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Assessing the Impact of Agrivoltaic Systems on Pasture Plant and Soil Microarthropod Communities

Michele Moretta[1] | Riccardo Rossi[1] | Enrico Palchetti[1] | Marco Moriondo[1,2] | France Joshua Rabit[3] | Giacomo Santini[3] | Filippo Gallese[2] | Anita Maienza[2] | Marco Bindi[1] | Alberto Masoni[3]

[1]Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence (UNIFI), Florence, Italy | [2]Institute of BioEconomy of the National Research Council (CNR-IBE), FIorence, Italy | [3]Department of Biology (BIO), University of Florence (UNIFI), Florence, Italy

Correspondence: Riccardo Rossi (r.rossi@unifi.it)

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ABSTRACT

Agrivoltaic systems (AVS) integrate renewable energy production with agricultural use, creating novel microclimatic gradients that can affect ecosystem structure and function. However, the ecological consequences of these gradients on vegetation composition and soil biological quality remain poorly understood, particularly in pasture-based AVS configurations. In this study, we investigated seasonal and spatial changes in plant functional groups and soil microarthropod communities across shading gradients in a Mediterranean AVS pasture using the Pasture Value (PV) and the Soil Biological Quality-arthropods (QBS-ar) indices. Results revealed marked seasonal differences driven by panel-induced microclimatic variability. In spring, strong microclimatic contrasts generated pronounced differences across treatments, with inter-row areas showing higher PV and QBS-ar values and supporting more diverse plant and soil faunal communities. These areas supported the co-dominance of legumes and a richer assemblage of microarthropods, indicating a positive relationship between productive, nitrogen-fixing vegetation and soil faunal diversity. By contrast, shaded under-panel zones hosted stress-tolerant forbs and showed reduced QBS-ar values, indicating lower biological quality. These integrative indicators can guide AVS pasture management while supporting long-term monitoring of soil fertility and ecosystem functioning.

1 | Introduction

The degradation of soil biological quality represents a major challenge for modern agriculture, as conventional practices can enhance short-term productivity while undermining sustainability and biodiversity (Karlen and Rice 2015; Le Campion et al. 2020). At the same time, policies promoting renewable energy to achieve climate neutrality, such as the European Green Deal (European Commission 2019), may reduce the availability of arable and fertile lands.

Agrivoltaic systems (AVS), which integrate photovoltaic energy production with agricultural activities such as crop cultivation or livestock grazing, have emerged as a promising solution to mitigating this land-use conflict (Goetzberger and Zastrow 1982; Mamun et al. 2022). Ongoing technological advances and the decreasing cost of photovoltaic modules have further stimulated interest in large-scale, ground-mounted AVS installations (Meneguzzo et al. 2015; Rosslowe and Petrovich 2025). Systems combining livestock grazing (e.g., sheep) with photovoltaic infrastructures have gained attention for their potential to modulate vegetation growth, reducing excessive biomass accumulation and management requirements, while maintaining sufficient forage availability and delivering additional ecological and economic co-benefits (Kochendoerfer et al. 2019;

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Byrnes et al. 2018; Freehill-Maye 2020; Udroiu 2023). For instance, pasture-based AVS have been shown to maintain comparable lamb growth rates to open fields (≈ 120 g head^{-1} day^{-1}), while allowing for higher stocking densities and reduced water consumption under shaded conditions. Moreover, partial shading from photovoltaic panels helps preserve forage productivity during the summer, enhances animal welfare by mitigating heat stress, and increases overall land-use efficiency up to 200% through the joint production of renewable energy and livestock products (Andrew et al. 2021). However, potential trade-offs affecting crop yields and livestock feed must be considered in integrated AVS to maintain an optimal balance between agricultural production and energy generation.

The installation of AVS directly affects plant growth and development by modifying local microclimatic conditions through dynamic shading, which alters solar radiation, air and soil temperatures, and water availability (Weselek et al. 2019; Amaducci et al. 2018; Moretta et al. 2025a, 2025b). Beneath photovoltaic panels, temperatures are often lower and more stable, particularly during hot seasons (Armstrong et al. 2016; Yue et al. 2021), and soil moisture may increase due to reduced evaporation, although the magnitude of this effect depends on module layout, spacing, and seasonal precipitation patterns (Hassanpour Adeh et al. 2018; Du Hamel et al. 2023). These changes have been observed to improve organic carbon stocks (Luo et al. 2024), while they may also entail potential risks such as salinization, reduced infiltration capacity, and increased pH (Chen et al. 2025). In turn, such modifications can influence plant productivity, community composition, and overall ecosystem functioning in context-dependent ways (Armstrong et al. 2014; Zhang et al. 2024). In temperate and cool climates, shading typically reduces biomass and species richness beneath the panels, whereas in Mediterranean environments, lower solar radiation can alleviate heat stress and enhance forage quality and availability, especially for shade-tolerant grasses (Vaverková et al. 2022; Adeh et al. 2019; Gill 2024; Moretta et al. 2025b).

Nonetheless, plant responses to exogenous factors remain difficult to generalize even within a single environment, as they vary depending not only on local conditions but also on species-specific functional traits and adaptation strategies. In this context, grasses are generally more tolerant to shade and respond positively to increased moisture, while legumes may be constrained by limited nodulation and lower carbon assimilation under reduced irradiance (Pang et al. 2019; Van Sambeek et al. 2007). Moreover, shallow-rooted annuals may struggle under dry conditions caused by limited rainfall when growing beneath partially or fully panel-covered zones, whereas deep-rooted species can access water redistributed by photovoltaic modules to surrounding areas (Pierret et al. 2016; Nippert and Holdo 2015). Consequently, plant community composition adapts to the shading gradients induced by AVS, resulting in spatial variations of soil organic matter content and nutrient availability (Bertoldo et al. 2024).

These different patterns form the basis of bottom-up processes typical of grassland ecosystems, where the quality and abundance of plant-derived resources, such as root exudates and litter, drive the distribution of soil biota, including microarthropods (van Eekeren et al. 2022). Such interactions are further reinforced by feedback effects, as the decomposition of organic matter and nutrient recycling by microarthropods enhance soil fertility and can thus promote the growth and development of key plant species for agricultural or grazing purposes (Menta et al. 2023; Orgiazzi et al. 2016). Recent studies have provided more detailed evidence of these dynamics. As an example, Fusco et al. (2023) demonstrated that, across contrasting Alpine habitats, soils supporting richer and more functionally diverse microarthropod communities, such as those in undisturbed forests, exhibited higher biological quality and nutrient turnover, thereby enhancing vegetation stability and productivity under different management regimes. Similarly, Culliney (2013) emphasized the pivotal ecological roles of soil fauna, particularly detritivorous arthropods, in accelerating decomposition rates and nutrient cycling, ultimately enhancing soil structure and fertility.

At the same time, pedofauna is highly sensitive to varying edaphic conditions, which can strongly influence their activity, spatial distribution, and ecosystem functions (Delcourt et al. 2023; Erktan et al. 2020). In disturbed or compacted soils, epiedaphic and hemiedaphic microarthropods often dominate, whereas euedaphic forms are more prevalent in well-structured, biologically active soils (Lavelle et al. 2006; Wallwork 1970; Maienza et al. 2023). While moderate shading and increased soil moisture under AVS can favor soil fauna, excessive humidity or reduced organic inputs may depress its diversity and abundance (Moscatelli et al. 2022; Meloni et al. 2020). Furthermore, the optical properties of photovoltaic panels, including reflection and polarization, may also affect microarthropods' orientation and behavior, contributing to the multifaceted faunal responses under AVS installations (Fox et al. 2007; Egri et al. 2016).

