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**Study of methodological approaches for biodiversity
monitoring in Nature-based Solutions (NBS) inter-
ventions, using Soil and Water Bioengineering
(SWBE) techniques in the Mediterranean region.**

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*To my grandmas,
Ida and Creusa*

“Quando sei a un bivio e trovi una strada che va in su e una che va in giù, piglia quella che va in su. È più facile andare in discesa, ma alla fine ti trovi in un buco. A salire c'è più speranza. È difficile, è un altro modo di vedere le cose, è una sfida, ti tiene all'erta” (Tiziano Terzani)

ABSTRACT

In the context of the current climate crisis, the intensification of extreme meteorological events necessitates a shift in hydrogeological risk-mitigation strategies, promoting a transition toward Nature-Based Solutions (NBS). Among these, Soil and Water Bioengineering (SWBE) represent a bioinspired solution for slope stabilisation, as it combines geotechnical safety with the restoration of ecological functionality. However, the scientific validation of such techniques is often caught up in disciplinary fragmentation and by the lack of long-term monitoring protocols capable of assessing both the evolution of slope stability and the success of environmental recovery. This study aims to address this gap through the development and application of an integrated, multidisciplinary monitoring approach. The research focuses on shallow landslides in the Northwest Tuscany (Pomezzana case study, 1996 flood events), comparing sites restored using SWBE techniques and naturally evolved landslides.

Subsequently, the core of the research focused on a dual-phase long-term monitoring campaign, focusing on both slope stability and ecological recovery. The first phase involved a comparative stability analysis between a landslide restored with SWBE techniques and an adjacent landslide left to natural evolution. Data acquired from the multi-approach protocol were incorporated into slope-stability modelling to quantify the temporal evolution of the Factor of Safety. The results demonstrate that, in the SWBE restored site, the physiological degradation of wooden structural elements is effectively compensated by the progressive increase in soil-root reinforcement. This dynamic equilibrium ensures that the Factor of Safety remains stable over time, contrasting with the fluctuations observed in the natural evolution scenario.

Parallel to the mechanical assessment, the second phase expanded to a comprehensive multi-taxon monitoring of biodiversity. This investigation evaluated the effectiveness of ecological restoration by analysing three key biological factors: vegetation composition, soil macrofauna communities, and soil microorganisms. Through the analysis of alpha-diversity indices, the study assessed the capacity of SWBE interventions to reactivate ecosystem functions and support complex biological communities comparable to those found in natural succession. As a significant added value to the ecological investigation, the research presents preliminary insights from an ongoing advanced analysis of beta-diversity. Utilising shotgun metagenomic sequencing of the soil microbiome combined with phytosociological surveys, this current work aims to explore the functional co-occurrence networks between plant communities and microorganisms, seeking to unveil the deeper ecological dynamics activated by Soil and Water Bioengineering techniques.

In conclusion, the dissertation confirms that Soil and Water Bioengineering structures are not static infrastructures but dynamic and resilient systems. The results provide new

operational guidelines for design, species monitoring, and maintenance, offering an essential knowledge base for planning sustainable interventions that integrate technical safety with biodiversity restoration.

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1. INTRODUCTION

1.1. Natural hazards and Climate change

In recent decades, the intensification of climate change has led to a significant increase in the frequency and magnitude of extreme weather events globally, worsening the risk of natural disasters and putting a strain on the resilience of territories (Debele et al., 2023; Lee & Romero, 2023; Ruangpan et al., 2019). In this scenario, slope instability phenomena, particularly shallow landslides triggered by intense rainfall, represent one of the most critical threats to natural ecosystems, infrastructure, and civil safety (Igwe & Una, 2019; Ruangpan et al., 2019; Singh, 2010). Inland areas and mountain environments are the most exposed to natural hazards. Hydrogeological risk management requires a deep understanding not only of current dynamics, but also of the geological and climatic history of the sites. As highlighted by studies conducted in vulnerable contexts, such as those of the Apennines or the Alps — for example, by analysing catastrophic events like the 1996 Versilia flood — historical research proves to be a fundamental tool for accurately estimating hydrogeological hazards and planning effective restoration interventions (Giannecchini & D’Amato Avanzi, 2012; Kumar et al., 2022; Su et al., 2024; Tofani et al., 2017).

