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Soil and water bioengineering impacts on biodiversity: multi-taxon monitoring in landslide restoration☆

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ABSTRACT

Landslides, as complex geomorphological disturbances, deeply reshape landscapes and influence ecosystem dynamics by exposing new substrates, redistributing soil and organic matter, and altering hydrological and nutrient cycles. In this context, Soil and Water Bioengineering (SWBE) techniques represent an effective Nature-Based Solution (NBS) that combines mechanical slope stabilisation with ecological restoration. This study evaluated the ecological effectiveness of SWBE interventions for shallow landslide restoration within mountainous forest environments of Central Italy. An integrated assessment of soil physicochemical properties and biological indicators—herbaceous and tree vegetation, soil microorganisms, and soil fauna—was carried out across three sites: a restored landslide (SWBE), a naturally recovering landslide (natural), and an undisturbed reference site (control). Vegetation emerged as the most responsive indicator of recovery, with the restored site showing significantly higher alpha diversity than both the natural and control sites. Although different pedological conditions characterised the three study sites, microbial communities' metabolic diversity and soil fauna composition showed strong resilience, reaching values comparable to undisturbed conditions. Overall, SWBE restoration effectively paired slope stability with the native ecological processes, promoting the establishment of diverse and functionally relevant plant communities. These findings highlight the dual benefits of SWBE as a sustainable solution for erosion control, slope stabilisation and biodiversity enhancement. Finally, long-term multi-taxon monitoring is suggested to further clarify the trajectories of ecological succession and ecosystem functionality in restored mountain environments.

1. Introduction

Landslides are complex geomorphological occurrences that transform the physical configuration of landscapes and trigger ecological changes at various scales. Such events expose new substrates, redistribute soil and organic matter, and alter hydrological patterns, thereby aiding nutrient cycling and fostering ecological succession and habitat colonisation (Walker and Shiels, 2013). Despite their ecological importance, landslides are excellent illustrations of the dynamic interplay between disturbance and succession (Walker et al., 2009); nevertheless, their ecological effects remain insufficiently investigated. Landslide colonists have adaptations that enable them to survive on disturbed, unstable substrates and to tolerate elevated temperature and water stress, which mimic climate change conditions on a habitat level in a natural environment (Walker and Shiels, 2013). Such natural disturbances create unusual vegetation gaps because most of the soil structure is removed, especially in rapid landslides caused by physical hazards such as earthquakes, wind, or extreme rainfall.

In recent years, increasing attention has been given to ecological restoration strategies that not only mitigate geotechnical risks but also enhance environmental resilience. Among these, Nature-Based Solutions (NBS) have emerged as innovative approaches that harness natural processes to restore, protect, and manage disturbed ecosystems, such as landslide areas (de Jesús Arce-Mojica et al., 2019; Debele et al., 2023;

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Nehren et al., 2023; Nesshöver et al., 2017). A specific category of NBS, known as Soil and Water Bioengineering (SWBE), combines living plant materials with structural elements such as wood and stone to stabilise slopes, control erosion, and restore vegetation cover (IUCN, 2016; Preti et al., 2022). This approach aims to simultaneously ensure mechanical stability and promote ecological functionality, offering a holistic alternative to traditional engineering approaches (Gonzalez-Ollauri and Mickovski, 2017; Mickovski, 2021; Moreau et al., 2022). Different ecological restoration techniques demonstrate their positive effects in different environments for natural hazard mitigation, from coastal to mountainous areas. The application of techniques and materials inspired by nature, which have a lower environmental impact and maintenance cost, offers numerous advantages. Along watercourses and streambanks, SWBE restoration procedures have been proven to improve bank stability and flexibility (Cavaillé et al., 2013, 2018), and, from an ecological perspective, increase the number of microhabitats (Cavaillé et al., 2015; Janssen et al., 2019). The SWBE approach results in better taxonomic diversity of aquatic macroinvertebrates and ground beetles (Janssen et al., 2021), greater diversity of plant species (Cavaillé et al., 2015), and fewer invasive alien species (Martin et al., 2021) than civil engineering techniques. In hilly and mountainous areas, the application of SWBE techniques for shallow landslide restoration or soil erosion mitigation emphasises the importance of soil-water-root interactions. In addition to the SWBE design for landslide restoration, vegetation performs an important role through various paths, including root strength, evaporation, and transpiration (Sidle and Bogaard, 2016). Numerous studies have shown the positive effects of roots in improving the chemical (Smith et al., 2023), biophysical (Fattet et al., 2011) and even mechanical characteristics of the soil (Gray and Sotir, 1996), as is also the case for streambanks (Cavaillé et al., 2015; Janssen et al., 2019; Rousset et al., 2025). Root system architecture is a pivotal factor in shallow landslide susceptibility, determining preferential water pathways and influencing the transpiration rate of the plants (Stokes et al., 2009), whereas forest canopy and litter layer interception of effective rainfall usually plays a minor role in modifying water and pore pressure propagation in shallow soil (Sidle and Bogaard, 2016). For a successful bioengineering project, engineers and stakeholders are required to highlight all effective benefits and ecosystem services by documenting the technical, ecological, economic, and social values (Rauch et al., 2022; Rey et al., 2019). According to previous data, civil "gray" engineering techniques have little environmental value, favouring invasive alien species at the expense of native species (Tisserant et al., 2024). On the other hand, SWBE techniques ensure several ecosystem services due to the ecological processes activated by native and alien plants (Löbmann et al., 2020; Tisserant et al., 2021). However, further technical assessment of SWBE methods combining engineered structures and vegetation is crucial for gaining insights into slope stabilisation efficiency (modelling and prediction) and for identifying technical limits for such NBS in natural hazard mitigation and ecological restoration projects. Several studies have evaluated the technical effectiveness of natural hazard control in terms of soil erosion, torrential floods, and shallow landslides (Takaoka, 2024), as well as for ecological restoration in degraded areas (Kakinuma et al., 2025; Su et al., 2024), and for stream renaturation (Herrick et al., 2006; Symmank et al., 2020; Walker et al., 2009). The socio-economic aspects of SWBE techniques and other NBS have been addressed in many studies, highlighting their significant social value and the restored relationship with the landscape experienced by citizens (Nesshöver et al., 2017; Punetha et al., 2019). The naturalistic value of these techniques has consistently emerged in post-implementation monitoring (Janssen et al., 2019; Kettenhuber et al., 2023; Lu, 2014), where the choice of suitable species facilitated the colonisation by native species. Multi-taxon monitoring proves to be an essential tool for investigating the added value of soil and water bioengineering techniques in shallow landslide restoration, aiming to reconcile hazard control and ecological restoration through a multidisciplinary approach (Burrascano et al., 2021; Kettenhuber et al., 2023; Rey et al., 2019).

