canale Monterano Turkey oak (24 Oct 2007) while the lowest number of taxa (7) related to the minimum QBS-ar (71) was detected in San Giorgio umbrella

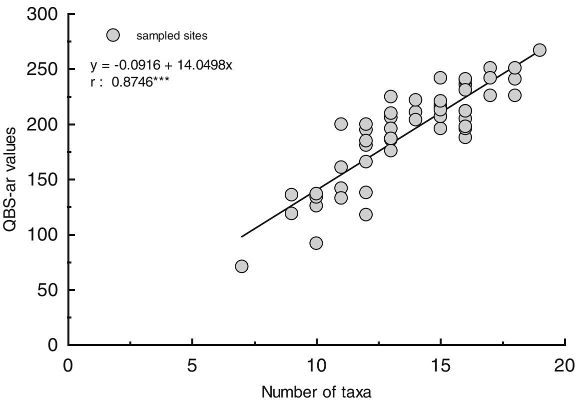


Fig. 3 Relationship between number of eco morphological taxa and QBS-ar values

pine (04 Jun 2008). The distribution of QBS-ar values among samples is shown in Fig. 4. The soil samples characterised by QBS-ar >200 came from the least disturbed woodlands. Soil samples with a QBS-ar between 150 and 200 were gathered mainly in deciduous stands. Then the 90 % of the soil plots where QBS-ar varied from 100 to 150 were collected from umbrella pine and Tolfa Turkey oak stands. Finally, the samples linked to lower values of QBS-ar (<100) came exclusively from the coastal umbrella pine stands.

The relationship between physical and chemical properties of soils and biodiversity of microarthropod has been investigated on a subset of plots, representative of the different types of composition and forest management considering also soil compaction. Soil analyses revealed a significant inverse relationship ($r=-0.69$, $p<0.01$) between soil bulk density and QBS-ar (Fig. 5). It is well known that one of the most important effects of compaction is to increase the bulk density (Han et al. 2009; see squares in Fig. 5). Correlation analyses revealed that the taxa more vulnerable to soil compaction were Coleoptera (adults), Protura, Pseudoscorpiones, Chilopoda and Symphyla. QBS-ar values are also directly correlated with coarse sand and skeleton (data not shown).

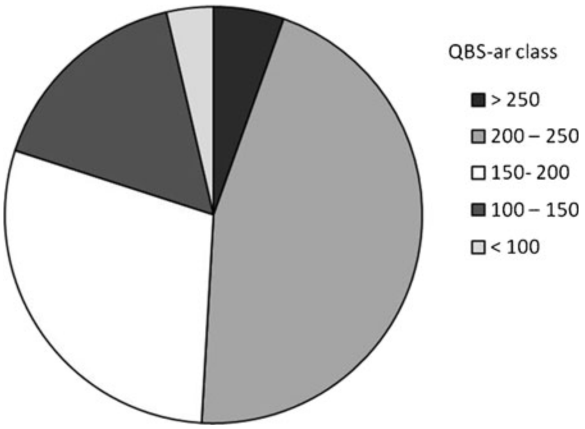


Fig. 4 Distribution of QBS-ar values

PCA results

On the whole, the first two components accounted for 46.1 % of total variance (Fig. 6). PC1 (31 % of the variance) shows a significant inverse correlation with QBS-ar (Fig. 7); it may be interpreted as a forest soil quality gradient. The sample plots related to the maximum soil quality were grouped by negative PC1 scores. They belong to the different types of deciduous forest and include the unique plot related to the evergreen holm oak. The taxa contributing significantly to the biological gradient were: Protura, Diplura, Coleoptera, Pauropoda, Diplopoda, Symphyla, Chilopoda, Diptera (larvae) and Opiliones (Fig. 8a). On the opposite side of PC1, the sample plots linked to low diversity of soil microarthropods are more scattered. These sample plots are related to forest plots affected by disturbance due to soil compaction (see below). PC2 (15 % of variance) is related to the central role of Pseudoscorpiones (Fig. 8b) while PC3 (12 % of variance) are related to the presence of Diplopoda (data not shown). Due to the relation to only one variable, caution must be used in interpreting these axes.

Performing the PCA without the disturbed plots reduced the variance of PC1 (24.2 %) being linked to only few taxa of microarthropods (Pseudoscorpiones,

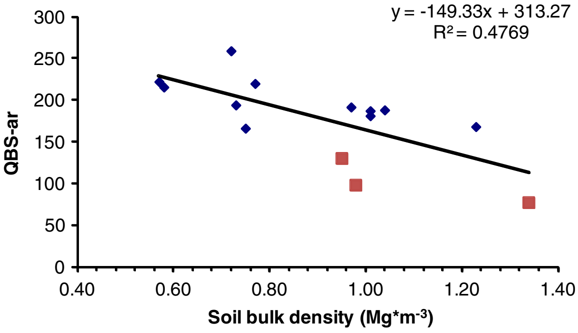


Fig. 5 Inverse linear relationship (r = 0.69; p < 0.01) between bulk density and QBS-ar. Soil samples with clear signs of compaction are indicated by *squares*