However, the traditional approach to risk mitigation, based mainly on “grey” civil engineering works (rigid concrete structures), is increasingly limited in terms of economic sustainability, ecological impact, and adaptability to ongoing environmental changes. Consequently, there is an urgent need for a paradigm shift towards solutions that integrate hydraulic and geotechnical safety with the restoration of ecological functions (Eggermont et al., 2015; Fernandes & Guiomar, 2018; IUCN, 2016; Moreau et al., 2022; Nehren et al., 2023; Nesshöver et al., 2017).

1.2. Nature-based Solutions (NBS) and Soil and Water Bioengineering (SWBE)

To address these critical issues, the concept of Nature-Based Solutions (NBS) has gradually gained international recognition. NBS are defined as actions aimed at protecting, sustainably managing and restoring natural or modified ecosystems, addressing social challenges effectively and adaptively (Eggermont et al., 2015; IUCN, 2016; Nesshöver et al., 2017). In the specific context of hydrogeological instability mitigation, Soil and Water Bioengineering (SWBE) techniques gain more importance due to their vast applicability, and bio-inspired approach, well-known worldwide for its effectiveness, from urban to natural environments. This technical discipline combines principles of hydraulic engineering, geotechnics and plant

ecology, using plants not only as “aesthetic” elements, but as actual living “building materials”, often in combination with inert materials such as wood, stone or steel (Evette et al., 2009; Preti et al., 2022; Rey et al., 2019; Schiechl & Horstmann, 1980).

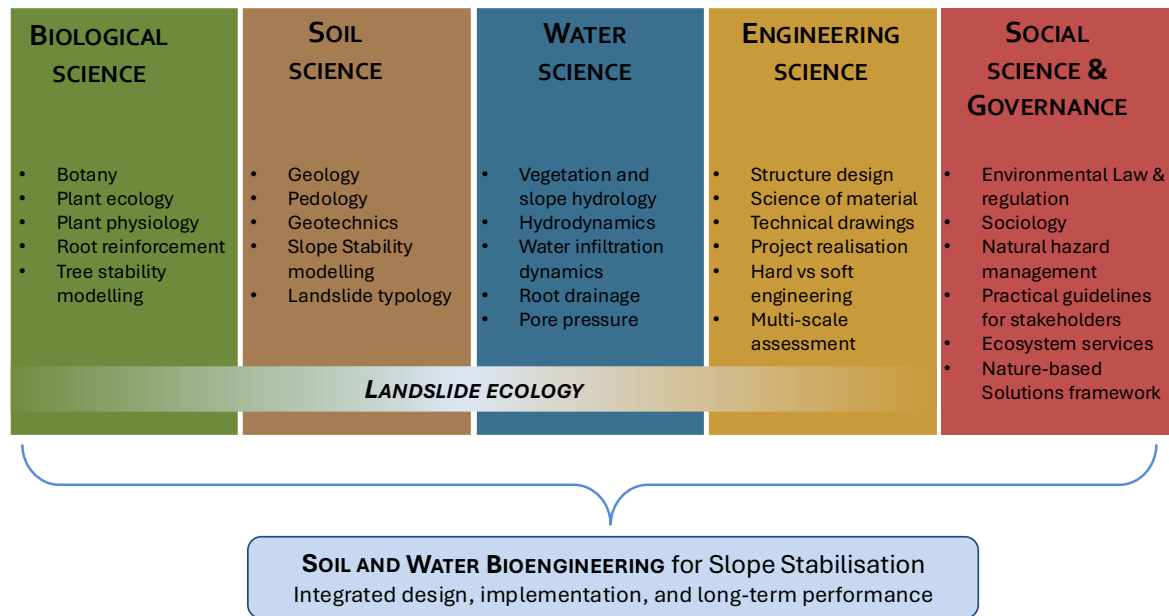


Figure 1: Geo-sciences involved in the Soil and Water Bioengineering approach, specifically for slope stabilisation.