Although recognising the value of such multidisciplinary approaches, a comprehensive understanding of how SWBE techniques influence ecological trajectories compared to natural succession is still required to validate their effectiveness beyond technical stabilisation. Therefore, the primary aim of this study was to evaluate the ecological restoration dynamics of SWBE interventions in a mountainous environment (Apuan Alps, Central Italy). To understand the long-term ecological outcomes of these NBS approaches, the specific objectives were to: **(i)** assess the recovery of biodiversity and ecosystem functionality through an integrated analysis of soil physicochemical properties and three bio-indicators: vegetation, the community-level physiological profile (CLPP) of soil microorganisms, and soil fauna; and **(ii)** compare the ecological trajectories of a restored landslide (**SWBE**) with both a naturally recovering landslide (***natural***) and an undisturbed reference site (***control***).

2. Materials and methods

2.1. Site description

The study area is in Pomezzana, within the municipality of Stazzema (Lucca, Italy), on the southwestern border of the Apuan Alps Regional Natural Park (Coordinates in WGS84, Latitude: 43°59′16.7“ N, Longitude: 10°18’52.4” E; Tuscany). The area lies between 450 and 600 m a.s.l. and is characterised by steep terrain. The slopes exhibit a Northwest exposure with an average inclination of 65% (Giachi et al., 2024). The bedrock consists of Oligocene micaceous sandstones intercalated with slaty schists. The overlying soils are moderately deep, with an A–Bw–BC horizon sequence. These soils are gravelly and pebbly, with a clay loam texture; they are non-calcareous, moderately acidic, and exhibit moderate base saturation in the A horizon and low base saturation in the Bw horizon. The soils are well-drained and generally classified as Eutric Cambisols (in some cases, Leptic), according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022).

Before the landslide events, the slope was covered by a thermophilic deciduous forest (European forest class 8), specifically dominated by chestnut stands (typology 8.7, "Chestnut Forests"), which were actively cultivated until the 1980s. The local microclimate is typical of the Apuan Alps, with the potential for high humidity, particularly at lower elevations near the local stream network.

The geographical area was the epicentre of an extreme meteorological event in 1996 (the "Versilia flood"). The exceptional rainfall intensity on saturated soils triggered widespread linear translational phenomena and debris flows (Preti et al., 2025). Through preliminary field surveys and historical maps from the Tuscany Region, three comparable landslides that occurred during the same 1996 event were identified on the same slope. These sites (Fig. 1A) share consistent pedoclimatic conditions, exposure, and pre-event vegetation structure, but differ in their post-event management:

- Restored landslide (SWBE): A landslide covering approximately 1.3 ha (200 m long, 70 m wide). In 1998–1999, it was stabilised using bioengineering techniques, such as double live wooden cribwalls and live palisades to manage water runoff and control erosion.
- Naturally evolved landslide (natural): A landslide left to natural ecological succession, acting as a benchmark for unassisted vegetation recovery.
- Control landslide (control): An unrestored landslide, naturally evolved site with no subsequent anthropogenic disturbance, located at a lower elevation closer to the stream, providing a baseline for undisturbed environmental conditions.

To evaluate ecological dynamics, field surveys were conducted at each of the three sites, both within the disturbed landslide area (SWBE1, natural1, control1) and in the immediately adjacent, undisturbed forest

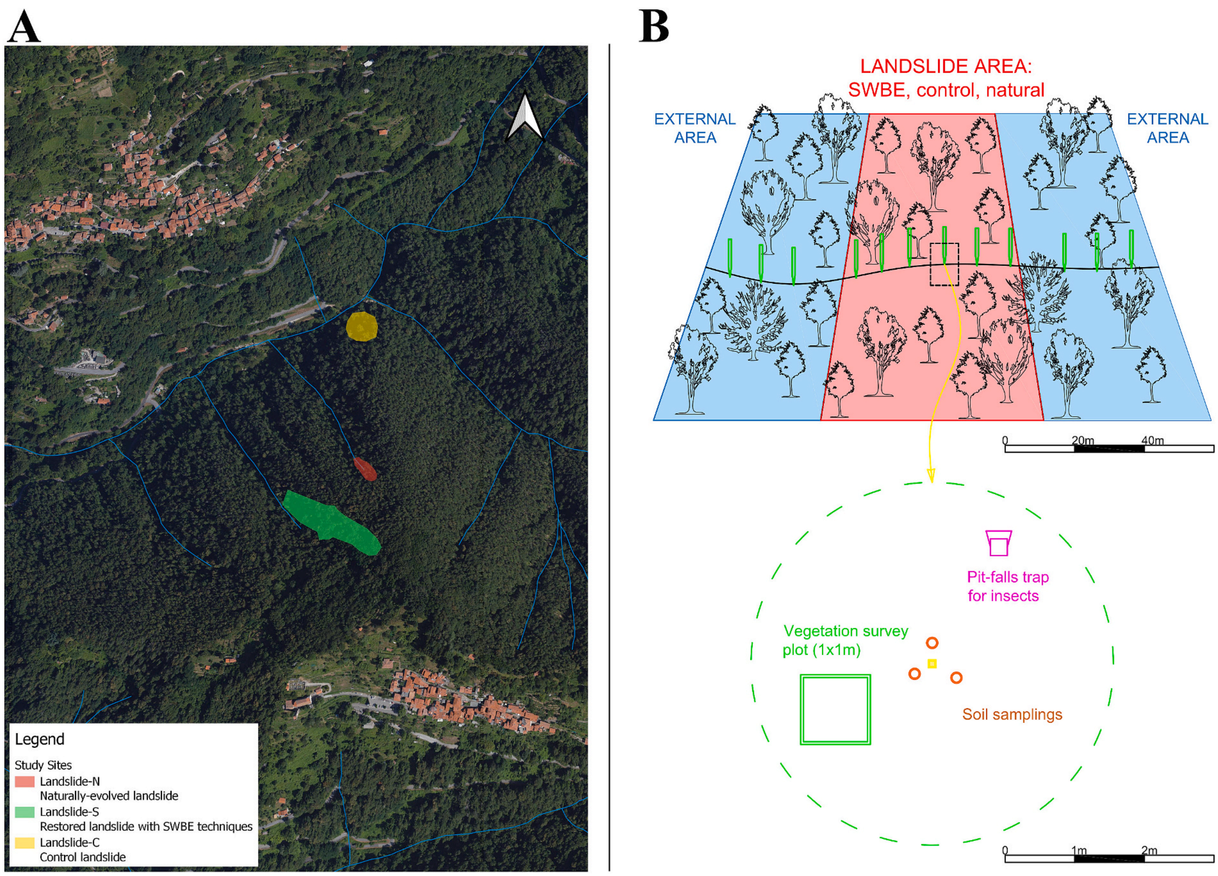

Fig. 1. Location of the three studied landslides. (A) Location of the landslides: SWBE (restored landslide, green area), natural (naturally evolved landslide, red area), and control (control landslide, yellow area). (B) Schematic representation of the multi-taxon sampling design applied during field trials across the three landslides.