Given the functional complexity of vegetation and soil microarthropod communities in response to microclimatic variability induced by solar panels, there is a growing need for integrative, site-specific tools to assess their composition and interactions. The adoption of synthetic indices that capture complementary aspects of agroecosystem functioning allows for a comprehensive evaluation of plant and soil responses across shading gradients. Among indices based on plant species composition previously proposed as proxies for forage quality and pasture integrity, the Pasture Value (PV) index stands out for its simplicity, stability over time and broad applicability (Argenti et al. 2006, 2017). This synthetic indicator quantifies the overall pastoral quality of a plant community by weighing species according to their forage value and has been widely used in Mediterranean and Alpine grasslands to assess the ecological and productive status of pastures, providing valuable guidance for conservative grazing management (Argenti and Lombardi 2012; Pornaro et al. 2019; Pittarello et al. 2018). On the other hand, the Soil Biological Quality-arthropods (QBS-ar) index offers a practical and affordable means to characterize soil arthropod communities without requiring species-level identification, relying on eco-morphological traits to infer their adaptation to edaphic conditions (Parisi et al. 2001, Parisi et al. 2005; Menta et al. 2018; Gallese et al. 2025; Mantoni et al. 2021; D'Avino et al. 2022; Naglič et al. 2024). Although these indices perform well individually, they have not yet been applied in an integrated and comprehensive manner to capture the combined effects of shading and moisture gradients on both plant and soil arthropod communities and their interactions within an AVS.

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Previous studies have demonstrated that AVS-induced microenvironmental gradients regulate plant productivity and functional composition, which in turn shape soil microarthropod communities, forage quality, and overall pasture suitability (e.g., Bai et al. 2022; Li et al. 2023; Menta et al. 2023). However, the integrated plant-soil-environment interactions have rarely been explicitly addressed from a functional perspective. Because the combined assessment of vegetation and soil conditions has been demonstrated to be crucial for guiding adaptive grazing management and identifying areas with differing suitability for pasture use (e.g., Amorim et al. 2020), the joint application of the PV and QBS-ar indices is expected to provide an effective framework for interpreting the effects of AVS-induced gradients in grassland systems and supporting spatially explicit management strategies, such as rotational grazing and targeted grazing allocation.

Accordingly, the present study aims to provide a comprehensive understanding of how microclimatic gradients induced by photovoltaic modules influence the composition of plant and soil microarthropod communities in a managed Mediterranean pasture. To this end, by integratively assessing PV and QBS-ar indices across two seasons and multiple shading treatments, our approach is intended to capture the effects of shading intensity and precipitation patterns on above- and below-ground biodiversity and ecosystem functioning. Based on these objectives and the ecological mechanisms expected in Mediterranean pastures, we tested the following hypotheses: (H1) the effects of AVS-induced microclimatic gradients on plant functional composition and soil microarthropod communities differ between seasons, reflecting differences in environmental conditions such as temperature, light, and soil water status; (H2) shading intensity and soil moisture jointly drive the spatial distribution and functional responses of plant and microarthropod communities, with areas receiving optimal light and water supporting a higher abundance of key pasture species and enhanced soil biological quality; (H3) plant community composition is functionally linked to soil microarthropod community structure, reflecting mutual influences between PV and QBS-ar indices along microclimatic gradients.

By addressing these hypotheses, the study provides a mechanistic basis for the informed management of pasture-based AVS, guiding grazing intensity, spatial use of shaded and unshaded areas, and vegetation control strategies that jointly sustain forage quality, soil biological functioning, and biodiversity.

2 | Materials and Methods

2.1 | Study Area and Experimental Design

The study was conducted at the AVS located in Sant'Alberto (Ravenna, Italy; 44.51019° N, 12.1552° E), within the Po River Valley. This site, operational since 2012, covers approximately 70 ha and consists of a mixed grass–legume pasture integrated with ground-mounted photovoltaic panels.

The site is characterized by a temperate climate with hot summers and cold winters. The mean annual temperature is 15°C (minimum 5°C in January; maximum 25.6°C in July), and annual precipitation averages 767 mm, with November as the wettest month (87 mm) and January the driest (49 mm). According to the official pedological map of the Emilia-Romagna region (1:250,000; Figure 1), about two-thirds of the study area belong to unit 2Aa, which includes flat, very deep, fine-textured, calcareous and moderately alkaline soils with moderate oxygen availability. The remaining area corresponds to unit 3Ad, characterized by similar flat and very deep soils, but with medium texture and slightly higher oxygen availability. Overall, the soils can be classified as silty sand in the 0–60 cm layer, with an average composition of approximately 50% sand, 40% silt, and 10% clay (Regione Emilia-Romagna 2024).

Photovoltaic modules are mounted on south-facing ground structures tilted at 35°, with tables 3.5 m wide and rows spaced 8 m apart, resulting in a ground cover ratio (GCR) of 38%. Panel height varies between 1.3 m at the lower edge and 3.3 m at the upper edge, creating a clear shading gradient across the field. The installation contributes about 45 GWh of electricity annually.

Before sowing in 2020, the soil was plowed to a 30 cm depth, tilled, and rolled to ensure optimal seed–soil contact and crop establishment under the AVS configuration. The site is managed under a rotational grazing system using Sardinian sheep breeds, with photovoltaic panel rows spacing and layout designed to minimize interference with grazing activity and pasture management.

The field experiment was carried out at the AVS site following a randomized complete block design with three blocks (B1, B2, B3) randomly distributed across the study area. Within each block, three transects were laid out perpendicular to the photovoltaic panel rows and spaced 20 m from each other, to capture spatial heterogeneity in light exposure and shading. Along the photovoltaic-induced shading gradient (Figure 1), four treatments were defined: TR1 (inter-row fully exposed, ~7% shading), TR2 (inter-row with water run-off from panels, ~6% shading), TR3 (front under panel, ~67% shading), and TR4 (rear under panel, ~82% shading). Three external control areas (CT1, CT2, CT3) were established along the perimeter of the AVS system. These control plots were not affected by panel shading or runoff but were cultivated and managed in the same way as the panel-covered meadow area. Due to their small size only a single sampling unit was identified and sampled.

2.2 | Data Collection and Processing

During two representative seasons (i.e., autumn 2023 and spring 2024), microenvironmental parameters, plant and microarthropod communities were surveyed within each block × treatment × replicate combination to assess the effects of the AVS on soil and biological components. Data were not collected during the extreme winter and summer seasons, as excessively low or high temperatures in the Mediterranean climate strongly limit vegetative growth and induce quiescence of microarthropods in deeper soil layers, which would have reduced the sensitivity of the survey to detect treatment effects. This approach is consistent with the recommendations of D'Avino et al. (2024), who indicate that soil sampling for QBS-ar determination should avoid cold and dry periods to prevent vertical migration, immobilization, and aestivation of soil microarthropods. All sampling plots were located in areas where