The key difference compared to traditional works lies in the temporal dynamics of their effectiveness. While “grey” structures (e.g. concrete walls) offer maximum resistance at the time of construction and then undergo inevitable physical degradation, SWBE interventions behave oppositely (Bischetti et al., 2021; Mickovski et al., 2022). The SWBE approach is a bio-inspired process in which natural processes that allow slope stabilisation are observed and studied to replicate those dynamics in artificial interventions (Stokes et al., 2014; Zaimes et al., 2019). Compared to traditional concrete structures, SWBE techniques also have a lower cost in terms of both construction costs and carbon footprint (Rauch et al., 2022; von der Thannen et al., 2021). In the early stages, stability is often ensured by inert or auxiliary components, but over time, the growth of root systems and the development of the aerial part increase the mechanical and hydrological performance of the structure (Bischetti et al., 2021; Preti et al., 2025; Tardio & Mickovski, 2023). This approach, now codified in technical manuals and industry regulations (Associazione Italiana per l’Ingegneria Naturalistica - AIPIN, 2022; Regione Lazio, 2006; Zeh, 2007), thus makes it possible to transform a defence structure into an active element of the landscape, capable of evolving and self-regenerating (Böll et al., 2009; Mickovski et al., 2023; Tardio & Mickovski, 2023).

1.3. Slope stability and soil-root reinforcement

The technical effectiveness of SWBE is primarily based on the mechanical and hydrological interactions between plants and soil. The main contribution to slope stability is provided by root reinforcement: roots penetrate the substrate and act as tension fibres within a composite matrix, increasing the apparent cohesion of the soil and its resistance to shear during potential landslide movements (Arnone et al., 2016; Bischetti et al., 2009; Hofmann et al., 2015; Vergani et al., 2012; Zayadi et al., 2020).

To quantify this reinforcement, scientific research has developed various modelling approaches operating at different scales, as extensively reviewed by Mao et al. (2022). Historically, the most widely used approach is the perpendicular model (Wu-Waldron model), which assumes that all roots break simultaneously during shear. However, recent experimental evidence suggests that this assumption often leads to an overestimation of stability. Consequently, more advanced approaches, such as Wu-Waldron modified models or the Fibre Bundle Models (FBM), have been introduced to account for the progressive failure of roots: roots break sequentially based on their diameter and elasticity, rather than all at once (Mao, 2022; Murgia et al., 2022; Pollen-Bankhead & Simon, 2010; Schwarz, Preti, et al., 2010). This transition from simple equilibrium models to dynamic mechanical models allows for a more realistic estimation of the safety factor at the slope scale (Giadrossich et al., 2017, 2019; Schwarz, Lehmann, et al., 2010).

Furthermore, vegetation significantly enhances slope stability by improving soil structure through the formation of stable, water-resistant aggregates (Burri et al., 2009; Erktan et al., 2016; Schwarz, Preti, et al., 2010). This process is driven by the combined actions of roots and the associated microorganisms. Roots and symbiotic fungi bind soil particles and biochemical exudates, as well as mucilage, substances that facilitate the flocculation of clay particles and the binding of larger grains into stable clusters. The strength of soil aggregates is not only critical to the stability of slopes but also plays a key role in ecosystem functioning in general (Böll et al., 2009; Graf et al., 2015; Graf & Frei, 2013). By enhancing aggregate stability, vegetation improves the overall shear strength and porosity of the soil matrix, creating a more resilient substrate that can better withstand the erosive and destabilising forces of water (Mao, 2022; Murgia et al., 2022).