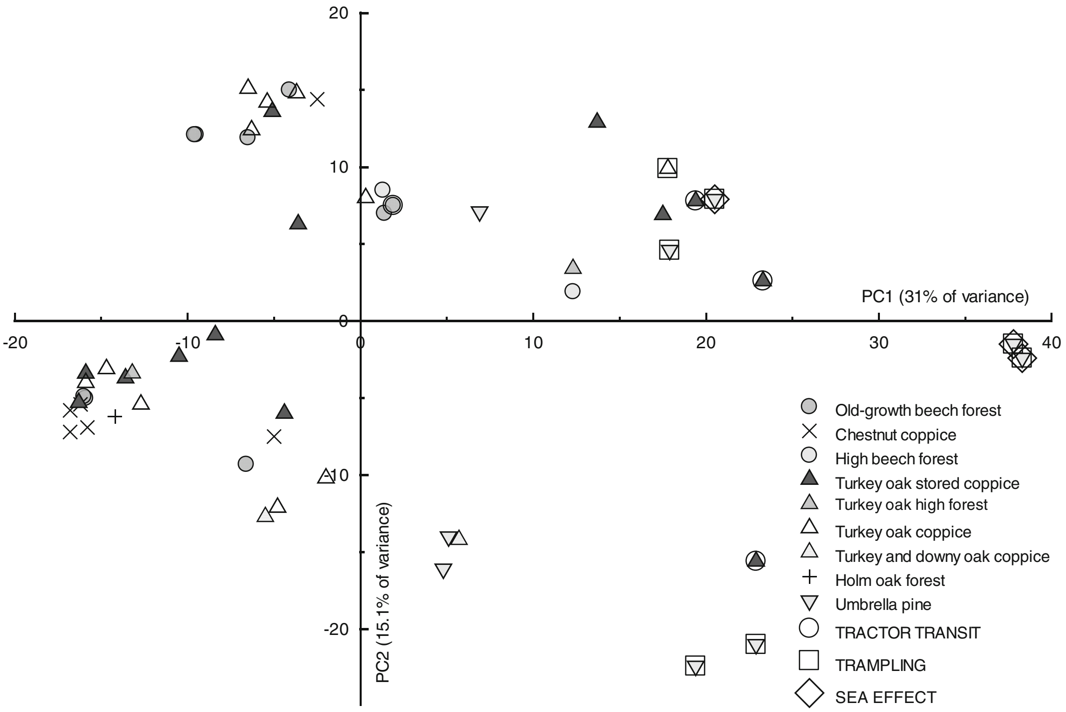


Fig. 6 PCA for the plots investigated. *Symbols* refer to forest types and to the most significant impacts on soil

Opiliones and Coleoptera). Interestingly, PC1 scores are still related to QBS-ar values as a soil quality indicator (r=0.72; p<0.05) that suggested a gradient in biodiversity between more "natural" and more "disturbed" forests. Since this axis is linked to the presence of Pseudoscorpiones, this taxon deserves particular attention for biomonitoring because it may be at the top of the trophic chain. PC2 (18.5 % of total variance) is related to the presence of Protura in the soil.

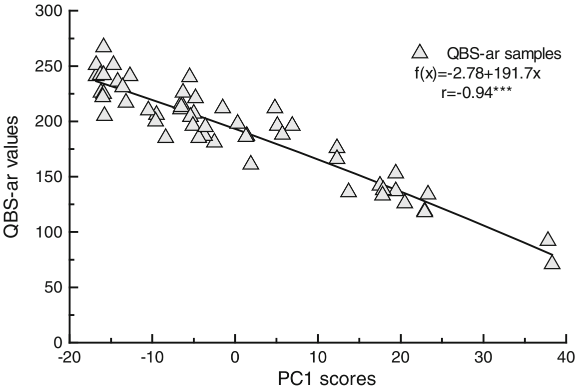


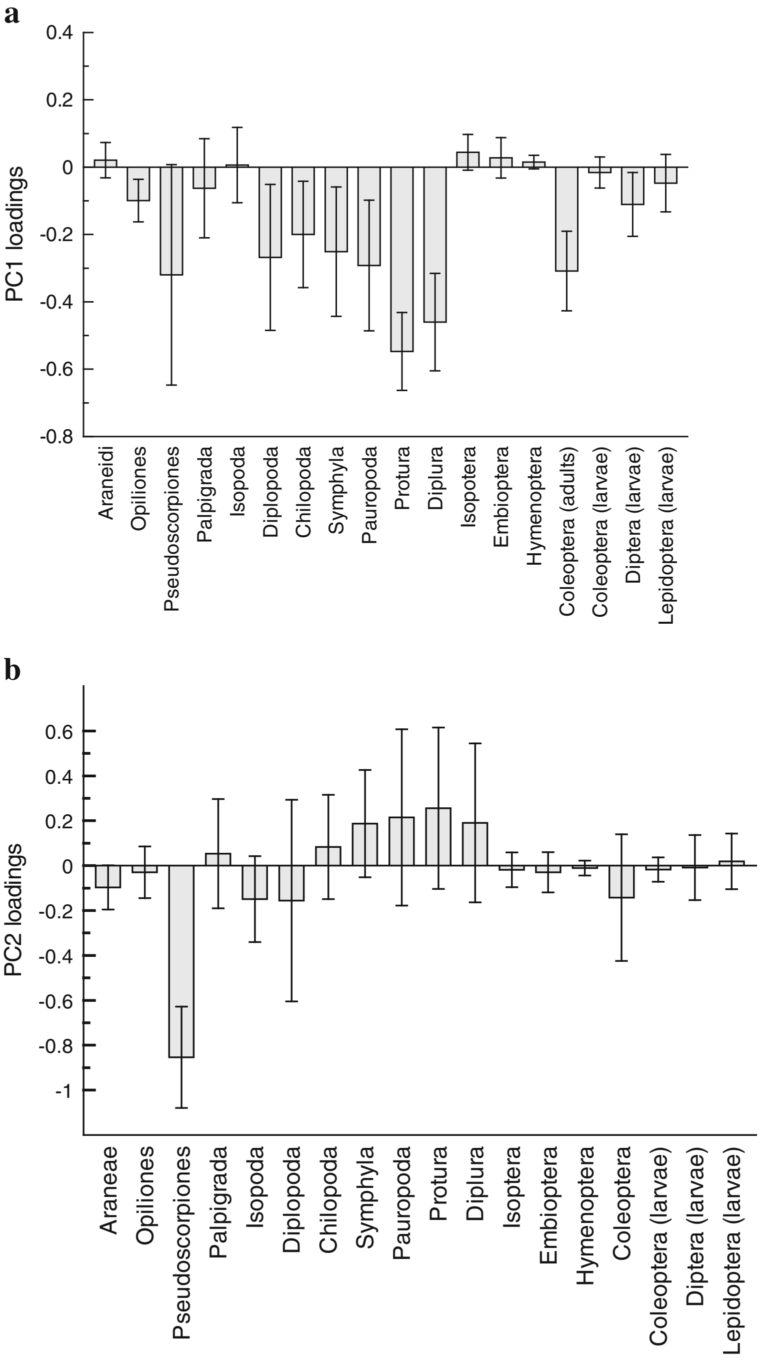
Fig. 7 Relationship between PC1 coordinates and QBS-ar values