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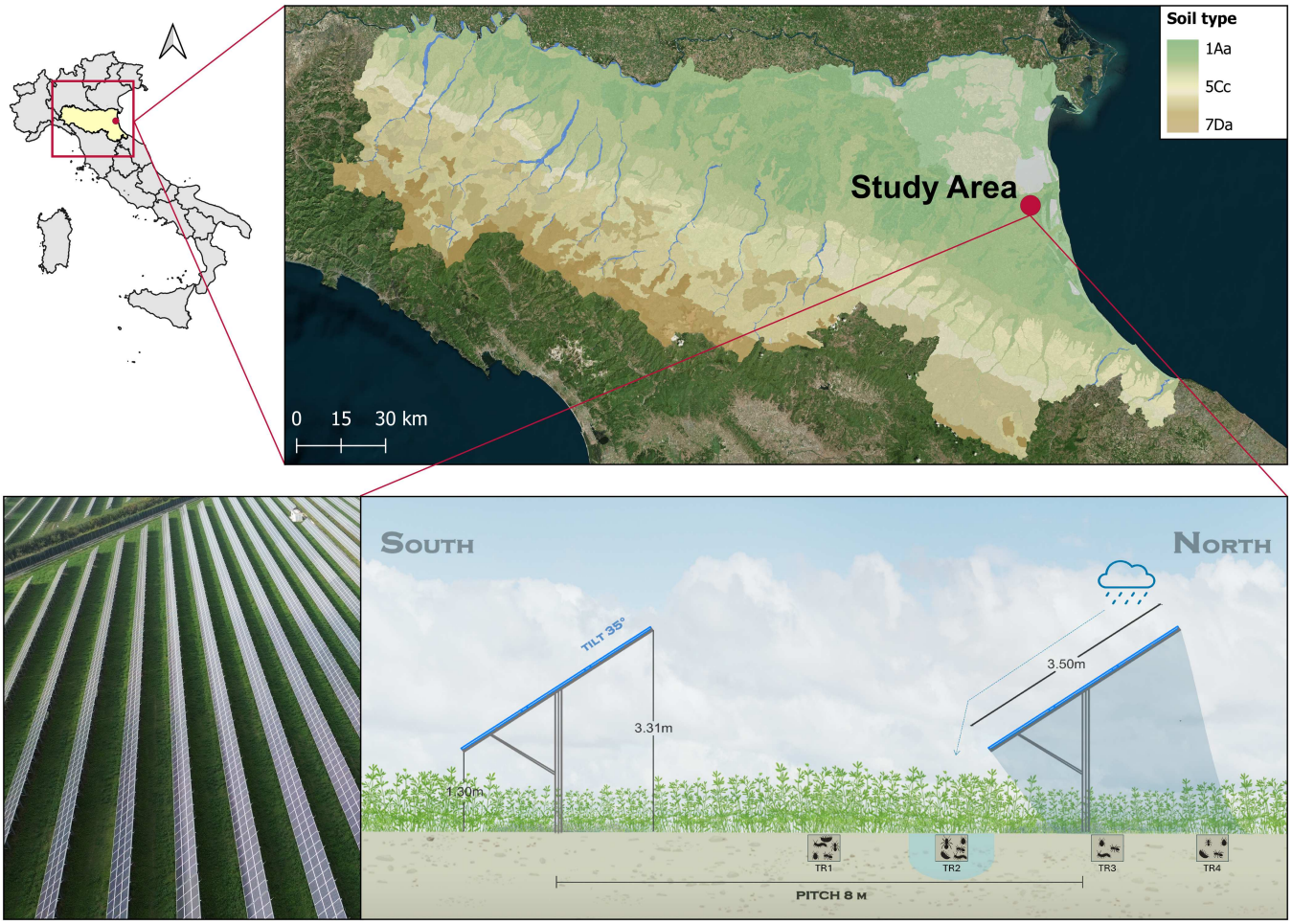

FIGURE 1 | Location and technical layout of the study area, along with the arrangement of the sampling treatments (TR1, TR2, TR3 and TR4). The soil map (1:250,000) is based on the official pedological cartography of the Emilia-Romagna region, encompassing soil units ranging from delta plain soils (1Aa) to those of the lower (5 Cc) and upper Apennines (7 Da; *Source:* https://geoportale.regione.emilia-romagna.it/).

grazing sheep had been suspended since late summer 2022, to exclude short-term effects on soil and vegetation conditions.

2.2.1 | *Microenvironmental Data*

Air temperature (T, °C) and relative humidity (RH, %) were recorded every 15 min using data loggers with built-in T/RH sensors (HOBO Pro v2, Onset Computer Corporation, Pocassette, MA, USA) positioned outside (CT1), between (TR1) and under the photovoltaic panels (TR3). In addition, soil volumetric water content and soil temperature were determined in triplicate using a portable time-domain reflectometry probe (FieldScout TDR 350, Spectrum Technologies Inc., Aurora, IL, USA) on the day of year (DOY) 326 (Autumn 2023), and on DOY 100 (Spring 2024).

Furthermore, the framework developed to estimate crop growth within a photovoltaic system, which combines the GroIMP platform and its associated radiation model (Hemmerling et al. 2008) with the crop growth model described in Moretta et al. (2025b), was applied in this study. In brief, a detailed 3D reconstruction of the analyzed AVS was generated in GroIMP, and the radiation intercepted by each object in the scene, including soil and photovoltaic panels, was computed at an hourly time step. The ground-level radiation, simulated at a 1×1 m spatial resolution in GroIMP, was then used as a direct input to spatially drive an alfalfa growth model embedded within the same platform. This model also requires air temperature, rainfall, relative humidity, and wind speed at the same temporal resolution to spatially simulate plant morpho-physiological processes as influenced by radiation reduction, water stress, and temperature stress. The framework demonstrated strong robustness in accurately estimating biomass production ($R^2 = 0.94$, RMSE = 110.35 g m^{-2}) and leaf area index (LAI; $R^2 = 0.96$, RMSE = 0.31). In the latter case, it also reliably simulated canopy surface temperature as a function of shading and water stress ($R^2 = 0.83$, RMSE = 0.88°C).

Here, the model simulation for the 2023–2024 growing season provided data on Intercepted Soil Radiation (ISR, MJ m^{-2} day^{-1}) and the water balance in the tested sampling plots under full-sun and shaded conditions. The ISR was calculated at an hourly scale as the difference between incoming radiation and that intercepted by the crop and was then aggregated daily. The daily water balance was expressed as the Fraction of Total Soil Water (FTSW, unitless), defined as the ratio between the actual soil water content and the maximum soil water capacity, i.e., between field capacity and wilting point. FTSW values range from 1, when soil water is at field capacity, to 0, when soil water reaches the wilting point.

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To capture the short- to mid-term effects of these micro-environmental variables on plant and soil communities, rather than their immediate daily fluctuations, the data were averaged over the 15 days preceding the sampling date.

2.2.2 | *Plant Data*

On the same sampling days (DOY 326, 2023 and DOY 100, 2024), the botanical composition of the pasture was assessed in each experimental unit using a 1 × 1 m quadrat, randomly placed within each treatment area. Plant species were visually identified by a single experienced observer to minimize human bias between sampling dates. The relative cover of plant species (%) was then quantified and classified into three functional groups: palatable grasses (G), legumes (L), and species belonging to other botanical families (O). Within a pasture system, G typically represents the primary forage component providing bulk biomass, L contributes to nitrogen fixation and improves forage quality, and O includes forbs and non-leguminous plants, which may influence biodiversity and ecosystem functions (Menta et al. 2011; Birkhofer et al. 2011). Based on the collected data, a Pasture Value (PV) index was calculated for each experimental unit following the methodology of Argenti et al. (2017; Equation 1).

$$PV = \frac{\Sigma SC_i \cdot SI_i}{5} \quad (1)$$

where SC_i is the relative cover (%) of each *i*-botanical species within the sampled quadrat, and SI_i is the specific index of forage value for that species, ranging from 0 to 5. For the functional groups considered in this study, the SI values were assigned as follows based on Argenti et al. (2006): G = 1.95, L = 2.99, O = 0.29.

Experimental areas were classified according to Argenti et al. (2006) as high-quality pasture (PV > 25), intermediate-quality pasture (15 < PV ≤ 25), and low-quality pasture (PV ≤ 15).

Subsequently, for each treatment, three plants from the most representative species of the functional groups were collected, placed in separate bags, and refrigerated until processing. In the laboratory, leaves from each sample were individually detached, arranged on a white background, and photographed perpendicularly from above using a tripod-mounted digital camera. A metric ruler with millimeter markings was included in each image as a scale reference to calibrate measurements in the ImageJ imaging software (https://imagej.nih.gov/ij/). The total leaf area of each plant was quantified (cm^2) using a color-thresholding approach and then averaged across the three replicates to obtain the mean total leaves area per species and treatment.

2.2.3 | *Microarthropod Data*

The assessment of soil microarthropod communities was carried out through soil sampling performed on DOY 326 (2023) and DOY 100 (2024), following the standardized QBS-ar protocol proposed by D'Avino et al. (2024). Both sampling dates were selected when soil temperature ranged from approximately 14°C (DOY 326) to 24°C (DOY 100) and soil moisture was close to field capacity, ensuring optimal conditions for the detection of active soil fauna (Menta et al. 2018; Table S1). To prevent escape of soil fauna during collection, the vegetation above each sampling point was clipped prior to soil removal. For each treatment (TR1–TR4) along the transects and in the controls (CT1–CT3), three undisturbed soil subsamples were collected at 0–10 cm depth (10 × 10 × 10 cm soil cube), avoiding the transition between the plough layer and the subsoil (Figure 2A–C). In total, 78 soil samples were collected, including 72 from treatment plots (2 time points × 3 blocks x 4 treatments × 3 replicates) and 6 from control plots (2 time points × 3 blocks × 1 treatment × 1 replicate).