In parallel with the mechanical effect, vegetation plays a crucial but complex hydrological role. Through precipitation interception and transpiration, plants reduce soil water content and maintain higher matrix suction (negative interstitial pressures), generally improving slope stability conditions (DiBiagio et al., 2024; Gonzalez-Ollauri & Mickovski, 2017b, 2017a; Tardío et al., 2016). However, discussions about the net effect of vegetation on soil water dynamics

are still ongoing. While root water uptake promotes stability, research highlights that root systems can also act as preferential flow paths (macropores) that facilitate rapid water infiltration into the soil matrix (Delgado-Gonzalez et al., 2023; Pollen-Bankhead & Simon, 2010; Qin et al., 2022). Under specific conditions, such as intense rainfall events, this increased permeability may lead to a faster soil saturation or localised increase of pore water pressure, potentially triggering instability (Arnone et al., 2016; Bordoni et al., 2015; Vergani et al., 2017a). Therefore, the overall stability is the result of a dynamic trade-off between the stabilising effects of root reinforcement and suction, and the potentially destabilising effects of increased weight and infiltration capacity (Lann et al., 2024; Wang et al., 2019).

1.4. Landslide ecology and Biodiversity assessment

While radical reinforcement guarantees safety, the added value of NBS lies in their ability to restore degraded ecosystems. Landslides should not be considered solely as destructive events, but as complex “ecological disturbances” which, by removing existing vegetation and exposing new mineral substrate, change the ecological succession (Restrepo et al., 2009; Sidle & Bogaard, 2016; Walker, 2013). The discipline of “landslide ecology” highlights how these areas, if properly managed and monitored, can evolve into biodiversity hotspots, hosting specialised pioneer species (Buma & Pawlik, 2021; Takaoka, 2024; Walker, 2013; Walker et al., 2009). SWBE interventions accelerate these natural processes. Unlike grey structures, which often create ecological barriers and reduce habitat connectivity (Kettenhuber et al., 2023; Martin et al., 2021; Rauch et al., 2022), bioengineered structures provide microhabitats conducive to the establishment of diverse flora. Recent studies emphasise the importance of assessing not only taxonomic richness (number of species) but, above all, functional biodiversity, i.e. the variety of biological traits that make the plant community resilient to environmental stresses (Cavaillé et al., 2018; Janssen et al., 2019; Tisserant et al., 2021, 2024).

Ecological recovery also extends to the invisible component of the system: the soil. The presence of living plants stimulates biological activity in the rhizosphere, promoting the return of microbial communities (bacteria and fungi) essential for the nutrient cycle and the formation of stable aggregates in the soil, thus closing the circle between physical stability and ecological functionality (Bardgett & Van Der Putten, 2014; Eisenhauer et al., 2017; Izquierdo et al., 2005; Philippot et al., 2013). Choosing the appropriate SWBE technique and plant species for restoration is crucial both for technical factors like soil stability and erosion, and for plant-soil interactions, ensuring the intervention improves soil stability, organic matter, and microbial communities (Fagorzi et al., 2025; He et al., 2022).

Completing this complex picture is the soil fauna, which plays a key role in the interface between vegetation, soil and microorganisms. Soil fauna acts as a sensitive indicator of the quality of microhabitats and the complexity of restored food chains. The presence of specific functional groups (e.g. detritivores, predators) provides valuable information on the degree of maturity of the ecosystem and the rate of biological interaction taking place. SWBE works directly to influence colonisation by these organisms, whose activity is fundamental for pedogenesis and the maintenance of long-term fertility. Understanding these interconnected dynamics necessarily requires the adoption of a multitaxon approach (Brunbjerg et al., 2017; Burrascano et al., 2021; Kettenhuber et al., 2023; Yan et al., 2021). Only by simultaneously investigating the various biotic components is it possible to fully appreciate the functional relationships that support habitat restoration. The application of these integrated ecological surveys to the SWBE techniques monitoring represents the doctoral thesis objective, to provide practical guidance for optimising the design and maintenance strategies of the works, thus ensuring the success of the restoration in terms of both slope stability safety and biodiversity.