QBS-ar as an index of compaction disturbance on forest soils

A significant variation of QBS-ar was observed between undisturbed forest plots and plots disturbed by tractors (p<0.001), recreation or grazing (p<0.001). The statistical analysis on EMI data also revealed a change in biotic soil quality among disturbed/undisturbed sampling plots (Table 2). On plots impacted by tractors or not impacted, taxa that contributed most to dissimilarity between plots were Pauropoda followed by Diplopoda, Diplura, Protura, Pseudoscorpiones and Chilopoda, respectively (average dissimilarity 30.2; Fig. 9a). Where there are impacts due to recreation, seven taxa (Diplura, Symphyla, Protura, Coleoptera, Pauropoda, Diplopoda and Pseudoscorpiones) appear to be the best indicators of lack of disturbance (average dissimilarity, 39.9 %; Fig. 9b). Protura is the only taxon always absent in disturbed areas.

In order to deepen the effect of compaction on soil biota and to eliminate noise due to forest composition, the disturbance within the same forest type was analysed in two specific cases: umbrella pine and Turkey oak stands. The results show that in the Turkey oak of Tolfa, a decline of QBS-ar was recorded in soil

Fig. 8 PC1 (**a**) and PC2 (**b**) factor loadings. The *line* represents the 95 % bootstrap confidence interval of coefficient loadings



samples affected by tractors used for the wood harvesting (Table 2). According to the NPMANOVA test, the microarthropod community showed a clear difference between soil plots disturbed by tractors and undisturbed plots confirming the general results. The average dissimilarity was 28.9 % and Diplura, Protura and Diplopoda were absent from disturbed plots, while Pauropoda and Pseudoscorpiones decreased in frequency (Fig. 10a). In the umbrella pine cenosis (Orbetello, San Giorgio, Tarquinia Lido), soil compaction produced by recreation showed significant differences in QBS-ar between compacted and non-compacted plots (Table 2). However, NPMANOVA indicated no statistically detectable differences in the

Table 2 QBS-ar (mean±standard deviation), K-W test results (on QBS-ar values) and NPMANOVA test results (on EMI data)

Forest type	Type of impact	QBS-ar		K-W test	NPMANOVA
		Not trampling	Trampling		
All stands	Tractor	207.6±28.4 (*n*=43)	137.7±17.4 (*n*=4)	Hc: 10.02***	F: 8.20***
Turkey oak (Tolfa)	Tractor	196.4±37.1 (*n*=10)	130±9.6 (*n*=3)	Hc: 5.63*	F: 6.24**
All stands	Recreational use	207.6±28.4 (*n*=43)	118.7±28.3 (*n*=7)	Hc: 17.02***	F: 20.08***
Umbrella pine	Recreational use	201.3±9.2 (*n*=3)	116.3±30.2 (*n*=6)	Hc: 5.45*	F: 1.68 ns

K-W test Kruskal–Wallis test, *ns* not significant

*$p<0.05$; **$p<0.01$; ***$p<0.001$

composition/functionality of microarthropod communities. Yet a considerable average dissimilarity (34.0 %) between disturbed and undisturbed plots was registered using the SIMPER procedure. The difference recorded was mainly due to the absence of Diplura, in the disturbed sample plots, and Pauropoda, Psuedoscorpiones, Symphyla, Diplopoda and Chilopoda, occurring less frequently (Fig. 10b).

In umbrella pine stands, an analysis of the effect of the sea on soil habitat was carried out by comparing disturbed forest areas close to the sea with undisturbed plots far from the sea. QBS-ar was significantly lower on two of the forest plots located near the coast where marine aerosol effects are stronger: San Giorgio and Orbetello. No significant variations of microarthropod communities were evident using NPMANOVA analysis. The average dissimilarity (SIMPER) between the forest plots close to the sea and forest plots farther from the sea was 40.9 %. The taxa primarily contributing to this dissimilarity was Diplopoda which were absent from plots close to the sea (data not shown).

In Soriano nel Cimino (Mt. Cimino) beech forest, where only one sampling plot is distinctly altered by tractors, the data suggest that QBS-ar is lower. In this case as well, the soil site disturbed by vehicle has shown a simplification of microarthropod community due to the absence of the Chilopoda and the Pauropoda.

QBS-ar community patterns in stands with no compaction

The study of the relationship between forest structure/composition and soil biological quality, described by QBS-ar/EMI data, was carried out after removing the sample plots disturbed by compaction (tractor transit and recreational use).

Seasonal variation (spring vs. late summer) in QBS-ar and microarthropod communities, were investigated because summer drought is the key climatic factor that affects beech and oak productivity in Mediterranean environment (Di Filippo et al. 2010; Piovesan et al. 2008). However, in woodlands dominated by Turkey oak and beech, differences in QBS-ar between spring and summer were not significant (Table 3). The analysis of EMI data showed a similar result. Therefore, QBS-ar does not seem to be influenced by dry summers in deciduous Mediterranean forest.

Forest management

QBS-ar does not vary significantly between structural stages (Table 3). Moreover, it is not influenced by the presence of natural gaps, and finally it does not differ between sampled plots affected by recent coppice practices.

In contrast, the analysis of variation in EMI groups among the different structural stages revealed changes in microarthropod community structure. Excluding the umbrella pine data from the two different statistical tests (K-W test and NPMANOVA), enhanced the NPMANOVA test. So the microarthropod community changed significantly, while the QBS-ar values did not show significant differences among various types of forest structure.