(SWBE2, natural2, control2), as shown in the sampling design (Fig. 1B). External plot sampling established a baseline reference to control for site-specific variability.

2.2. Sampling design for biodiversity assessment

A multidisciplinary sampling design was applied to investigate the ecological effect of the SWBE restoration project (Fig. 1B), through an alpha-diversity assessment using a multi-taxon approach.

In the three landslides, we identified a representative transect cutting across the study area; along each transect, 12 sampling stations were marked with wooden pickets at fixed intervals, numbered from right to left: 6 inside the landslide area and 6 outside (three on either side). Each of the 12 pickets served as the centre of a circular plot (3 m in diameter). Within each plot, a vegetation survey was conducted within a 1 m^2 area, where soil samples were subsequently collected for physicochemical and microbiological analyses. Arthropod biodiversity was assessed using pitfall traps, which is a well-established method for soil fauna surveys (Latella and Gobbi, 2015). Nine traps were used at each site: 3 inside the landslide (1) area and 6 outside (3 on each side) (2). Soil microorganisms, herbaceous species, and macroarthropods were selected as the three most suitable bio-indicators for biodiversity quality evaluation and for quantifying the effects of SWBE restoration projects on ecological processes (Di Nuzzo et al., 2021; Kettenhuber et al., 2023).

2.3. Herbaceous plants survey

In June 2024, we conducted a field survey on the herbaceous component in a 1 m^2 area (Kent, 2012), repeated for the 12 pickets at each study site. To minimise subjective errors, the sampler positioned themselves at each picket and then randomly threw the sampling frame within the virtual area of 3 m in diameter. The surveys included vascular flora (herbaceous species and woody species regeneration), estimating the percentage coverage of the aerial part of each species as a metric of abundance for calculating alpha-diversity indices, such as taxa richness and the Shannon index (Eq. 1). From a technical perspective, as demonstrated in various studies on SWBE projects (Bischetti et al., 2021; Giupponi et al., 2019), the herbaceous component, in addition to tree and shrub components, is vital for evaluating slope stability. Furthermore, it plays a crucial role in assessing soil surface erosion before and after restoration projects. From an ecological standpoint, herbaceous species are particularly sensitive to natural or anthropogenic changes and disturbances, serving as indicators of habitat quality and aiding the assessment of potential vegetation. The species richness and abundance indices were quantified through the floristic analysis conducted in the field.

2.4. Soil sampling for physicochemical and microbiological analyses

Undisturbed soil cores were collected using standardised stainless-steel cylinders (V = 174.18 cm3, H = 12) to determine bulk density; these cylinders were inserted (6 per landslide, 3 inside and 3 outside as reference) from the soil surface after removal of the litter layer. For the analysis of soil microorganisms and other physicochemical variables, samples were collected at each plot at a depth of 5–20 cm. This depth corresponds to the “active zone,” where root exudates and high organic matter content maximise microbial activity while remaining buffered from the stochastic environmental fluctuations of the surface layer (Philippot et al., 2013). In the laboratory, the soil samples were sieved (<2 mm) to remove rock fragments and coarse particulate organic matter. An aliquot of each sample was air-dried for measuring pH on a 1:2.5 (*w*/*v*) soil-to-deionised water suspension using an XS PC8 pH meter. Organic matter content was determined as loss-on-ignition after four hours at 460 °C in a muffle furnace. Particle-size distribution was determined in a composite dehydrated sample for each treatment by the hydrometer method (Gee and Bauder, 1986).

For microbiological analysis, 5 g aliquots of fresh soil were suspended in 50 mL of distilled water and homogenised in a Waring blender 8010ES (Christison, Newcastle upon Tyne, UK) three times for 1 min each at low speed, with intermittent cooling on ice after each minute to detach bacteria from soil particles. The supernatants obtained in this way were serially diluted up to 10^{-5} in sterile 0.8% NaCl solution. A 100 μL aliquot of the 10^{-3}, 10^{-4}, 10^{-5} dilutions was spread over the surface of Tryptic Soy Agar medium (pancreatic digest of casein 15 g/L, peptic digest of soybean meal 5 g/L, sodium chloride 5 g/L, bacteriological agar 16 g/L). The plates were incubated at 30 °C for 7 days. The number of colony-forming units (CFU) was determined for each dilution, and the CFU g^{-1}, expressed on a soil dry-weight basis, was calculated.

Community-level physiological profiling (CLPP) of the soils was evaluated using 100 μL of a thousandfold diluted soil suspension to inoculate EcoPlates (Biolog ™, Hayward, CA, USA). EcoPlates are 96-well microplates containing 31 different carbon sources and one negative control in triplicate (https://www.biolog.com/products/community-analysis-microplates/ecoplate/). The wells of the microplates also contain a redox potential indicator that changes from colourless to violet in the presence of metabolically active cells. Wells containing carbon sources that can be metabolised by the inoculated microbial community turn violet. The inoculated EcoPlates were incubated in an Omnilog (Biolog) for 7 days at 30 °C. Readings of the colour development in the wells of the EcoPlates were recorded, and the data were analysed using the Omnilog-PM System software (Biolog), which generated a time-course curve of violet dye formation. The kinetic data of the curves were exported, and the maximum height of the curves was used as a parameter to calculate the biodiversity indices. Substrate richness (T) and Shannon's diversity (H′) were determined as follows:

T = substrate richness (for soil fauna and vegetation species), which is the number of substrates used by the microbial community. To discriminate between used and unused substrates, a cut-off calculated as the average maximum height detected in the negative controls (no carbon source added) was used.

$$H' = -\sum pi*lnpi \quad (1)$$

where (for microbial community) p_i is the ratio of the maximum height recorded for a particular substrate to the sum of the maximum heights of all substrates; for soil fauna and vegetation, $p_i = n_i/N$; n_i = density of each group, N = sum of the density of all groups.

2.5. Soil fauna monitoring

Pitfall traps consisted of transparent plastic glasses (400 mL capacity, 9 cm diameter) filled with approximately 200 mL of apple vinegar, supplied with a drop of surfactant to capture and preserve the arthropods (Latella and Gobbi, 2015). The monitoring was conducted during 2024, from June to November, when macroinvertebrates are most active in terms of foraging and reproduction. Traps were serviced every 15 days, and captured specimens were transferred to the laboratory for further identification. Sometimes non-target taxa were incidentally collected; however, they have been recorded due to their conservation concern. Soil arthropods have been identified to the order or family level. Taxonomic richness has been evaluated for alpha diversity comparisons among study sites.