2. RESEARCH OBJECTIVES

This research addresses the critical intersection between hydrogeological risk mitigation and the ecological restoration effectiveness of Soil and Water Bioengineering (SWBE) approaches, with particular emphasis on rainfall-induced shallow landslide in mountain environments. While the SWBE approach is widely recognised as a nature-based solution, its implementation in mountain environments faces a significant dual challenge. On the one hand, the mechanical and geotechnical performance of these techniques in stabilising shallow landslides is well-established. On the other hand, their role as drivers of ecological recovery remains largely not explored or focused just on the vegetation development rather than on functional biodiversity. The following knowledge gaps hinder the transition of SWBE from a purely technical stabilisation tool to an ecological restoration strategy:

- The technical-ecological issue: in steep mountain terrains, engineering requirements often dictate the choice of structures, potentially overriding ecological succession goals, in those situations where it is possible. There is a lack of evidence on whether technical efficiency can go alongside the restoration of ecological functionality.
- Multi-taxon data scarcity: most monitoring focuses on surface vegetation, neglecting the complex interactions between soil fauna and microbial communities in the plant-soil environment.

- Ecological trajectories: it remains understudied whether SWBE restoration projects could eventually converge with natural ecological trajectories, time-evolution differences, and whether permanent management is required.

The study is embedded within the framework of the National Biodiversity Future Centre (NBFC), a national research initiative funded under the PNRR – NextGenerationEU program (CN5), which aims to enhance the knowledge, monitoring, and valorisation of biodiversity across a wide range of terrestrial and freshwater ecosystems. NBFC promotes multidisciplinary and integrative research strategies to investigate biodiversity patterns, ecological processes, and their temporal dynamics, covering scales from taxonomy to genomics and including participatory approaches such as citizen science. Within this context, SWBE has emerged as an effective and nature-based approach for natural hazard mitigation, combining engineering principles with biological components to stabilise slopes and reduce hydrogeological risk. While the mechanical and geotechnical effectiveness of SWBE interventions is well documented in the literature, an important knowledge gap persists regarding their quantitative impacts on biodiversity recovery and ecological functionality, particularly when compared to natural succession processes. This gap is especially evident in mountainous areas, where natural hazards are typically more severe and technical–functional performance often takes precedence over ecological considerations in restoration planning.

Previous studies have demonstrated that SWBE techniques can provide positive ecological functionality and deliver valuable ecosystem services, particularly in fluvial and riparian habitats. However, in upland and mountainous settings—such as shallow landslides and degraded slopes—the extent to which technically efficient SWBE solutions that ensure slope stability can simultaneously promote environmental and biodiversity enhancement remains insufficiently explored. A key open question is whether the para-natural vegetation and habitats that develop on SWBE-restored slopes can evolve towards stable, resilient, and self-sustaining ecological systems comparable to those arising from natural recovery processes.

In this framework, the present study, developed within NBFC Spoke 3 (“Assessing and monitoring terrestrial and freshwater biodiversity and its evolution”), aims to evaluate the effects of SWBE interventions on biodiversity in landslide-affected areas. Specifically, the research pursues the following objectives:

- a) Develop a multidisciplinary monitoring methodology for assessing biodiversity variation in restoration works based on SWBE techniques.

- b) Quantify biodiversity changes through a multi-taxon approach, encompassing soil fauna, vegetation, and soil microorganisms.
- c) Using long-term monitoring evidence to define a practical vegetation management framework to assess plant development within SWBE interventions and its trajectory towards natural ecological succession.

Study areas were selected based on the occurrence of Soil and Water Bioengineering (SWBE) interventions within the Mediterranean region, specifically in forested contexts and across hilly to mountainous landscapes. Preliminary analyses revealed marked heterogeneity in climatic conditions, vegetation patterns, and soil characteristics among the initially proposed sites. To limit spatial and temporal variability and to ensure greater comparability of biodiversity data, the research design was refined to focus on a single, well-defined geographical area: the locality of Pomezzana, within the municipality of Stazzema (Lucca Province, Italy). This area is characterised by numerous degraded slopes resulting from the extreme flood event of 1996, which triggered widespread landslides throughout the Versilia River catchment. Based on cartographic data provided by the Apuan Alps Regional Park and local territorial authorities, landslides associated with the 1996 event were identified and mapped. Subsequent cartographic analyses and field surveys led to the selection of three representative landslides as study sites: (1) a naturally evolved landslide with absence or few anthropological disturbances (CL landslide), (2) a naturally evolved unrestored landslide lacking any stabilisation measures (NL landslide), and (3) a landslide restored through SWBE techniques (SWBE landslide).