A more detailed analysis was carried out for Turkey oak stands considering the different structural conditions in the various forest areas studied. Similar to the results found on the total data, QBS-ar did not change significantly between various types of management (high forest, stored

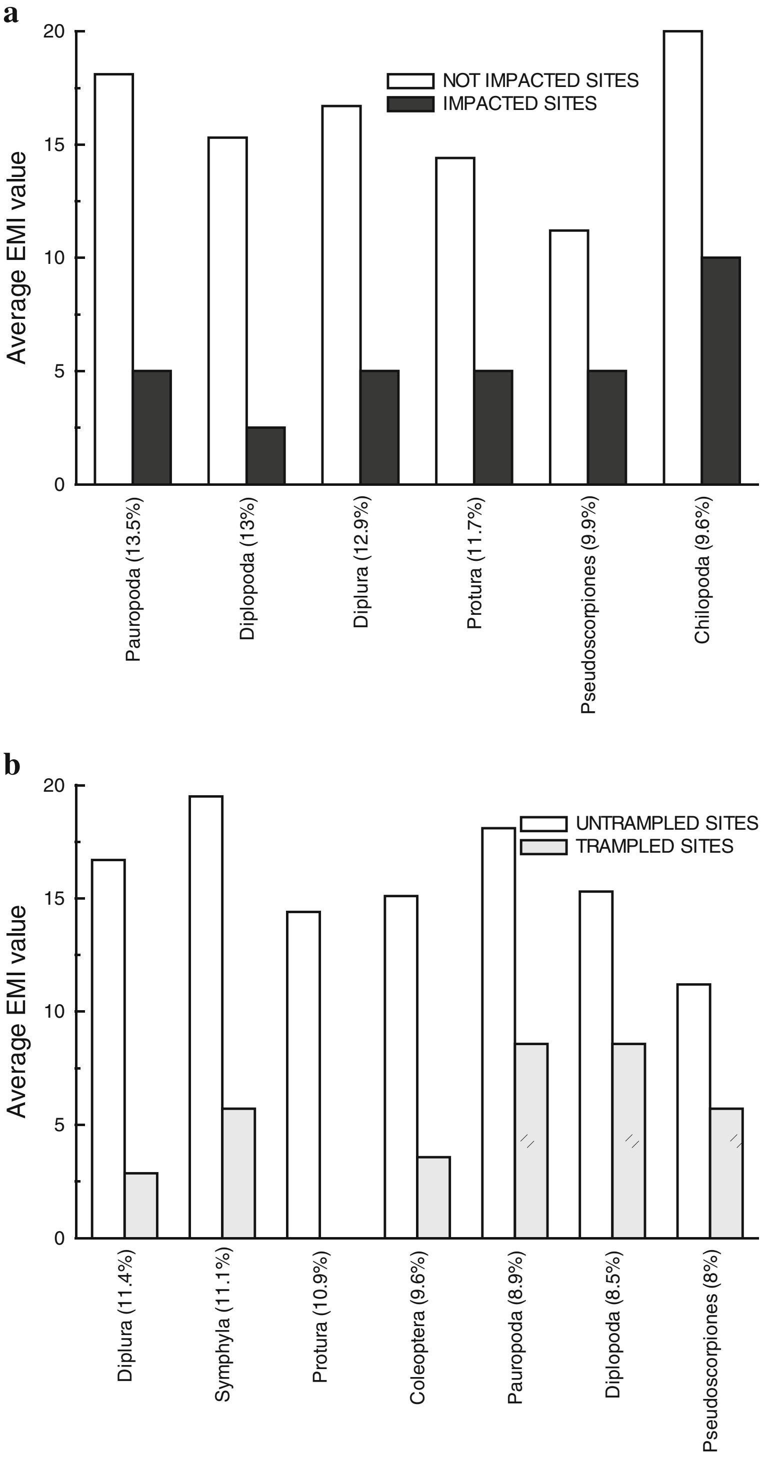
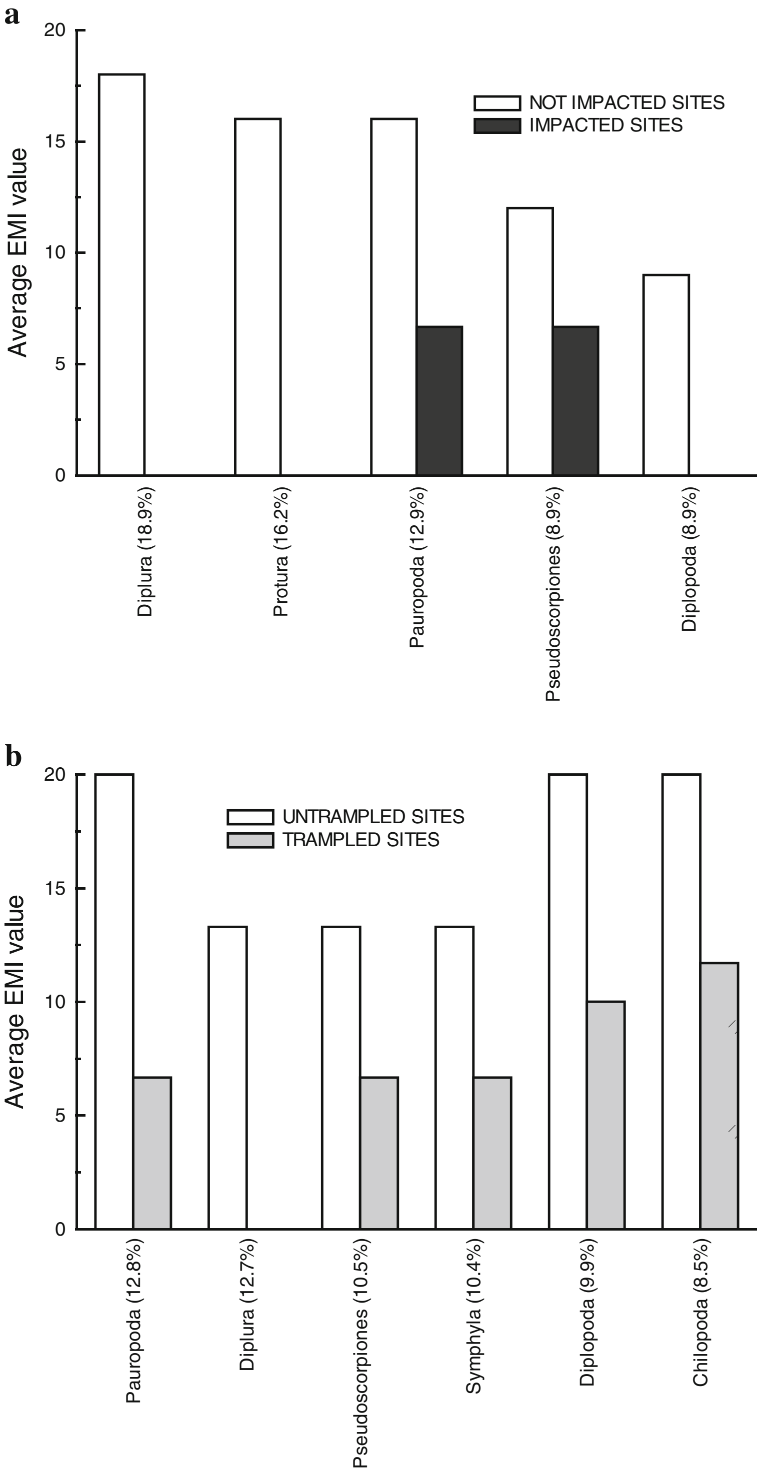