2.6. Statistical analysis

Statistical analyses were conducted using R software version 4.4.1 (R Core Team). Data exploration followed the ecological statistics guidelines proposed by Zuur et al. (2010). We recognise that pseudoreplication presents an issue in the broader comparisons of our analyses. To mitigate this and ensure reliable statistical analyses, we analysed each site separately, keeping comparisons between sites strictly qualitative. Moreover, external samples served as a reference point, accounting for intrinsic site variabilities. For the herbaceous vegetation, soil fauna, and soil microbiota, alpha diversity was assessed by calculating taxa or substrate Richness (T) and the Shannon diversity index (H′). For each alpha diversity index, assumptions of normality and homoscedasticity were verified using the Shapiro-Wilk test and Levene's test, respectively, using the function '*shapiro.test()*' of the '*stats*' package (R Core Team, 2024), and the '*leveneTest()*' function of the *car* package (Fox and Weisberg, 2019). Based on these results, ANOVA tests or non-parametric Kruskal-Wallis tests were performed to evaluate the main effects of "Site" (SWBE, *control*, *natural*), "Position" (internal vs. external), and their interaction, using the function '*aov*' and '*kruskal.test()*' of the package stats (R Core Team, 2024), followed by post hoc Tukey's HSD test or by Dunn's post hoc test. Boxplots were prepared with ggplot2 (Wickham, 2016). ANOVA / Tukey tests and Kruskal-Wallis / Dunn's post hoc tests were conducted on both alpha-diversity indices. A Non-Metric Multidimensional Scaling (NMDS) ordination, based on Bray-Curtis distance, was used to visualise community composition patterns between disturbed (internal plots) and undisturbed (external plots). Statistical differences in soil variables were evaluated using a multivariate approach to account for environmental heterogeneity. A PCA was performed on standardised soil parameters. Both compositional differences in biological communities and shifts in soil physicochemical profiles between external and internal plots were statistically tested at each site using a one-way PERMANOVA via the 'adonis2()' function of the 'vegan' package (Oksanen et al., 2001). Spearman correlations between soil properties, environmental variables and bioindicators composition and diversity were computed for the three sites using the Hmisc v5.2–2 (Harrell, 2025) and corrplot v0.95 (Wei and Simko, 2024) packages. Statistical significance was set at $p < 0.05$ for all analyses.

3. Results

3.1. Soil properties

While individual edaphic parameters exhibited specific trends—such as overall textures ranging from loam to sandy loam (Table S1) and pH following a site-specific baseline gradient—a multivariate approach provided a comprehensive understanding of the environmental heterogeneity. Principal Component Analysis (PCA) and PERMANOVA testing were employed to evaluate the overall shifts in the soil physicochemical profiles among the three sites.

First, a preliminary comparison of only the undisturbed external plots confirmed that the three study areas are different from each other (Fig. S2). Baseline pedological characteristics exhibited significant differences between SWBE, control, and natural sites (pairwise comparisons: $p < 0.05$). The PCA indicated that the variables contributing most strongly to site differentiation were soil pH, particle-size fractions, and bulk density.

Multivariate analysis revealed significant differences between the internal (disturbed) and external (undisturbed) positions at all sites: SWBE (PERMANOVA; $p = 0.001$), *control* (PERMANOVA; $p = 0.003$), and *natural* (PERMANOVA; $p = 0.004$). The PCA biplots (Fig. 2, panels A-C) visually show these distinctions between disturbed and undisturbed areas. In the SWBE site (Fig. 2A), the first principal component explained 53.3% of the total variance, driven mainly by silt, clay, and sand contents and bulk density; the second principal component explained 25,7%. In the *control* site (Fig. 2B), the first principal component explains 58,7% of the total variance, driven by the same variables of SWBE, showing how the disturbance affects soil texture and bulk density. The second principal component explains 22,8% of the variance. In the *natural* site (Fig. 2C), the first principal component

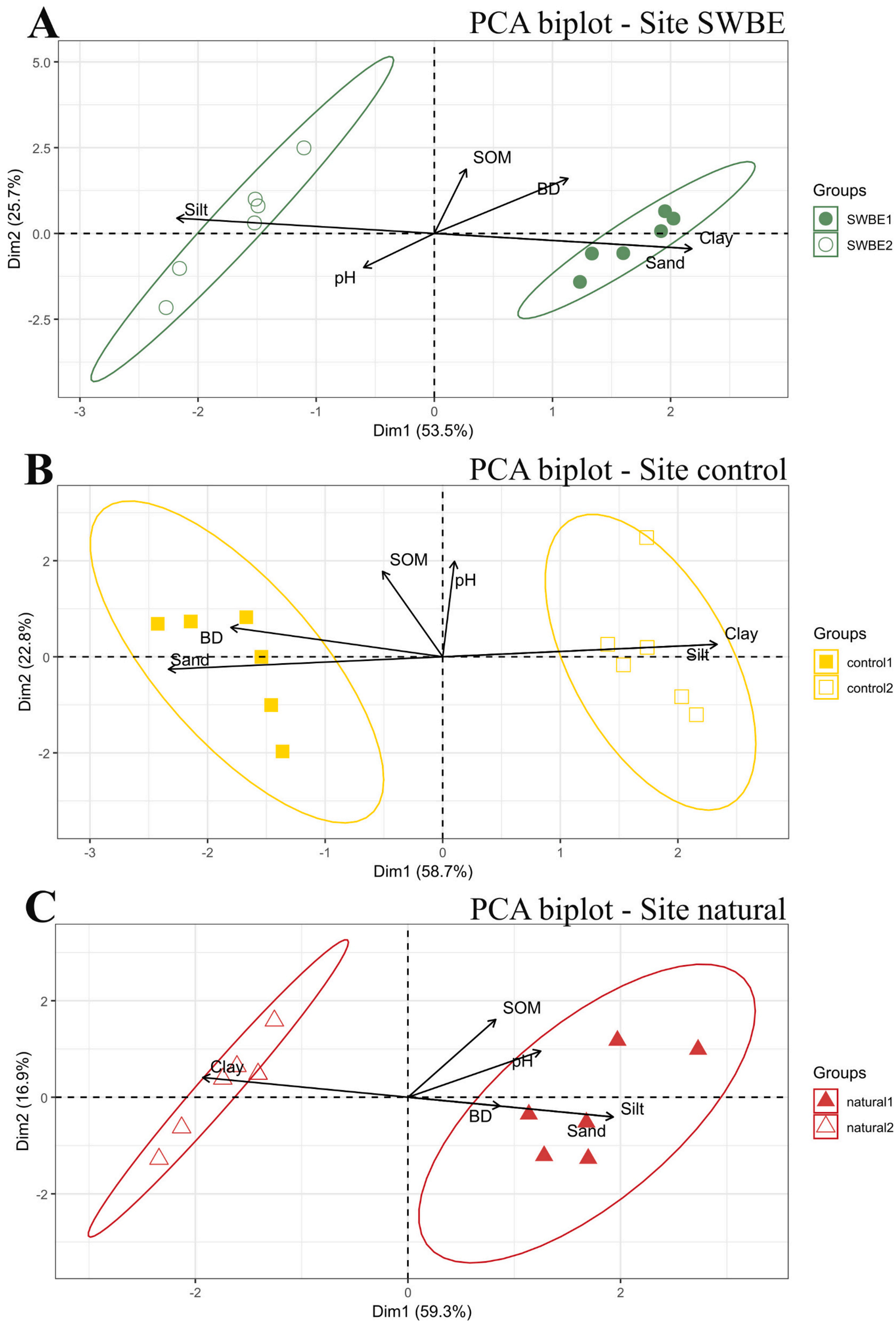

Fig. 2. PCA biplots for each study site. A) SWBE restored landslide site (green); B) *Control* site (yellow); C *Natural* site (red). Solid symbols represent internal plots, while open symbols represent the external plot. The axes indicate the percentage of the total variance explained. Soil variables: silt, sand, and clay contents, soil organic matter (SOM), bulk density (BD), and pH.

explains 59,3% of the total variance and shows that clay content describes the differences between internal and external plots.