Samples were immediately placed in sealed black plastic containers and transported to the laboratory (within 4 h), where they were processed for microarthropod extraction using Berlese–Tullgren funnels following the protocol by Parisi et al. (2005), modified by Gallese et al. (2025). Specifically, each soil sample was placed under a 60 W incandescent lamp positioned approximately 30 cm above the funnel (Figure 2D). The extraction lasted 7 days, in line with recommendations that the duration should be related to soil moisture and never less than 5 days (Menta et al. 2018). The lamps created a thermal gradient, progressively drying the soil and forcing organisms downward into a collecting vial containing ethanol:glycerol (2:1), where they were preserved until identification. Microarthropods were examined under a stereomicroscope (Carl Zeiss Vision Italia Spa, Varese, Italy) at 80× magnification and identified using standard taxonomic keys (Parisi et al. 2005; Menta et al. 2018; D'Avino et al. 2024) at the taxon level. Presence/absence and counts were recorded manually and an ecomorphological index (EMI) was assigned to the morpho-functional groups scored for QBS-ar evaluation. Microarthropods were categorized as epiedaphic (1 < EMI ≤ 4), hemiedaphic (4 < EMI ≤ 8), or euedaphic (8 < EMI < 20) as reported in Menta et al. (2015) and the highest EMI score was recorded and subsequently summarized to calculate the QBS-ar for the associated soil sample, according to D'Avino et al. (2024). The relative abundance (proportional contribution of a specific group to the total microarthropod community extracted in the samples) of the arthropods that form each soil category (Epiedaphic, Hemiedaphic, Euedaphic) was counted for each sample.

2.3 | Statistical Analysis

All statistical analyses were performed using R software (v. 4.3.3; R Core Team, 2024).

Control samples (CT1–CT3) were pooled and analyzed as a single CT group due to the low number of replicates available in each area, imposed by landscape constraints. Differences in QBS-ar index among treatments (TR levels) and between seasons (spring-autumn) were analysed using generalized mixed effects models (GLMMs) with TR and season as fixed factors and blocks as random factors. The cover (%) of plant functional groups and relative abundance (%) of soil microarthropod functional groups (Epiedaphic, Hemiedaphic, Euedaphic) were compared using the same factors in a GLMM with a Beta error distribution using the *glmmTMB* package. When significant effects were detected ($p < 0.05$), multiple pairwise comparisons among the factor levels were performed using Tukey-adjusted

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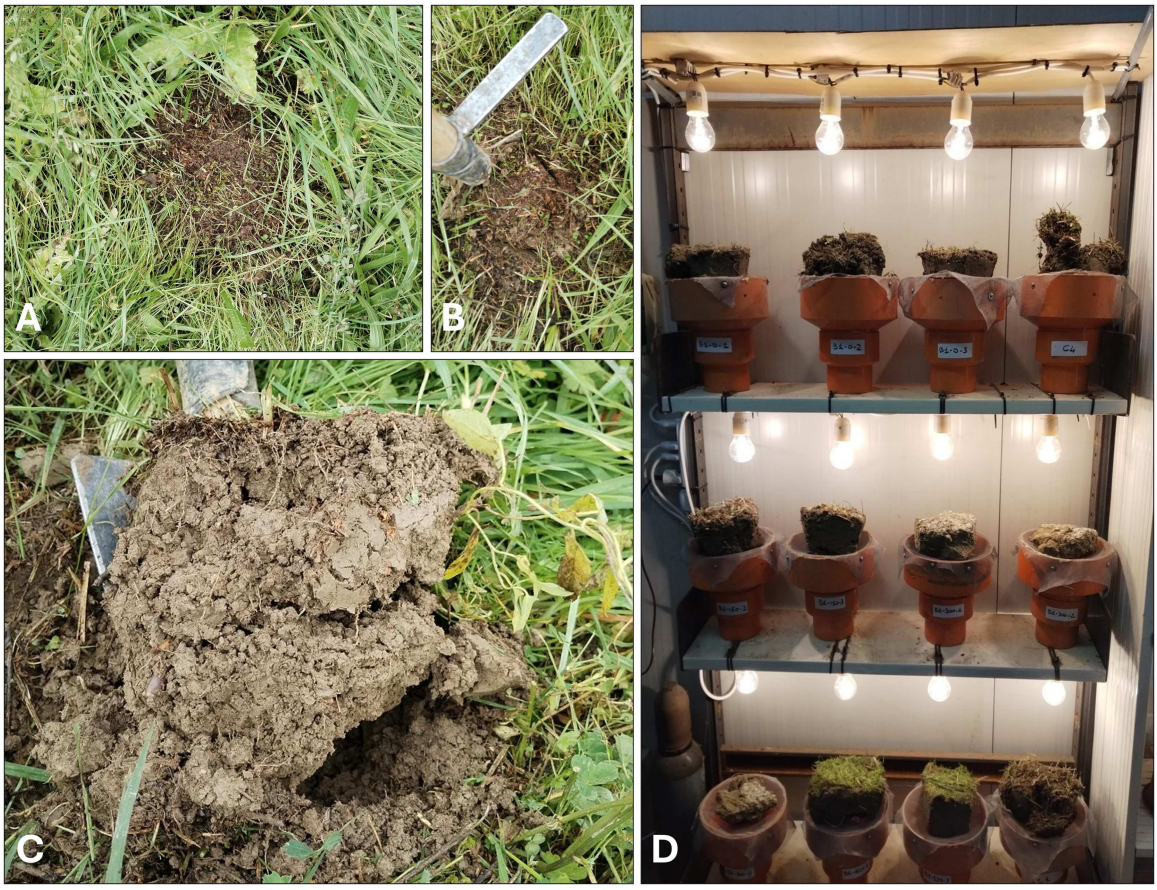

FIGURE 2 | Procedure adopted for soil sampling and extraction of microarthropods in the AVS. (A) Removal of the vegetation layer at the sampling point. (B) Collection of a standardized soil cube ($10 \times 10 \times 10$ cm) using a steel corer. (C) Example of extracted soil samples before laboratory processing. (D) Berlese–Tullgren funnels used for microarthropod extraction with 2 mm mesh, with soil samples placed under a light-heat gradient to induce organism migration into the collecting vials.

contrasts with the *emmeans* package. To assess the influence of AVS-induced microclimatic gradients on plant and microarthropod community composition, a Principal Component Analysis (PCA) was performed considering only data from the inter-row and under-panel treatments (TR1–TR4). Finally, the relationships between the variables across treatments were evaluated using the Pearson correlation coefficient (r).

3 | Results

3.1 | Plant Community Composition

Across seasons, clear shifts were observed in the relative abundance of functional groups (Figure S1A). Grasses (G) significantly decreased from autumn to spring ($p < 0.05$), while legumes (L) and other species (O) showed no significant seasonal variation.

During both sampling campaigns, consistent differences also emerged in the relative cover of functional groups along the shading gradient imposed by the photovoltaic panels (Figure 3). G represented the dominant component in both seasons, particularly in the control (CT) and front under-panel (TR3) treatments, where their cover was significantly higher than in the other plots. In autumn, grass cover peaked in CT and TR3, whereas inter-row (TR1) and rear under-panel (TR4) areas displayed lower values. L prevailed in TR1 and TR2 across both seasons, showing markedly higher percentages than in the shaded treatments, with the highest values recorded in spring. In contrast, TR3 and TR4 exhibited negligible legume presence, indicating that these under-panel conditions were unsuitable for nitrogen-fixing species. Conversely, O became increasingly dominant toward the shaded zones, particularly in TR4, where they reached the highest cover in both seasons. In spring, TR4 values were significantly greater than those of all other treatments, while in autumn the same trend was evident though less pronounced, with O species nearly absent in CT, TR1, and TR2 but sharply increasing under TR3 and TR4.

3.2 | Microarthropod Community Composition

The taxonomic composition of the soil arthropod community reflected these functional patterns, with Acarina and Collembola representing the dominant groups across all treatments and seasons (Table S2). In autumn, Acarina abundance was particularly high in TR2 and TR4, while Collembola peaked in TR2 and declined under the shaded positions (TR3–TR4). Minor taxa, such as Hymenoptera, Coleoptera larvae, and Isopoda contributed to seasonal and spatial variability, showing higher occurrence in spring and in the rear under-panel area (TR4).