Fig. 9 Average EMI value of taxonomic groups with major contribution to dissimilarity for plots impacted by tractors (**a**) and tourist trampling (**b**) (SIMPER procedure; cut off, ≈70 %, EMI data)

coppice and coppice). Analysing EMI data of Turkey oak stands, no significant differences were noted among the soil biota of the three types of forest management.

Additionally, the effect of a natural forest gap was evaluated specifically for Mt. Cimino old-growth beech forest. No significant variations of QBS-ar and soil community among closed stand/natural gap emerged.

Fig. 10 Average EMI value of the taxonomic group with major contribution to dissimilarity between Turkey oak plots impacted/not impacted by tractors (**a**) and umbrella pine plots impacted/not impacted by trampling (**b**) (SIMPER procedure; cut off, ≈70 %)



In old growth beech forests, soil quality was not adversely influenced by gaps originating from large tree-falls allowing sunlight to fall directly on the soil.

Finally, QBS-ar and microarthropod communities did not vary between closed stands and/recently coppiced stands of chestnut and Turkey oak.

Table 3 QBS-ar (mean±standard deviation), K-W test results (on QBS-ar values), NPMANOVA test results (on EMI data), and post hoc test results for NPMANOVA test

Forest type	QBS-ar				K-W test	NPMANOVA
	Season					
	Spring	Late Summer				
Beech (M. te Cimino)	217.7±10.2 (n=3)	196.7±16.7 (n=3)			H: 2.4 ns	F: 1.82 ns
Turkey oak (Tolfa)	202.7±45 (n=4)	193.2±44.7 (n=4)			H: 0.19 ns	F: 1.82 ns
	Forest management					
	High forest	Gap high forest	Coppice	Stored coppice		
All stands	200.1±18.3 (n=13)	196.5±13.4 (n=2)	228.2±33.3 (n=6)	221.7±26.4 (n=7)	H: 5.2 ns	F: 2.6*
Without umbrella pine stand	200.6±20.7 (n=10)	196.5±13.4 (n=2)	228.2±33.3 (n=6)	221.7±26.4 (n=7)	H: 5.1 ns	F: 2.9**
Turkey oak	191.5±36.1 (n=2)	–	226.6±36.9 (n=5)	219.7±20.7 (n=4)	H: 1.4 ns	F: 1.2 ns
	Natural forest cycle					
	Closed stand	Natural gap				
Beech	202.9±18.4 (n=8)	196.5±13.4 (n=2)			H: 0.15 ns	F: 2.23 ns
	Forest management					
	Closed stand	Recently coppiced				
Chestnut	224.3±37.9 (n=3)	212.7±12 (n=3)			H: 0.43 ns	F: 0.94 ns
Turkey oak (Tolfa-Monterano)	217.7±31.4 (n=11)	200±32.7 (n=13)			H 1.34 ns	F: 0.85 ns
Turkey oak (Tolfa)	219.7±20.7 (n=4)	180.8±38.7 (n=6)			H: 3.32 ns	F: 0.8 ns
Turkey oak (Monterano)	235±42.3 (n=3)	216.4±14.4 (n=7)			H: 0.65 ns	F: 0.91 ns
	Composition					
	Beech	Chestnut	Turkey oak	Umbrella pine		
All stands	201.6±17 (n=10)	218.5±25.8 (n=6)	208.1±32.7 (n=24)	201.3±9.2 (n=3)	H: 1.84 ns	F: 2.92**
						Post hoc test: BE/UP* and TO/UP*
	Site effect within forest type					
	M.te Cimino	Vico lake				
Beech	210.2±14.4 (n=6)	181±7.1 (n=2)			H: 4.39*	F: 4.93*
	Tolfa	Canale Monterano	Vetralla	Tarquinia		
Turkey oak	196.4±37.1 (n=10)	222±24.8 (n=10)	191.5±36.1 (n=2)	214±36.8 (n=2)	H: 3.24 ns	F: 1.92 ns

Factors analysed: season, forest cycle and management, composition and sampling locality. The analyses were performed after removing the heavy impacted (tractor/car transit, trampling and sea effect) plots

K-W test Kruskal–Wallis test, *ns* not significant, *BE* Beech, *TO* Turkey oak, *UP* umbrella pine

*$p<0.05$; **$p<0.01$; ***$p<0.001$

Forest composition

The average, QBS-ar value for each forest type was >200, and the chestnut shows the higher average value (Table 3). However, no variations of QBS-ar among beech, chestnut, Turkey oak and umbrella pine stands emerged. A clear change of microarthropods community structure between the four forest cenosis was observed using EMI data. The subsequent pairwise comparisons between the various cenosis indicated that soil biota of umbrella pine was significantly different from those of Turkey oak and beech. Seven taxa contributed most to the average dissimilarity between the three deciduous forest habitats and umbrella pine according to the SIMPER procedure (Fig. 11). Protura and Opiliones were always absent in umbrella pine stands while Isopoda and Diplopoda increased in abundance.