The ordination vectors in the respective panels indicate that soil pH and texture fractions (sand, clay and silt) are the main drivers of the differences between disturbed and undisturbed conditions. This multivariate evidence confirms that the geomorphological event causes an ecological disturbance in the three sites.

3.2. Composition and alpha diversity of herbaceous vegetation

For the forest component, field surveys revealed the same vegetation typology (*Castanea sativa*, *Acer* spp., *Corylus avellana*, and *Ostrya carpinifolia*) at the three study sites, except for the landslide area, where a secondary forest development was observed. Unlike the other two sites, the SWBE-restored site features a well-developed alder and hornbeam thicket composed mainly of shrubs and young trees (Preti et al., 2025). Considering the differences in the tree and shrub components among study sites, we decided to conduct in-depth floristic surveys.

Multivariate analyses (NMDS) confirmed floristic composition differences between the internal and external plots within each site (Fig. 3A-C). Floristic communities of internal and external plots result in significant differences in SWBE (PERMANOVA; $p = 0.004$), *control* (PERMANOVA; $p = 0.015$) and *natural* (PERMANOVA; $p = 0.013$). The SWBE site (Fig. 3A) showed the greatest differences in composition between internal and external plots. By comparing the diversity indices between internal and external plots, different responses were observed for each of the sites, although these were not significant. In the SWBE internal plots, taxa richness and Shannon index, respectively, increased on average by 2.5 and 0.25 units more than external ones. In contrast, in the *natural* site, the alpha diversity indices in the internal plots were on average 2 taxa and 0.4 Shannon index units lower than in external plots. At the control site, alpha diversity indices showed similar averages across internal and external plots.

For the taxa richness index (Fig. 3D), no significant difference is detected, except for the SWBE1 and *natural*1 comparison (Tukey test; $p = 0.006$). In the Shannon index analysis (Fig. 3E), the results highlight statistically significant differences in three site/position comparisons. At the control site, both internal (*control*1, Tukey test; $p = 0.009$) and external plots (*control*2, Tukey test; $p = 0.035$) displayed higher values of the Shannon index than the natural internal plot (*natural*1). In the restored site, the internal plot (SWBE1) showed higher Shannon diversity index values (Tukey test; $p = 0.001$), indicating different recovery dynamics between the SWBE and *natural* sites in the disturbed area. The external plots of the three study sites showed comparable mean values of the Shannon index, with no significant difference. The control site maintained intermediate and stable values across both positions.

3.3. Alpha-diversity of soil microbial communities based on CLPP

Due to the intensive logistical and analytical requirements of the sampling and laboratory procedures, investigations of the below-ground biological compartments (soil microbiota and soil fauna) were focused on the SWBE-restored and control sites. Community-Level Physiological Profiling (CLPP) via Biolog EcoPlates was employed, as it is highly effective in distinguishing spatial and temporal shifts in the metabolic functions of microbial communities.

In contrast to the above-ground vegetation, multivariate analyses of the carbon-source utilisation profiles highlighted a functional stability within the soil microbial community. NMDS ordinations displayed highly overlapping clusters between the internal and external plots. PERMANOVA tests formally confirmed that the overall metabolic profiles did not significantly differ between disturbed and undisturbed areas within either the SWBE site ($p = 0.778$) or the control site ($p = 0.244$). This functional stability was mirrored by the alpha-diversity metrics (Fig. 4C-D). The Kruskal-Wallis rank-sum tests revealed no significant spatial variations in metabolic richness (number of utilised C-sources, $p = 0.288$) or metabolic diversity (Shannon index, $p = 0.832$) across the