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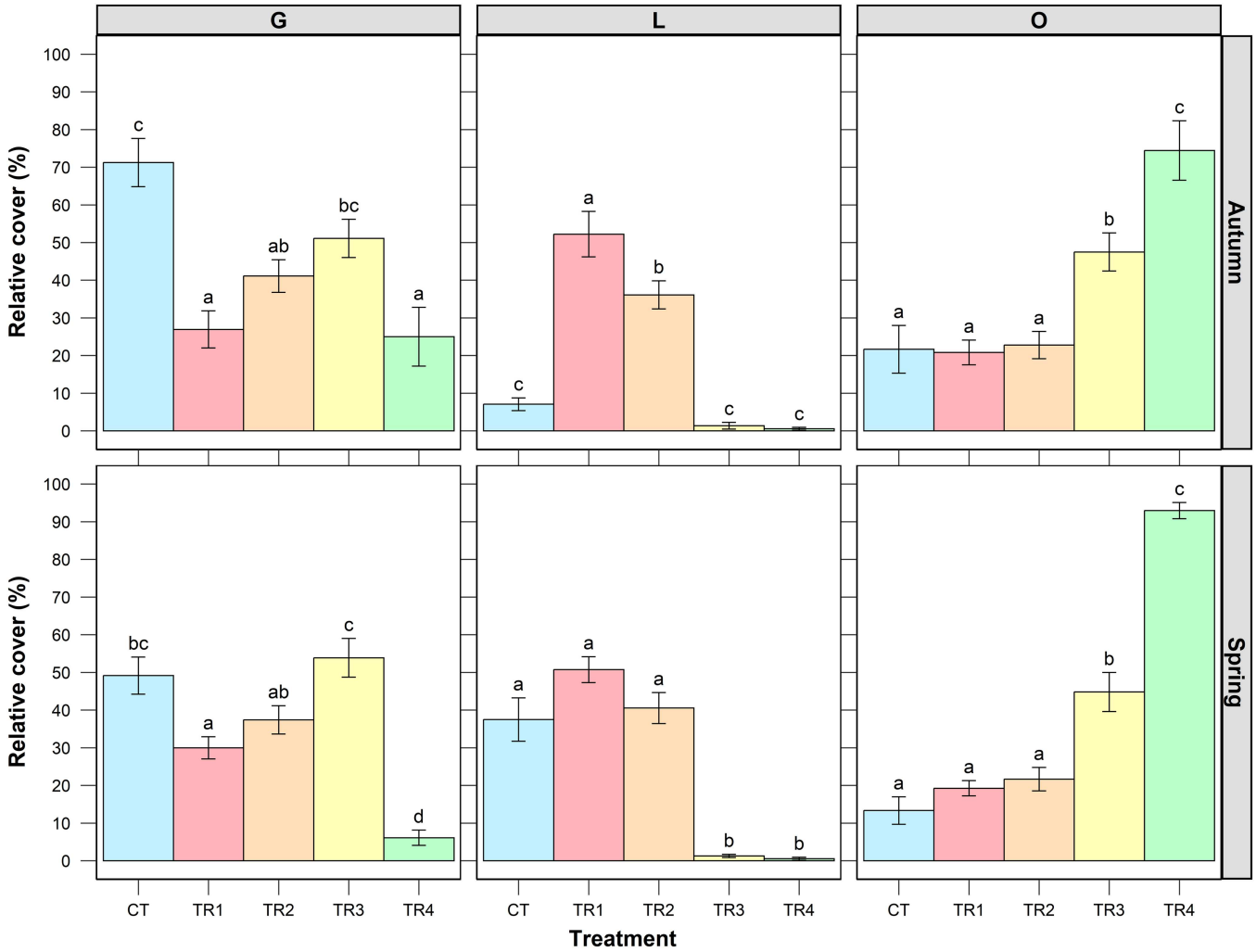

FIGURE 3 | Average (± standard error) relative cover (%) of plant functional groups (G, L, O) across treatments (CT, TR1–TR4) and seasons (autumn and spring). Different letters above bars indicate significant differences among treatments within the same functional group and season, according to Tukey's HSD test ($p < 0.05$).

Seasonal differences in the relative abundance of microarthropod functional groups were observed (Figure 4). Epiedaphic taxa represented the largest proportion of the community in both autumn and spring, with no significant variation between seasons ($p > 0.05$). Hemiedaphic microarthropods were significantly more abundant in autumn compared to spring ($p < 0.05$), accounting for over 60% of individuals in autumn and less than 40% in spring. Similarly, Euedaphic organisms showed a higher relative abundance in autumn than in spring ($p < 0.05$), although the magnitude of the seasonal difference was smaller compared to the hemiedaphic group.

These seasonal trends in functional group composition were further influenced by the distance from the photovoltaic panel rows, as reflected in the treatment effects (Figure 4). In autumn, epiedaphic organisms were significantly more abundant in CT, TR1, and TR2, with no differences among them, whereas TR3 and TR4 exhibited a strong reduction in abundance ($p < 0.05$). A similar trend was observed for Hemiedaphic microarthropods, which peaked in CT and were significantly lower in TR3 and TR4. Euedaphic organisms followed the same spatial pattern, with the highest abundance in TR1 and TR2 and significantly lower values in TR3 and TR4.

In spring, overall abundances were lower than in autumn, with no significant differences among treatments for Epiedaphic and Hemiedaphic groups. Nevertheless, Euedaphic microarthropods displayed a moderate decrease from CT to TR4, with significantly higher abundances in CT compared to TR3 and TR4 ($p < 0.05$), while TR1 and TR2 showed intermediate values.

3.3 | Impact of AVS on PV and QBS-ar

Both the PV and QBS-ar indices showed clear and significant differences among treatments and between sampling seasons (Figure 5).

In terms of the PV index, the only significant seasonal difference between autumn and spring was observed in the most shaded treatment (TR4), which exhibited lower values in spring ($p < 0.05$). Within each season, PV values followed a clear gradient, decreasing progressively from the non-shaded areas (CT and TR1–TR2), classified as high-quality pasture (33.28–43.16),

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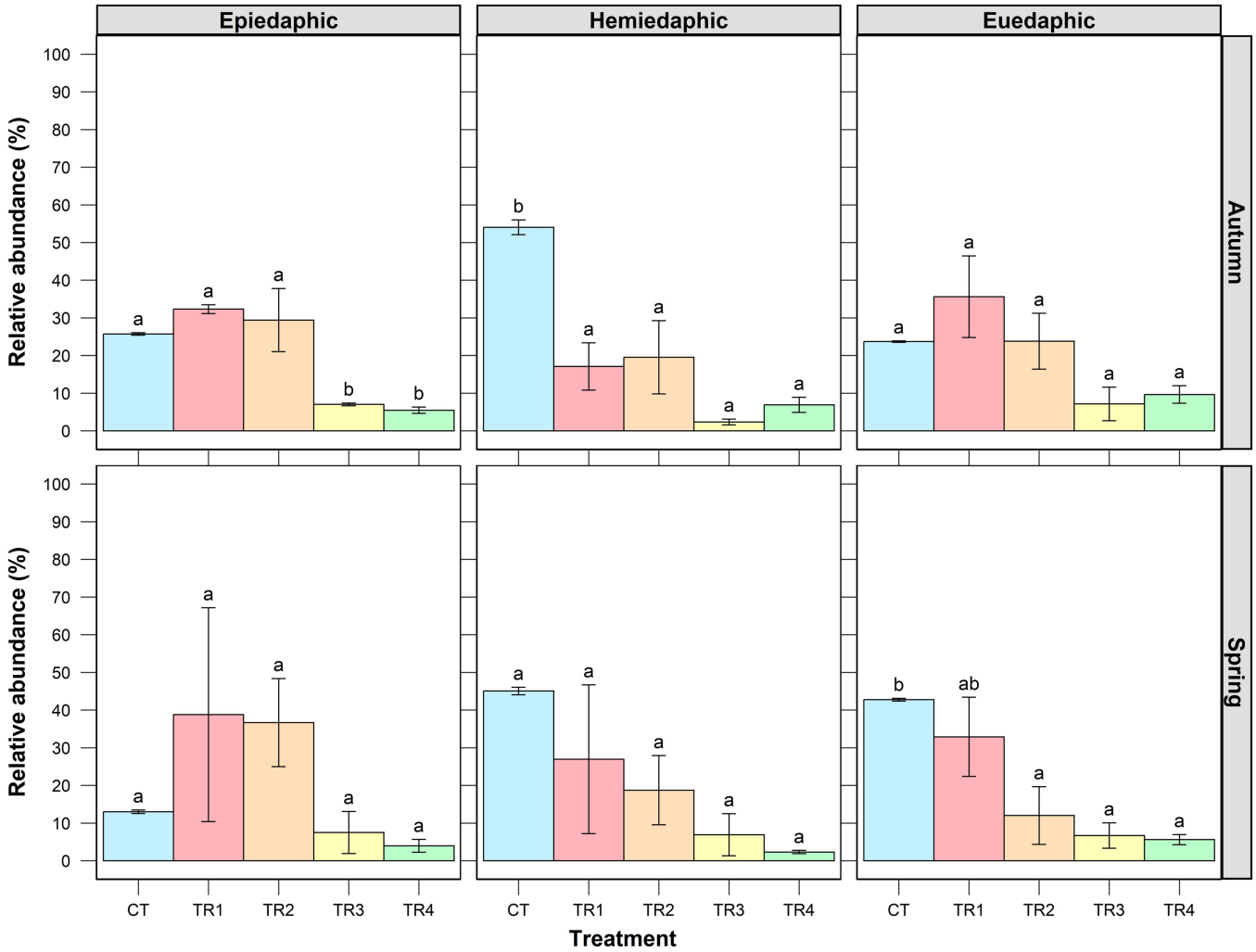