Site effect

Finally, a detailed study on variation of the biological soil quality among different sample plots was conducted for beech and Turkey oak stands. Significant differences of QBS-ar and microarthropod community structure were noticed between the two sample areas of Mt. Cimino and Ronciglione (Vico lake) (Table 3). The analysis of the contribution of individual taxa showed that Diplura, Protura, Pseudoscorpiones and Isopoda were responsible of 70 % of the total dissimilarity (Fig. 12), suggesting that in the past the Vico stand suffered an impact. No change of QBS-ar was noticed between Turkey oak stands dominated by *Q. cerris* on different sampling areas. NPMANOVA test revealed no significant differences in soil community structure, too. Yet some changes of soil biota community structure were revealed by SIMPER procedure which indicated seven taxa that contributed most to the average dissimilarity among the four forest plots (Fig. 13). In particular, Protura was always absent in the Tarquinia Turkey oak stand; this could be linked to the proximity to the coastline. Moreover, as for umbrella pine stand, Tarquinia Turkey oak stands are characterised for the highest frequency of Diplopoda. Palpigrada, a rare order in Italian soils, occur sporadically in Canale Monterano and Tolfa Turkey oak and they could be considered an indicator of stable areas.

Discussion

High biological soil quality in Mediterranean forest ecosystems

The soil of the various forest types of Central Italy is characterised by high biological activity on plots

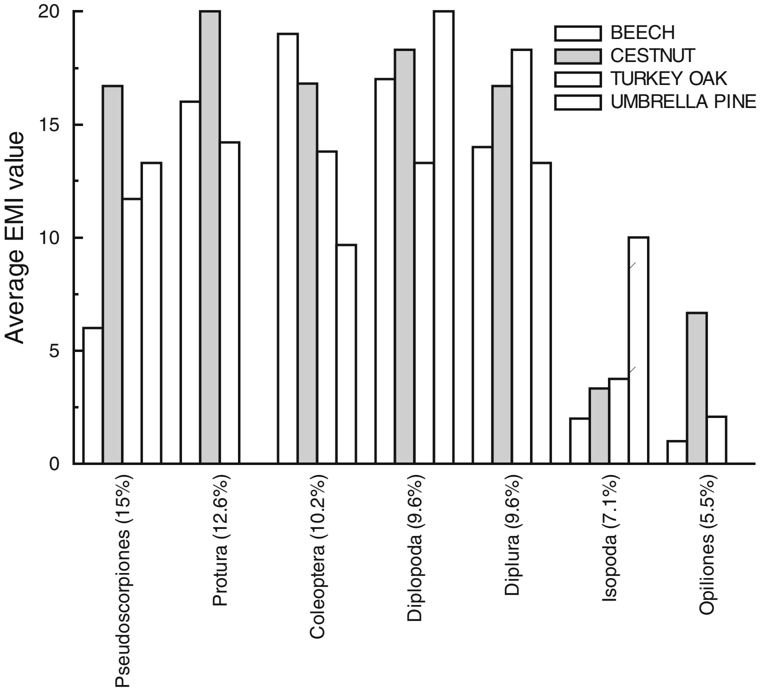


Fig. 11 Average EMI value of the taxonomic group with major contribution to dissimilarity between the habitat sampled (SIMPER procedure; cut off, ≈70 %). The analyses were performed after removing the heavily impacted plots (tractor/car transit, trampling and sea effect)

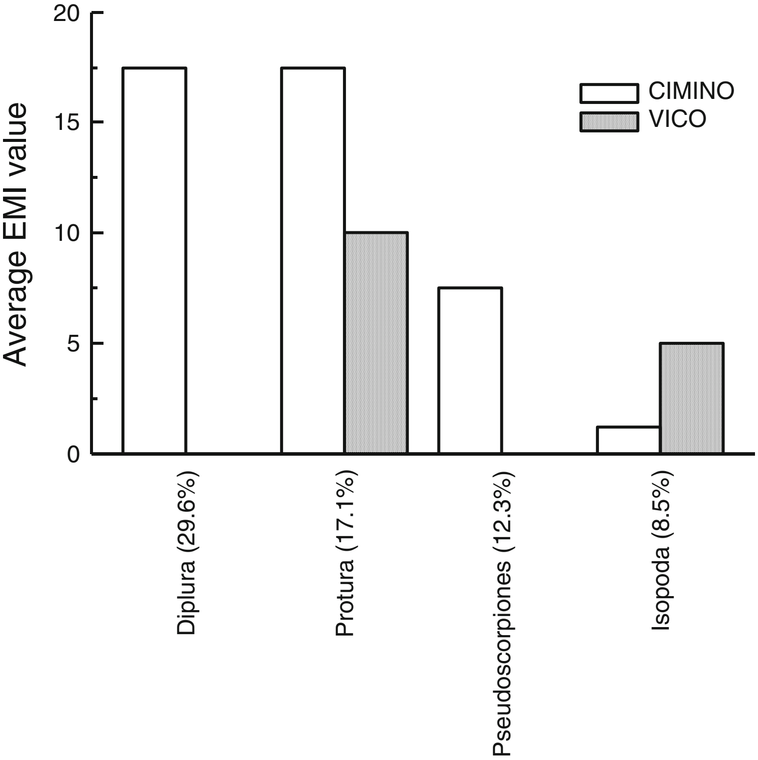


Fig. 12 Average EMI value of the taxonomic group with major contribution to dissimilarity between Mt. Cimino and Vico lake beech forest (SIMPER procedure; cut off, ≈70 %). The analyses were performed after removing the heavily impacted plots (tractor/car transit, trampling, sea effect)

undisturbed by soil compaction, as the QBS-ar index reaches values of >200. Comparing soil of different vegetation communities, the QBS-ar index reaches values clearly higher than those observed in cultivated fields (generally, <150; Tabaglio et al. 2008, 2009), in lowland meadows (average QBS-ar values range from