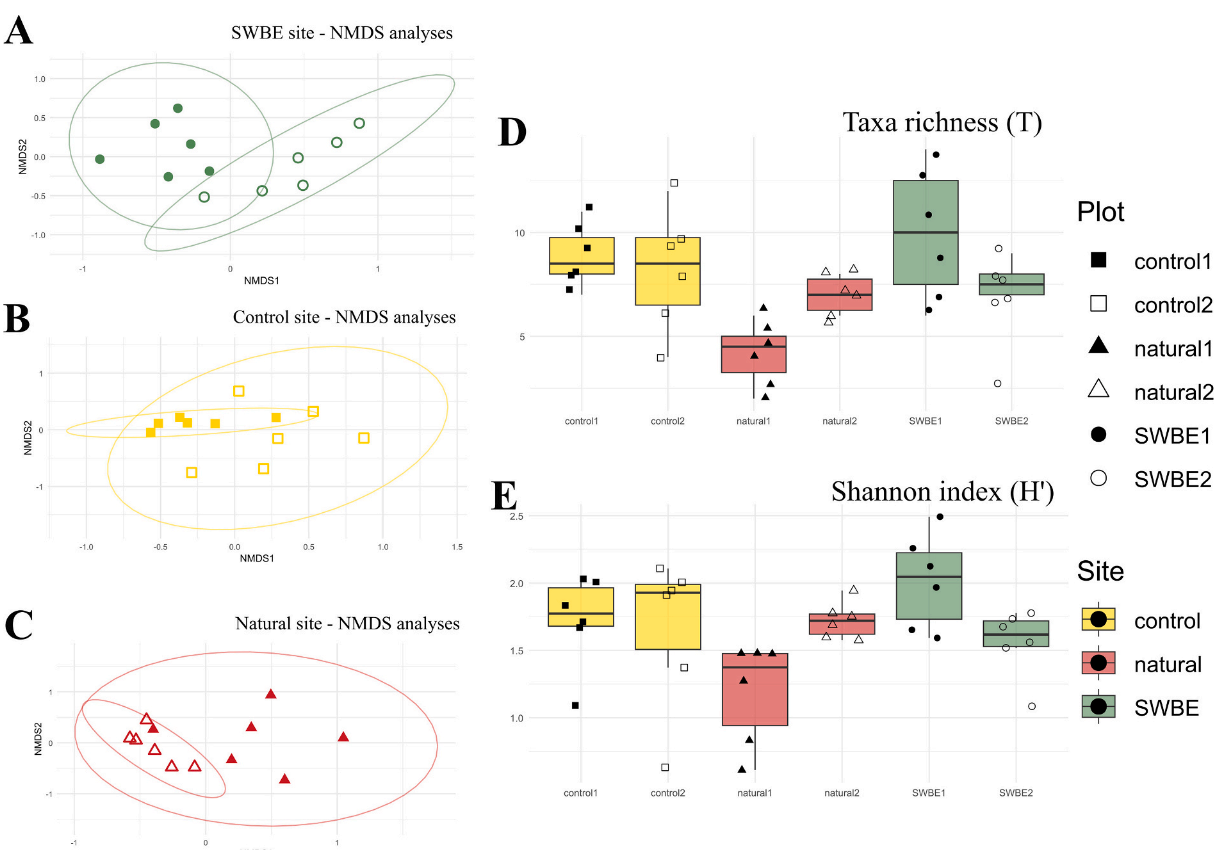

Fig. 3. NMDS analyses and boxplot distribution of alpha-diversity indices of the herbaceous component. A) NMDS analyses in the SWBE site; B) NMDS analyses in the control site; C) NMDS analysis in the natural site; D) Boxplot of the taxa richness (T) index; E) Boxplot of the Shannon index (H'). Boxplot boxes represent the first to third quartiles of observations, with the median indicated by a black horizontal line. Solid symbols represent the internal plot, while open symbols represent the external plot. The axes in the NMDS plots indicate the percentage of explained total variance.

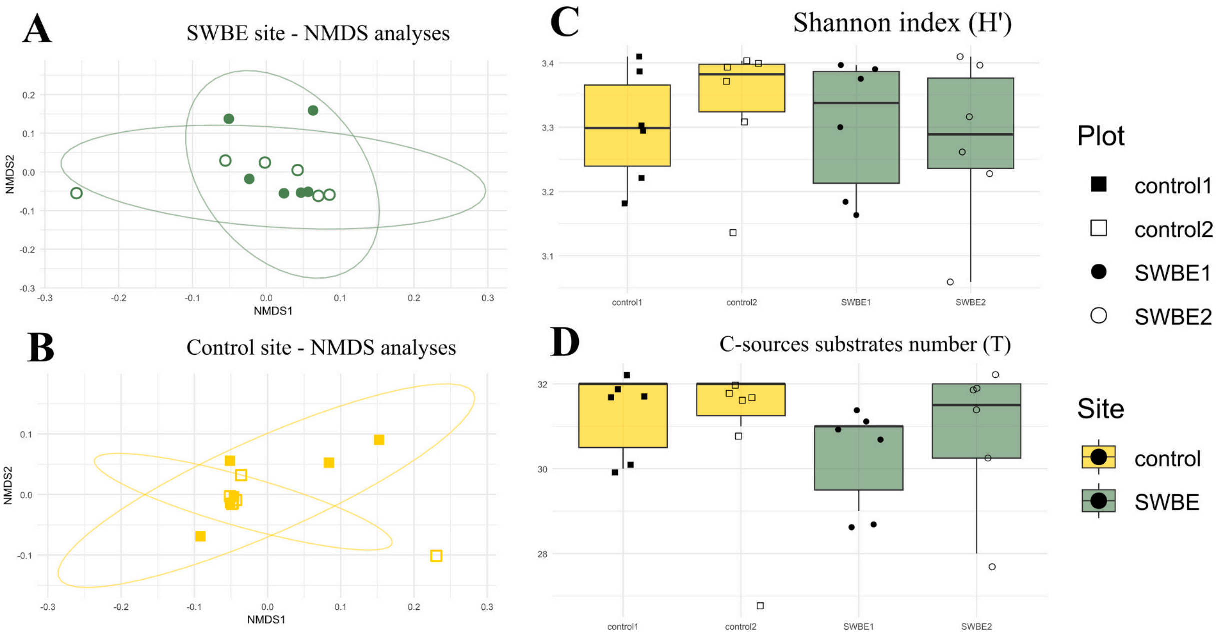

Fig. 4. NMDS analyses and boxplot distribution of alpha-diversity indices based on carbon substrate utilisation by microbial communities. A) NMDS analysis in SWBE site; B) NMDS analysis in *control* site; C) Boxplot for Shannon index (H′); D) Boxplot representing the number of carbon substrates used by microbial communities (T). Boxplot boxes represent the first to third quartiles of observations, with the median indicated by a black horizontal line. Solid symbols represent the internal plot, while the empty symbols represent the external plot. The axes in the NMDS plots indicate the percentage of explained total variance.

different disturbance regimes. These findings indicate post-disturbance metabolic recovery in both the actively restored (SWBE) and the control sites.

3.4. Soil fauna alpha diversity

Consistent with the microbial investigations, the study of soil fauna communities was conducted at the SWBE and control sites. Multivariate and univariate analyses demonstrated the resilience of soil fauna to the landslide event. NMDS ordinations and PERMANOVA testing showed no significant compositional divergence between disturbed and undisturbed plots.

The community composition results were supported by alpha-diversity index analyses (Fig. 5C-D). Species richness exhibited no significant differences between sites and internal/external positions. Similarly, for the Shannon diversity index, the ANOVA revealed no