FIGURE 4 | Average (± standard error) relative abundance (%) of soil microarthropod functional groups (Epiedaphic, Hemiedaphic, Euedaphic) across treatments (CT, TR1–TR4) and seasons (autumn and spring). Different letters above bars indicate significant differences among treatments within the same microarthropod functional group and season, according to Tukey's HSD test ($p < 0.05$).

to TR3, representing intermediate-quality pasture (24.04 in autumn and 24.39 in spring), and then to TR4, corresponding to low-quality pasture (14.40 in autumn and 8.11 in spring), with all differences being statistically significant.

The QBS-ar index exhibited more pronounced seasonal variations, reflecting the influence of panel-induced gradients. In TR2, TR3 and TR4, QBS-ar values were significantly higher in autumn than in spring ($p < 0.05$), indicating a seasonal decline in soil biological quality under increasing shading. Conversely, CT and TR1 did not show significant seasonal variation. When treatments were compared within each season, no significant differences were observed in autumn. In spring, however, QBS-ar values decreased progressively with increasing shading intensity, with the most pronounced reductions occurring in TR2, TR3, and especially TR4.

3.4 | Relationships Between Plant and Microarthropod Community Composition

Given that significant differences in the QBS-ar index were observed only in spring (Figure 5), all subsequent analyses were therefore focused on this sampling period. The PCA conducted on the combined dataset of microenvironmental, vegetation, and soil microarthropod indicators revealed a clear spatial segregation among treatments (Figure 6). The first two principal components accounted for 83.9% of the total variance (PC1 = 52.7%; PC2 = 31.2%). Along PC1, the strong positive correlation between ISR and both PV and QBS-ar indices indicated that radiation was the primary driver of pasture productivity and soil quality across the shading gradient. Accordingly, inter-row areas characterized by higher irradiance (i.e., TR1 and TR2) were positioned on the positive side of PC1. Nevertheless, water redistribution also appeared to influence these patterns. Specifically, PV was higher in TR1, where full irradiance occurred but soil moisture was more limited, whereas the QBS-ar vector pointed toward TR2, where rainwater runoff from the panels increased soil moisture availability. In contrast, TR3 and TR4 (under-panel areas) clustered on the negative side, corresponding to shaded zones with lower light availability and reduced plant development. Along PC2, both the FTSW and the QBS-ar index showed positive loadings, clearly separating TR4 from the other treatments. This pattern indicates that the rear under-panel areas (TR4), despite their reduced vegetation cover, maintained higher soil moisture levels and supported distinct soil faunal communities. The persistent shading that characterizes this position likely limited

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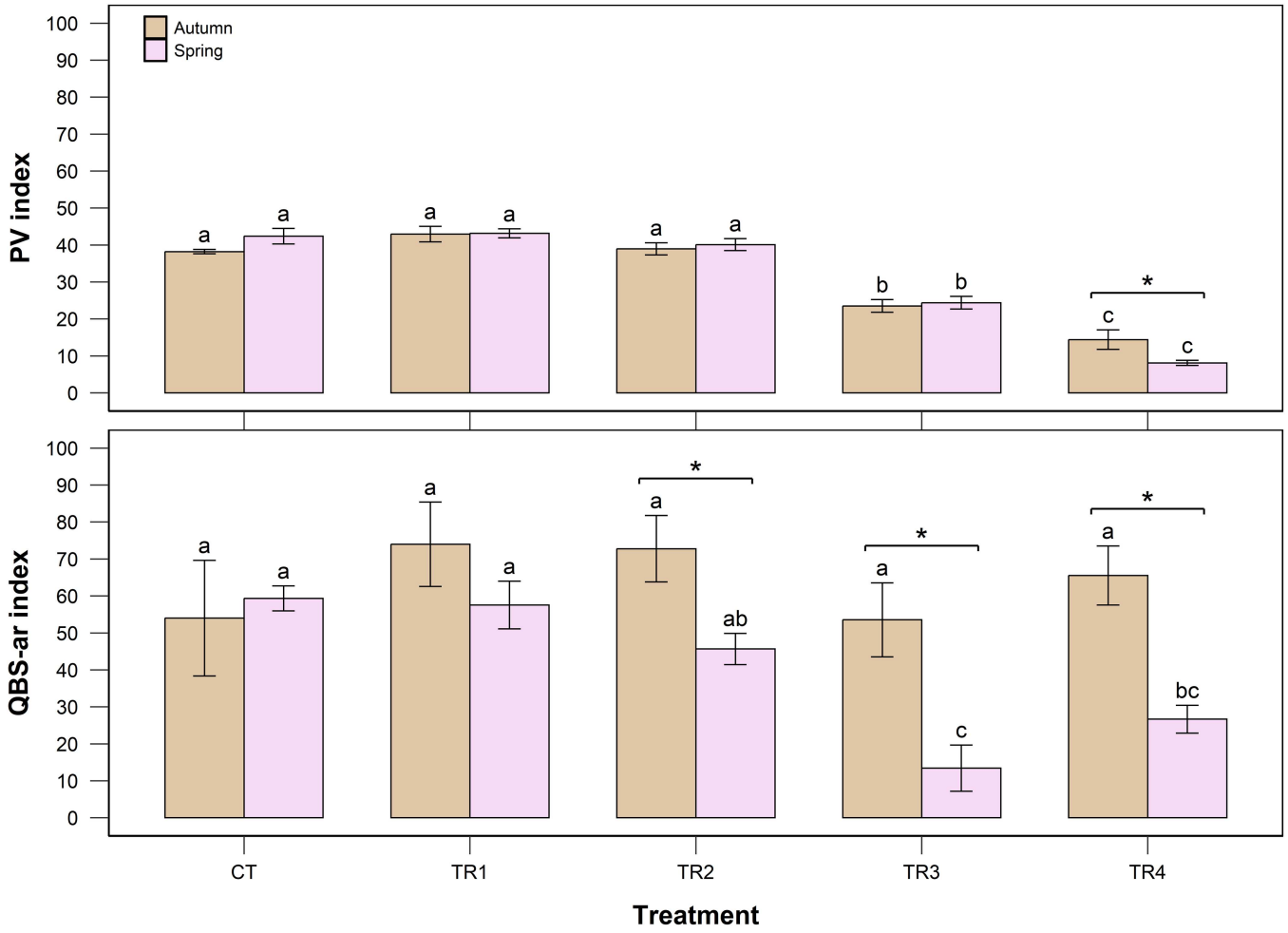

FIGURE 5 | Average (± standard error) PV and QBS-ar index across treatments (CT, TR1–TR4) and seasons (autumn and spring). Different letters above bars indicate significant differences among treatments within the same season, according to Tukey's HSD test ($p < 0.05$), while asterisks denote significant differences between seasons for the same treatment ($p < 0.05$).

evapotranspiration, leading to localized water accumulation and nearly permanent moisture conditions.