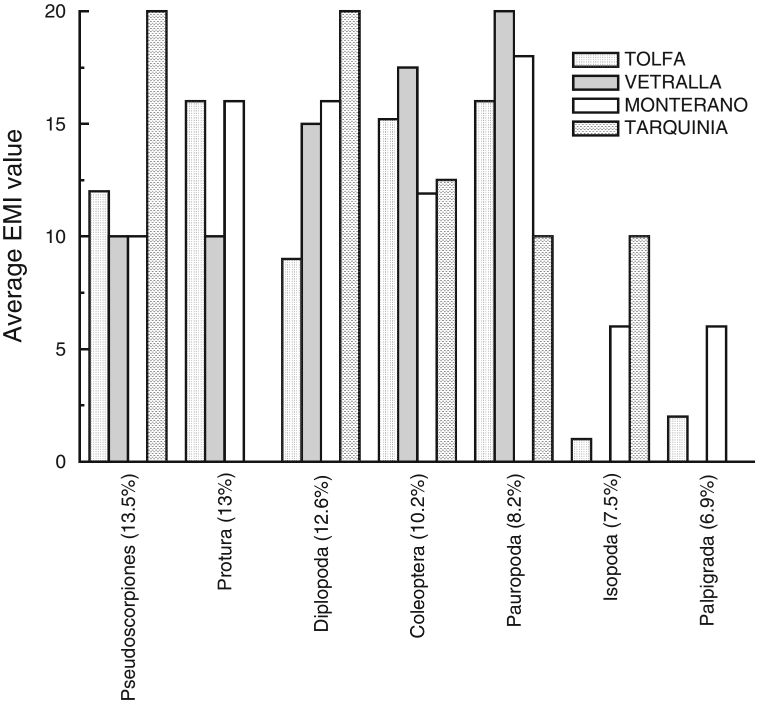


Fig. 13 Average EMI value of the taxonomic group with major contribution to dissimilarity between Tolfa, Vetralla, Canale Monterano and Tarquinia Turkey oak plots (SIMPER procedure; cut off, ≈70 %). The analyses were performed after removing the heavily impacted plots (tractor/car transit, trampling and sea effect)

70 to 200; Gardi et al. 2002; Menta et al. 2008, 2011), in managed chestnut woodland (157–107; Paparatti and Peroni, personal communication), in vaccinietum (*Empetro-Vaccinietum gaultherioidis*) and alpine fields (*Anthoxantho-Brachypodietum genuensis*), (QBS-ar average values are equal to 135 and 190, respectively; Leoni 2008) and in degraded areas, such as covered dumps (QBS-ar value was lower than 80; Menta et al. 2008). A previous study (Callaham et al. 2006) indicated a clear gradient of decreasing diversity of macroinvertebrate soil communities from hardwood stands to pine stands followed by pastures and cultivated fields. Our results confirm that hardwood soils are characterised by the highest biodiversity level and by a well-structured and mature microarthropod community, typical of stable ecosystems.

Another study revealed high QBS-ar values of a neighbouring plain oak forest in Latium (Central Italy) (Podrini et al. 2006). The Mediterranean ecology of Latium, where the warm-temperate evergreen forest meets the deciduous biome, should enhance the biodiversity status of the soil, too. Moreover, Central Italy was a refuge area during Quaternary glaciations and for this reason forest ecosystems are characterised by a high diversity of flora and fauna (Ricci Lucchi 2008). Indeed in a northern Italy beech forest, growing in a protected area (Guadine Pradaccio) the QBS-ar value was 172 (Menta 2008), probably because beech expanded in more recent times.

QBS-ar and forest composition/management

This study reveals no significant differences in the QBS-ar index values between several compositional/structural stages of deciduous hardwood forest in Central Italy (e.g. beech vs. oak vs. chestnut; coppice vs. secondary old-growth stands). In fact, canopy openings and silvicultural management (e.g. coppicing) do not seem to affect the QBS-ar index.

QBS-ar values in undisturbed umbrella pine plots, originating from reforestation activities (80–35 years; Bellarosa et al. 1996) are similar to those of centuries-old ancient woodlands. In these young forest stands, the composition of the microarthropod community most likely results from species living in the pre-existing vegetational habitat (grassland or cultivated field), colonisation of new species from nearby forests, and the subsequent interaction between these species. These soil animal communities are often impoverished and affected both by physical soil properties (granulometry) and by those derived from land-use (pH, stratification, quality and quantity of organic matter and porosity) (Huhta and Raty 2005). The poor potential for dispersal of many species inhabiting the soil is a key element restricting potential habitat colonisation. Experiments on microarthropod dispersal (Ojala and Huhta 2001) revealed that most collembolan have a potential capacity for colonisation over the distance of 30 m within 30 years since reforestation. Therefore, the reforested stands are characterised by a lower diversity, biomass and density of soil animal communities than the native forest stands. In particular, a simplified microarthropod community lived in the umbrella pine stands studied here. It differs from the other forest stands because of the absence of Protura, a taxon characterised by high adaptation to soil life, and by the absence of Opiliones. However, on undisturbed soil plots, the QBS-ar is comparable with that of deciduous forest due to the contribution of Isopoda and Diplopoda which compensate partly the decrease in Diplura and Coleoptera (adults). Despite of the abovementioned limitations, on the whole, soil animal communities could be able to recover in few decades. In contrast, in the umbrella pine nearest to the coast, a general impoverishment of the soil community is attributed to unfavourable environmental factors (e.g. sand soil) and stress (e.g. sea aerosol), but this requires further study.