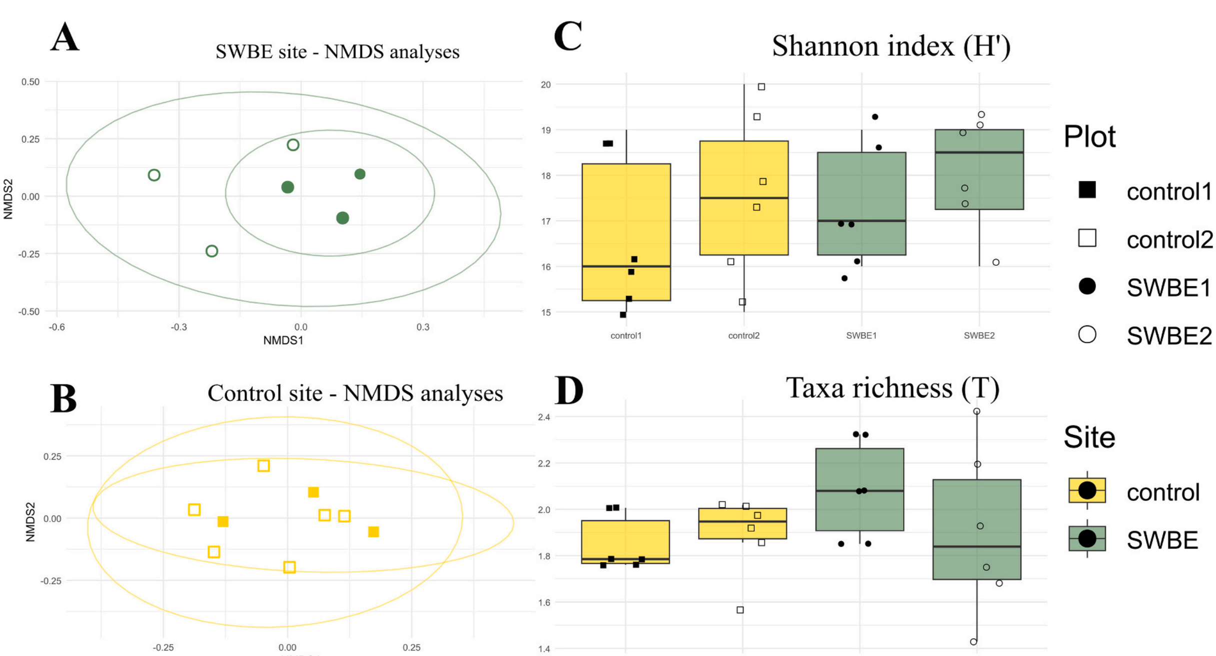

Fig. 5. NMDS analyses and boxplot distribution of alpha-diversity indices of soil fauna communities. A) NMDS analysis in the SWBE site; B) NMDS analysis in the *control* site; C) Boxplot of the Shannon index (H′); D) Boxplot of taxa richness (T). Boxplot boxes represent the first to third quartiles of observations, with the median indicated by a black horizontal line. Solid symbols represent the internal plot, while the empty symbols represent the external plot. The axes in the NMDS plots indicate the percentage of total variance explained.

significant effect of site or position (SWBE site, Tukey test; $p = 0.539$; *control* site, Tukey test; $p = 0.99$). The boxplot trends (Fig. 5D) revealed subtle site-specific dynamics: the *control* site showed a slight decrease in diversity within the landslide, and the SWBE site exhibited marginally higher internal Shannon values than those of its external plot.

4. Discussion

The integrated evaluation of soil properties and biological indicators provides complementary insights into the ecological conditions of the three study sites. Our findings showed that herbaceous vegetation is the biological indicator that reveals the most interesting ecological dynamics in the SWBE-restored, *control*, and *natural* sites (Fig. 6), whereas soil microorganisms and soil fauna showed interesting trends too, which deserve further investigation. These findings support the idea that the SWBE restoration project activated ecological processes that led to a different species composition, mitigating environmental stressors, specifically through soil erosion control and hydrological regulation (Preti et al., 2025).

4.1. Landslide disturbance effects and sites' pedological differences

The multivariate analysis revealed that soil physicochemical profiles were not uniform across the study areas, reflecting environmental heterogeneity. While individual parameters might suggest localised similarities in soil structure, the PERMANOVA and PCA results confirm significant baseline pedological divergence between the SWBE, control, and natural sites ($p < 0.05$). This divergence is primarily driven by gradients in pH, texture fractions, and bulk density, which define the unique environmental identity of each site. However, this edaphic variability is balanced by the homogeneity of arboreal vegetation across the external reference plots (Preti et al., 2025). The clear separation between internal (disturbed) and external (undisturbed) plots across all sites – accounting for over 50% of the variance along the first PCA axis – underscores the impact of the geomorphological event on soil structure. Specifically, the strong influence of silt or clay contents and bulk density in the ordination space suggests that the disturbance reshaped the physical matrix of the soil. The consistent multivariate response to disturbance across the three locations allows for a comparative assessment of recovery dynamics between disturbed and undisturbed plots.

4.2. Different ecological dynamics in species community recovery and alpha diversity

Herbaceous vegetation emerged as the most responsive bioindicator, with the main alpha-diversity indices (taxa richness and Shannon diversity) showing different trends across the three studied landslide sites. The restored site (SWBE) showed an increase in alpha-diversity indices in the internal plots compared to the external ones, while a decrease was observed in the naturally evolved site (natural), and a non-significant difference was found at the control site (control), which maintained intermediate values.

In the *control* site, herbaceous vegetation diversity appeared to have returned to pre-disturbance values after 30 years, even if NMDS analyses showed different floristic composition between internal and external plots; the plant community has autonomously converged toward an alternative stable state. In contrast, the naturally evolved site (*natural*) displayed a decrease in alpha diversity indices compared to its external plots; the steep slope and sand fraction are negative correlate to vegetation diversity (Fig. S6), acting as a natural restricting feature for spontaneous colonisation. In this site, post-landslide regeneration of deeper-rooted trees and shrubs proceeds slowly (Buma and Pawlik, 2021; Preti et al., 2025), leading to conditions of environmental stress that exert a strong natural selection pressure, reducing both species richness and overall slope stability (Hosseini et al., 2019; Bischetti et al., 2021). These differences were most pronounced in internal plots of SWBE, suggesting that vegetation (trees, shrubs and grasses) has well adapted to disturbance and restoration dynamics. Furthermore, the differences in floristic composition between internal and external plots of the restored site were also more pronounced than those observed in the other two sites, suggesting that the increase in alpha diversity indices is due to vegetation fragmented into more distinct communities compared to the lateral areas, similar to what was observed in other landslide vegetation monitoring (Gomes et al., 2020; Walker and Shiels, 2013). This result can be interpreted as the vegetation's adaptation to conditions of greater availability of trophic resources for plants (water and nutrients) as a result of the bioengineering restoration project, compared to conditions of marked environmental stress in the lateral areas, which promote greater natural selection for species richness. According to other ecological studies (Moi et al., 2020; Sheil and Burslem, 2013), the visible effect on the determined environment of the bioengineering work could be like conditions of moderate disturbance (Grime, 1998). This condition would favour the entry of new

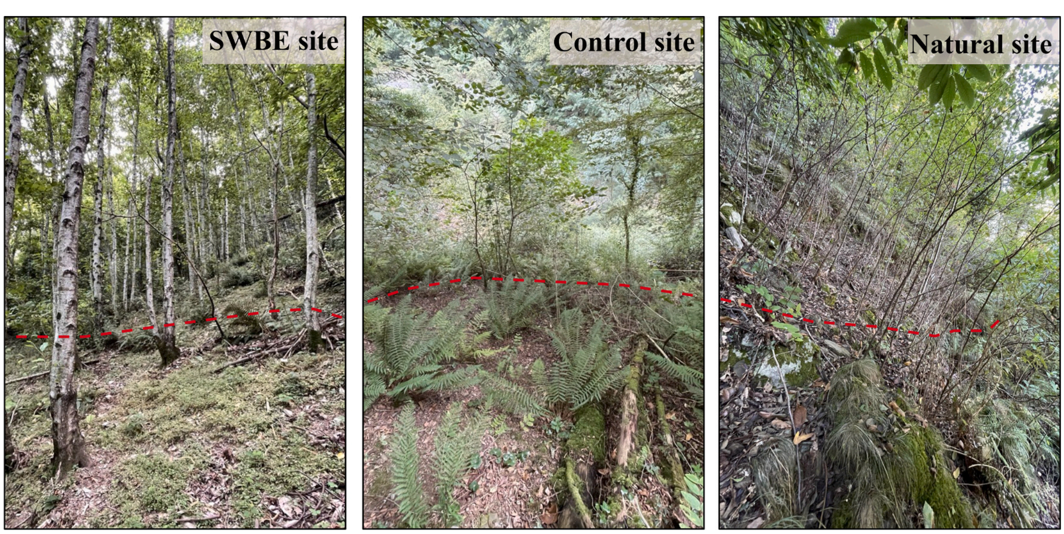

Fig. 6. Representative pictures of the three study sites (disturbed areas): SWBE site (left), *control* site (centre), and *natural* site (right). The dashed red lines indicate the spatial location of the sampling transects within each study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

species more than the exclusion of those pre-existing to the disturbing event, increasing species richness, as pointed out by the comparison between the diversity indices trends and that of the specific composition between internal and external plots, of the three sites.