Correlation analyses further supported the observed relationships among vegetation traits and microarthropod assemblages (Figure 7). In spring, the relative abundance of Euedaphic microarthropods was strongly and positively correlated with legume cover ($r = 0.86$) and negatively with 'Other' species ($r = -0.65$), showing no relationship with grasses ($r = 0.06$). Hemiedaphic forms showed positive correlations with both grasses ($r = 0.45$) and legumes ($r = 0.76$), but a strong negative correlation with 'Other' species ($r = -0.80$), indicating a preference for vegetation with greater legume and grass cover. Epiedaphic taxa also exhibited positive associations with legumes ($r = 0.73$) and, to a lesser extent, with grasses ($r = 0.32$), while being negatively related to 'Other' species ($r = -0.70$).

4 | Discussion

This study provides novel insights into the functioning of pasture ecosystems within AVS, showing how microclimatic gradients created by photovoltaic panels shape both plant functional composition and soil biological quality. In particular, seasonal patterns emerged as key drivers of ecological variability, affecting both plant community assemblage and soil faunal communities.

During autumn, the overall integrity of the AVS-managed pasture was driven by declines in PV values under the most shaded areas (TR3 and TR4), while the QBS-ar index remained stable across treatments (Figure 5). This pattern suggests that, although panel-induced microclimatic variations did not substantially alter soil biological quality, above ground vegetation structure was more sensitive to shading during this season. This response can be attributed to the reduced biological activity of plants under the generally unfavorable conditions characteristic of the Mediterranean cold season. Indeed, perennial grass growth is inherently constrained during the autumn–winter period by a combination of low temperatures and limited light availability, reflecting an adaptive strategy that promotes cold acclimation and ensures plant survival (Wingler and Hennessy 2016). In our study, this seasonal pattern is confirmed by the pronounced decline in total canopy leaf area of key pasture species, including *Dactylis glomerata* L. (−30.06%), *Trifolium repens* L. (−46.98%), and *Medicago sativa* L. (−25.74%) during autumn compared to spring (Figure S2). The reduction occurred consistently across all panel shading treatments, reflecting the generally low solar radiation at the experimental site (Figure S3), which contributed to more pronounced

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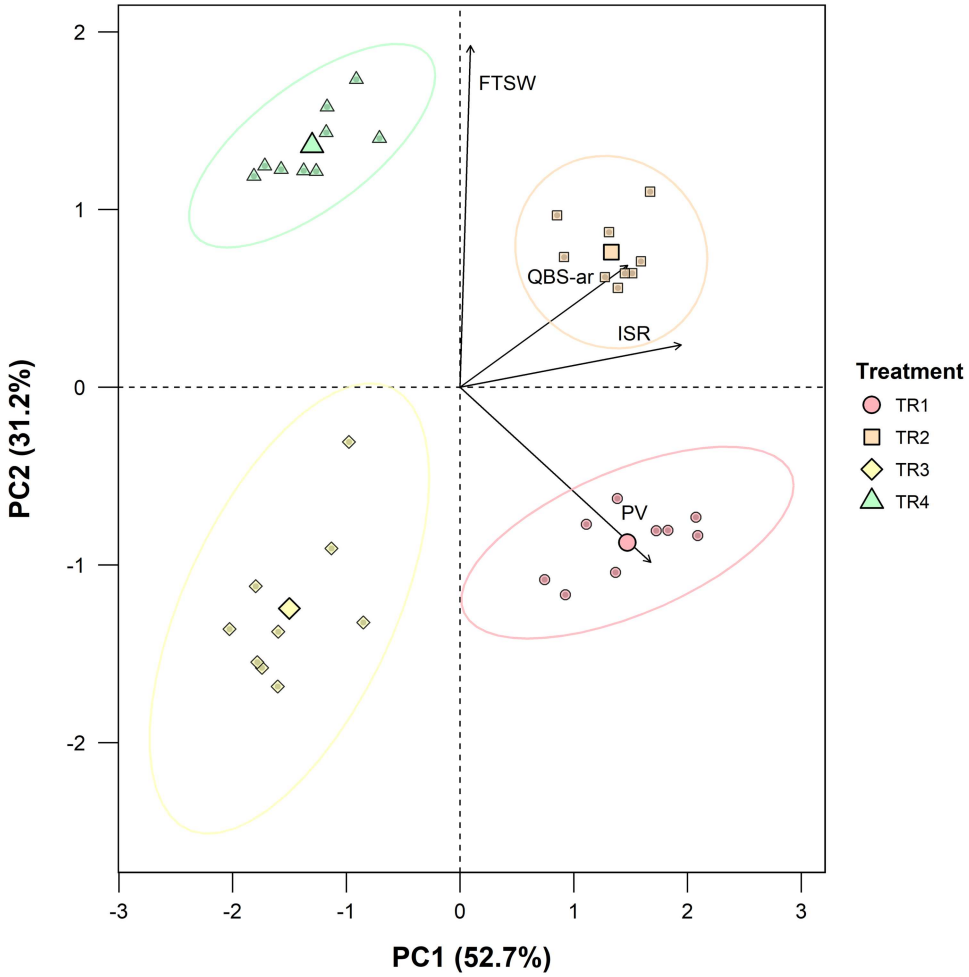

FIGURE 6 | Principal Component Analysis (PCA) biplot showing the distribution of observations by treatment (TR1–TR4) during spring (DOY 100). Individual points represent replicates, while larger points indicate group centroids. Ellipses depict 95% confidence intervals for each treatment. Variable vectors (arrows) illustrate the contribution and direction of each measured variable to the first two principal components (PC1 and PC2), with the percentage of variance explained indicated on the axes. Variables included are the Pasture Value index (PV), Soil Biological Quality index (QBS-ar), Fraction of Transpirable Soil Water (FTSW), and Intercepted Soil Radiation (ISR).

shading-gradient-related differences in PV. On the other hand, soil microarthropods, although generally resilient to cold, are known to respond to freezing risk by migrating to deeper soil layers (Holmstrup et al. 2018). This behavior likely explains the observed reduction in the relative abundance of Epiedaphic organisms beneath photovoltaic panels (i.e., TR3 and TR4), where the lowest recorded autumnal temperatures (Figure S4) may have prompted them to seek refuge in subsurface strata (Siepel 1994). Nevertheless, the QBS-ar index, which integrates the entire soil microarthropod community, buffered localized reductions in surface-dwelling organisms and reflected the overall stability of soil biological quality, in line with previous observations by Kardol et al. (2011).

Conversely, during the spring season, distinct differences emerged in both plant functional composition and soil microarthropod communities. This pattern was driven by active vegetative regrowth and increases in temperature and solar radiation, which amplified contrasts in resource availability, particularly light and water, across treatments. Notably, areas lacking rainfall redistribution from the photovoltaic panels but fully exposed to solar radiation (i.e., CT and TR1) favored the presence of therophyte plant species (i.e., *Geranium dissectum* L. and *Veronica persica* Poir.), reflecting their ecological adaptation to drier habitats with higher evapotranspiration rates (Midolo et al. 2024). Under high-shading conditions, plant distribution patterns indicate that light availability, rather than soil moisture, was the primary driver, as shown by the presence of shade-tolerant species beneath the photovoltaic panels (i.e., *Bromus mollis* L., *Daucus carota* L. and *Rumex alpinus* L.), where both dry (TR3) and moist (TR4) soils supported comparable plant assemblages (Jungová et al. 2025; Loarca et al. 2024). In this context, legumes, being typically heliophilous, predominantly colonized areas with high irradiance (i.e., TR1–TR2), whereas shaded zones (i.e., TR3–TR4) were mainly occupied by grasses and more stress-tolerant, ruderal taxa (Walgenbach and Marten 1981; Lin et al. 1998; Qin et al. 2010). This functional differentiation has direct implications for forage yield, as demonstrated by Pang et al. (2019), who reported that under moderate or dense shading conditions, leguminous species exhibit reduced adaptability and lower productivity compared to grasses. Consequently, the high irradiance in TR1 provided favorable conditions for the establishment and growth of key