It was quite surprising that the secondary old-growth beech forest has QBS-ar values similar to those of managed forests. However it should be noted that these forests sustained anthropogenic impacts from several ancient cultures (Villanoviana, Etruschi and Romans) who used forests to collect wood and food resources. In addition, this old-growth forest was utilised in the 1,800 s as parkland forests, for gathering resources. High forests are often pleasant places that make them particularly attractive for recreation and consequently attract heavier tourist impacts (soil compaction) compared with coppice stands which are usually frequented only by hunters and mushroom harvesters. The high soil biodiversity of coppice, even after the final rotation cut, could be linked to the maintenance of root structure and to the diffuse organic detritus on the ground after the cutting. It is well known that root apparatus, in particular ectomycorrhizae, feed many arthropods. However, it must be emphasised that the QBS-ar index investigates microarthropod communities on the basis of morphological characteristics so that community changes at lower taxonomical levels (e.g. genus and species) cannot be distinguished. In addition, QBS-ar does not consider changes in population density.

In Central Italy silvicultural practices and composition of deciduous forests do not seem to have any important effect on microarthropods community structure. The absence of a change in soil community structure could be linked to the litter layer that in these hardwood stands is thick enough to maintain a high organic matter level and a favourable microclimate in every season. Soil mesofauna seem to recover quickly after disturbances such as tree cutting (Bird et al. 2000) indicating a good level of ecosystem integrity (community resilience). The same aspect also emerged in conventional tillage condition where soil arthropod abundance was significantly higher in autumn compared with summer (Neave and Fox 1998). The authors suggested that, given sufficient time without soil disturbance, soil arthropod numbers are able to recover within the growing season. These results confirms the previous studies conducted on a temperate cool rain forest in west Canada where there were no significant differences in population density of arthropods between undisturbed forests on harvested plots and unharvested patches (Addison 2007). Additionally, in another recent study, regarding a beech forest, the hypothesis of Ponge et al. (1998), which predicts community changes during forest rotations, was refuted from a functional view point (Hedde et al. 2007). However several studies considering the effects of silvicultural practices on soil fauna found important impacts on soil forest fertility/productivity and in the terrestrial food chain (Moore et al. 2002). It is generally accepted that removal of trees by clear cutting, or other methods, has a significant effect on the invertebrate fauna of the forest floor (Heliovaara and Vaisanen 1984; Hoekstra et al. 1995). The effects on arthropod communities are complex and difficult to analyse since various taxonomic groups are affected and they react to impacts differently (Bird et al. 2000; Hill et al. 1975; Huhta et al. 1967; Lasebikan 1975; Vlug and Borden 1973). The separate analyses of the different impacts are a useful way to find clear patterns in such a complex system.

QBS-ar and the dry season

The results show that QBS-ar does not vary significantly with seasons (rainy season, spring; dry season, summer) in deciduous stands. Similarly no structural variation of microarthropod communities emerge. Studies on the Chilopoda community structure indicated that its changes through the year are very small (Grgič and Kos 2005). On the other hand, it is well known that in Mediterranean ecosystems, invertebrate abundance follows seasonal cycles with a peak during winter and a decline in summer (Touloumis and Stamou 2009). Since QBS-ar is based on qualitative data of soil fauna, in deciduous forest the index seems to be not affected by seasonal variations (summer drought) making it a good soil quality indicator. However, further research is necessary in ecosystems affected by persistently dry summers (e.g. macchia and Mediterranean pine forests) to confirm that seasonality is not a significant influence on the index. In the same way, the effect of temperature on QBS-ar should be analysed in a separate case study (Aspetti et al. 2010). Particularly, in forest ecosystems stable microenvironmental conditions exist throughout the year so that the microarthropod community (expressed by EMI form presence), under a thick litter layer, is less affected by seasonal changes. On the contrary, in cultivated fields, soil microarthropod communities (Neave and Fox 1998) are strongly affected by seasonality, as measured by QBS-ar values (Tabaglio et al. 2009).

QBS-ar and forest soil compaction

PCA analysis showed a clear soil quality gradient from the coastal reforestation stands, disturbed by recreational use, to the less-disturbed deciduous stands. The index seems to be very efficient in linking variation in arthropod communities in response to the impacts of soil compaction, also measured in terms of soil bulk density. Compaction modifies a variety of physical and chemical properties in the soil (pore space, organic matter, temperature and moisture) producing a considerable loss of biological forms best adapted to soil life. The PCA analysis revealed that nine functional groups reacted negatively to soil impacts (e.g. compaction). In particular, Protura, Symphyla and Pauropoda are taxonomic groups typical of stable environments (Bedano et al. 2006) linked to undisturbed soil (for their ecology, see ESM). Furthermore, recent studies on the effects of harvesting on soil (Addison 2007) reveal that Symphyla, Diplura and Diplopoda are the most sensitive groups not occurring in disturbed areas. In particular, Myriapoda has been shown to be absent on degraded soils (Menta et al. 2008) and sporadically present at low density in cultivated fields (Tabaglio et al. 2009). It is possible to hypothesise that the same groups could be studied in greater depth in order to create more discriminating indices of naturalness.

Conclusions

A more complete census of soil microarthropod communities is needed for biodiversity conservation. Soil-quality monitoring is often inaccessible to land managers because the measurement systems are too complex, too expensive or both (Herrick 2000), despite its utility as an indicator of environmentally friendly use of natural resources. This study has contributed to the development of efficient and low-cost biological indices of soil quality (Bongers 1990, 1999; Cortet et al. 2000; van Straalen 1998, 2004) that are based on microarthropod communities.

Since forest ecosystem are characterised by high values of QBS-ar (>200), values of <150 should be considered indicative of important regressive impacts (i.e. unsustainable resource use). In forest ecosystem management, QBS-ar could be an efficient index for evaluating the impacts of forest harvesting on soil (i.e. soil compaction due to logging). At the same time, QBS-ar can be a valuable tool in ecosystem restoration programs to monitor the development of soil functions and biodiversity and to prevent the negative effects of soil compaction when mechanisation is used (e.g. in Europe many LIFE projects include mechanised operations). Furthermore, this index could be implemented in environmental management programs of urban forestry and protected areas in relation to recreational use to prevent the negative effects of trampling. More in general, QBS-ar is a candidate index for continuous biomonitoring of soil communities to describe patterns and processes in the microarthropod biodiversity across the landscape. A deeper knowledge of soil biodiversity in response to landscape use will provide guidance in effective management planning for sustainable renewable resource use and nature conservation.

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