In addition to ensuring slope stability, the restoration project has promoted a distinct ecological dynamic that results in a different vegetation composition. The type of vegetation (chestnut grove), still widely present in the area, was considered very susceptible to extreme weather events because of the shallow root system of chestnut trees. The vegetation and ground cover developing on the SWBE restored site are composed of species (alder and hornbeam) with better geotechnical characteristics (Bischetti et al., 2009), contributing to slope stability in the Apuan Alps environment. As already highlighted in other research on the ecological impacts of SWBE techniques, in addition to slope stability improvement (Gonzalez-Ollauri and Mickovski, 2017; Gray and Sotir, 1996; Löbmann et al., 2020; Stokes et al., 2014), in addition to slope stability improvement, there is also an increase in biodiversity (Cavaillé et al., 2015; Janssen et al., 2019, 2021) and a lower presence of invasive species compared to traditional techniques (Tisserant et al., 2024). The studies mentioned above refer to riparian environments for bank restoration or stream renaturalisation. In mountain forest environments, studies on the ecological effects of SWBE are limited (Bischetti et al., 2021; Rey et al., 2024). Restoration projects using SWBE techniques were shown to improve the herbaceous species diversity while also allowing the development of tree vegetation (Janssen et al., 2019; Kettenhuber et al., 2023).

4.3. Ecological recovery of soil fauna and microbial communities

Microbial communities and soil fauna exhibited resilience and functional stability between disturbed and undisturbed areas at both the SWBE and control sites. Given the importance of soil microorganisms in terrestrial ecosystems and their symbiotic relationships with plants (Fagorzi et al., 2025; Philippot et al., 2013, 2021), further investigation through additional analyses is warranted. The microbial physiology analyses (CLPP) revealed no significant differences in carbon source utilisation between disturbed and undisturbed plots at both sites. Pairwise comparisons confirmed that the internal landslide bodies exhibited comparable substrate utilisation to their respective undisturbed external sites. This convergence indicates that microbial communities have fully recovered the pre-landslide metabolic diversity, despite the past disturbances. In the SWBE site, the positive correlation between exposure (northness) and microbial diversity (Fig. S6) suggests that canopy opening within the landslide body acts as a fundamental catalyst for decomposer communities. Research on the plant-soil-microorganism relationship has shown that greater plant diversity enhances soil microbial biomass, particularly soil fungi, by increasing root-derived organic inputs (Eisenhauer et al., 2017; He et al., 2022; Izquierdo et al., 2005; Pérez-Valera et al., 2020).

Soil fauna displayed a similar response. NMDS ordinations and alpha-diversity metrics confirmed the absence of significant differences in species composition between the internal and external plots in each site. In the control site, soil fauna richness is directly driven by clay content and low bulk density (Fig. S6), which are characteristics of undisturbed forest soils. In accordance with our results, previous studies have indicated the effectiveness of the SWBE technique on soil fauna in riparian environments (Calle et al., 2013; Cavaillé et al., 2013). In particular, SWBE interventions involving the use of live wooden crib walls (Janssen et al., 2019) provide habitats in which insects can serve as indicators of soil development and the degradation of wooden structures. The use of SWBE techniques is a low-invasive restoration method for local arthropod fauna, providing greater opportunities for certain species (xylophagous and saproxylic beetles) due to the addition of shelters and microhabitats, with positive implications for the entire food chain. Overall, these results indicate that the soil fauna communities have recovered pre-disturbance conditions at both the restored and control sites, indicating that soil fauna possess effective ecological strategies that allow them to adapt even to changes in plant community composition.

5. Conclusions

The integrated assessment of soil physicochemical parameters and biological indicators demonstrated that the Soil and Water Bioengineering (SWBE) restoration technique effectively promoted both slope stability and ecological recovery. Among the investigated components, herbaceous vegetation proved to be the most sensitive and responsive indicator of ecosystem restoration. The dynamics observed in our case study indicated that SWBE interventions not only mitigate erosion processes but also enhance habitat quality by fostering the establishment of native tree communities with improved geotechnical traits, such as alder and hornbeam. SWBE restoration reduces environmental stress and increases the availability of trophic resources for plants, thereby promoting changes in species composition. Future studies should investigate the temporal dynamics of plant communities in the future. Soil microorganisms and fauna exhibited a moderate response, reflecting the resilience of belowground communities after disturbance. Microbial metabolic diversity at both restored and control sites reached levels comparable to those of undisturbed reference conditions, suggesting a full recovery of soil functional potential. Soil fauna communities successfully recovered pre-disturbance conditions at both the SWBE and control sites, indicating their effective ecological adaptation.

Collectively, these findings highlight the ecological benefits of applying SWBE techniques on shallow landslides, which combine structural stability with the reactivation of ecological dynamics. Future studies should extend this approach to other landslides, covering different climatic and geologic conditions, but also different SWBE techniques and different landslide types. Additionally, to better understand the ecological succession in shallow landslide restoration projects, long-term multi-taxon monitoring data on different biological indicators should be collected and shared. Further investigations into plant–soil–microorganism interactions will be crucial to understand long-term dynamics of ecosystem recovery in restored mountain environments.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used Grammarly to improve the English writing. After using this tool/service, the author (s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Emanuele Giachi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Agnese Bellabarba:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Francesca Decorosi:** Writing – review & editing, Methodology, Investigation, Data curation. **Gergely Ujvári:** Writing – review & editing, Investigation, Data curation. **Marco Cabrucci:** Methodology, Investigation, Data curation. **Lorenzo Tagliaferri:** Writing – review & editing, Investigation, Data curation. **Matteo Bracalini:** Resources, Investigation, Data curation. **Patrizia Sacchetti:** Writing – review & editing, Resources, Investigation, Data curation, Conceptualization. **Giacomo Certini:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation. **Carlo Viti:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **Federico Preti:** Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2026.108085.

Data availability

Data will be made available on request.

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