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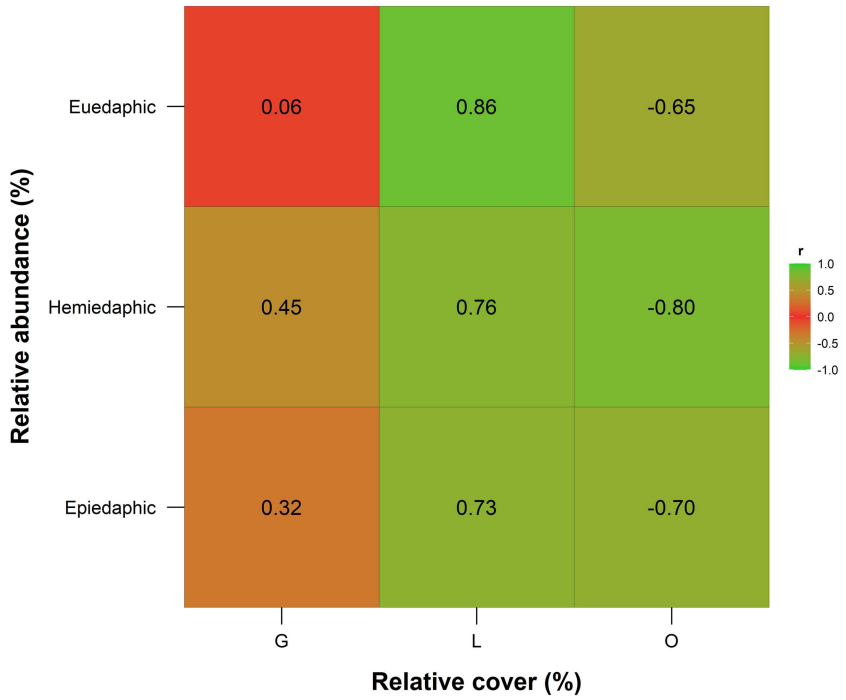

FIGURE 7 | Heatmap showing Pearson correlation coefficient (r) between relative cover (%) of plant functional groups (G, L, O) and relative abundance (%) of soil microarthropod functional groups (Euedaphic, Hemiedaphic, Epiedaphic) during spring (DOY 100).

forage legumes, thereby driving the association with the highest PV index (Figure 6).

Legumes play a crucial role in maintaining soil fertility and biological quality in pastures through biological nitrogen fixation (Ledgard and Steele 1992). As demonstrated by Kanté et al. (2021), their rhizodeposition significantly increases soil enzymatic activity and microbial efficiency by providing readily available carbon and nitrogen compounds, thus promoting greater trophic complexity within the soil food web. Similarly, Ma et al. (2022) demonstrated that root exudate hotspots create favorable microhabitats for soil fauna, which foster greater functional diversity among microarthropods. Overall, these mechanisms likely explain the spatial pattern observed in our study, where microarthropod relative distribution mirrored that of legumes along the shading gradient, with higher values recorded in the inter-row areas. This is further supported by the strong positive correlation between legume relative cover and microarthropod abundance across soil layers, coupled with a negative association with low-forage-value species (O; Figure 7). The latter, lacking nitrogen-fixing capacity, prevailed under less favorable microclimatic conditions, either warmer and drier soils (TR3) or excessively moist environments prone to waterlogging (TR4), and were consequently ineffective in sustaining soil biological quality.

The integrated modeling framework adopted in this study (Moretta et al. 2025b) was instrumental in characterizing these microclimatic gradients. By coupling process-based simulations of FTSW and ISR with field data, the model allowed us to quantify the combined effects of shading and soil water availability on plant-soil interactions, thereby providing a mechanistic explanation for the patterns observed across treatments. Consistent with these patterns, the QBS-ar index showed a clear tendency toward the microclimatic conditions under TR2 (Figure 6), where optimal combinations of soil moisture and irradiance were recorded (Table S3). This finding supports the notion that soil biological quality reaches its maximum under moist and thermally favorable conditions (Meloni et al. 2020; Moscatelli et al. 2022), which simultaneously promote the growth and functional performance of key pasture plant species.

The proposed integration of PV and QBS-ar indices in this study highlighted the value of a comprehensive, site-specific assessment of AVS pastures to guide targeted management strategies, such as reseeding, rotational grazing, virtual fencing, or establishing riparian buffer zones, that optimize both forage production and soil health (Bacon et al. 2025). Future research should focus on the interactions between grazing animals and AVS pastures, particularly (i) how selective feeding affects plant species and soil microarthropods distribution, and (ii) how animal excreta influence soil biological quality. Adopting such integrated, site-tailored approaches will be essential for sustaining both ecological function and productive capacity in pasture-based AVS systems.

5 | Conclusions

This study highlights how agrivoltaic systems (AVS) influence both plant and soil communities in pasture ecosystems through microclimatic gradients induced by photovoltaic panels. Across shading treatments, light availability and soil moisture jointly drove plant–soil interactions, with legumes supporting soil fertility and enhancing microarthropod communities. The combined use of PV and QBS-ar indices proved effective in capturing fine-scale ecological variation, providing a useful basis for adaptive, site-specific pasture management aimed at sustaining forage production and soil health under heterogeneous microenvironmental conditions. In this context, future

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studies should further explore the interactions between grazing animals and AVS pastures, providing valuable insights for designing more resilient and biodiversity-friendly agroenergy systems. Overall, our study underscores the value of microarthropods as indicators for assessing and monitoring soil quality, particularly in view of their potential integration within the framework of the Soil Monitoring Law, adopted by the Council of the European Union in 2024.

Author Contributions

Michele Moretta: conceptualization, data curation, methodology, formal analysis, investigation, writing – original draft preparation. **Riccardo Rossi:** conceptualization, data curation, Iinvestigation, writing – original draft preparation. **Enrico Palchetti:** project administration, funding acquisition, writing – review and editing. **Marco Moriondo:** formal analysis, methodology, writing – review and editing. **France Joshua Rabit:** investigation, data curation, writing – review and editing, supervision. **Giacomo Santini:** project administration, writing – review and editing. **Filippo Gallese:** formal analysis, methodology, writing – review and editing. **Anita Maienza:** formal analysis, methodology, writing – review and editing. **Marco Bindi:** funding acquisition, writing – review and editing. **Alberto Masoni:** investigation, conceptualization, methodology, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request.

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Supporting Information

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

Figure S1: Average (± standard error) (A) relative cover (%) of plant functional groups (G, L, O) and (B) relative abundance (%) of soil microarthropod functional groups (Epiedaphic, Hemiedaphic, Euedaphic), across seasons (autumn and spring). **Figure S2:** Mean (± standard error) total leaves area (cm^2) of the most representative species within each functional group (G, L, O) sampled across treatments (CT, TR1–TR4) and seasons (autumn and spring). **Figure S3:** Monthly mean differences (± standard error) in air temperature (ΔT, °C) and relative humidity (ΔRH, %) between (TR1) and under the photovoltaic panels (TR3) compared to the reference area (CT1). The dashed line denotes the zero-difference reference (Δ = 0). **Figure S4:** Monthly trends of total precipitation (blue bars), mean air temperature (red line), and mean daily global solar radiation (orange line) recorded at the experimental AVS site. **Table S1:** Average (± standard error) of soil temperature (T_{soil}, °C) and volumetric water content (VWC, %) measured during autumn and spring sampling across treatments (CT, TR1-TR4). **Table S2:** Average density (individuals m^{-2}) of arthropod taxa, classified by class and order, recorded in autumn and spring across experimental treatments (CT, TR1-TR4). **Table S3:** Fifteen-day mean (± standard error) of Fraction of Transpirable Soil Water (FTSW) and Intercepted Soil Radiation (ISR; MJ m^{-2} day^{-1}) from day of the year (DOY) 85 to 100 under shading treatments (TR1-TR4). **Table S4:** Pearson correlation coefficient (r) among Pasture Value (PV), Soil Biological Quality–arthropods (QBS-ar), Fraction of Transpirable Soil Water (FTSW, 15-day average), and Intercepted Soil Radiation (ISR, 15-day average) recorded during spring.

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