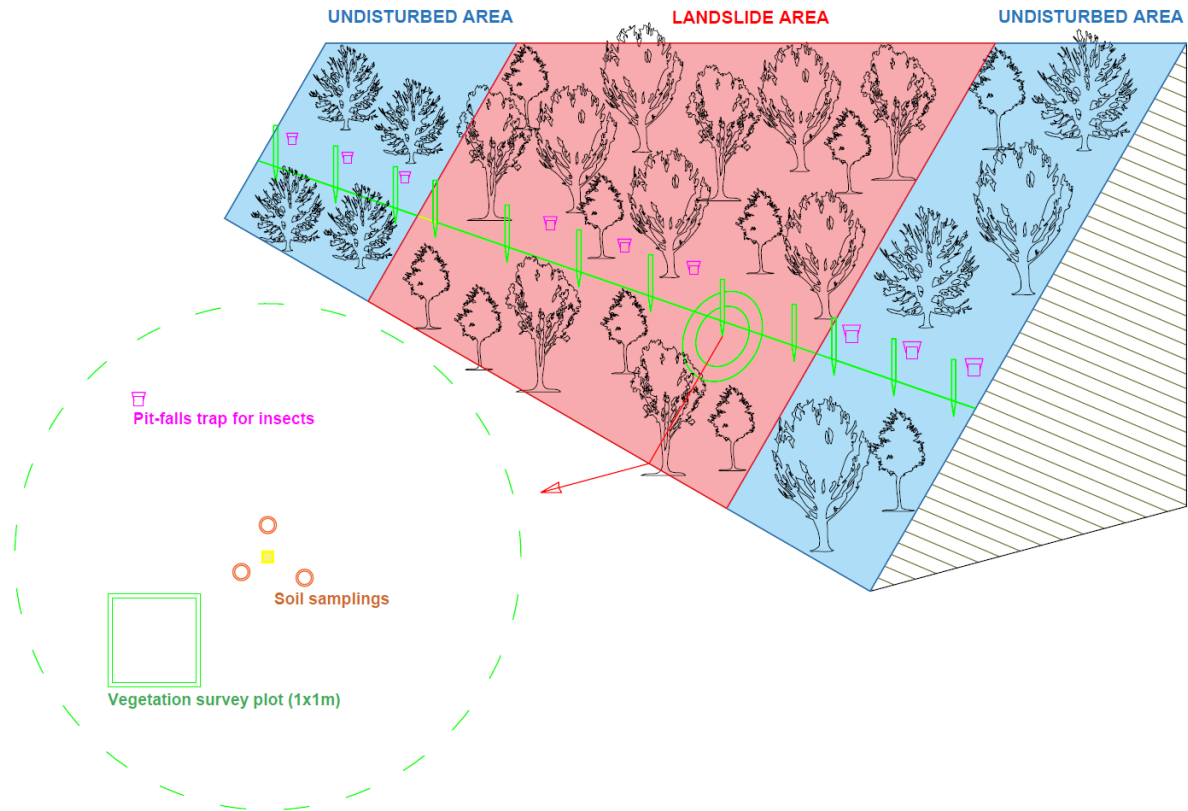


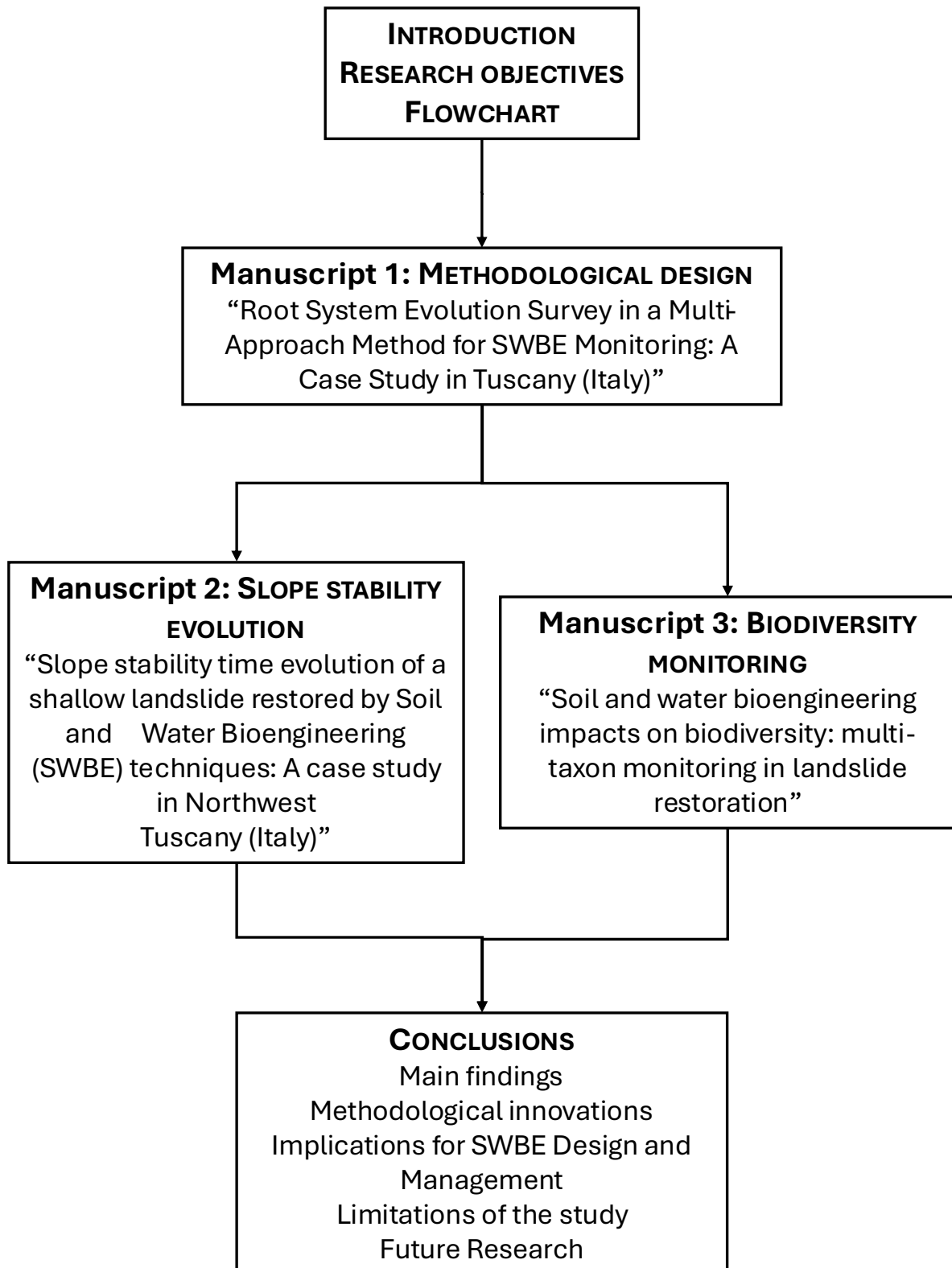
Figure 2: Integrated Multi-taxon sampling design. This framework illustrates the simultaneous assessment of above-ground (vegetation) and below-ground (microfauna and soil fauna) components. By applying this protocol across the **SWBE-restored**, **natural** and **control** sites, the study quantifies the biodiversity gain of engineering interventions against natural benchmarks.

The manuscript is structured to gradually integrate methodological development, technical performance assessment, and ecological analysis to provide a comprehensive evaluation of SWBE interventions. The first paper presents the conceptual framework and development of a multidisciplinary methodology for SWBE monitoring, trying to establish the tools needed to measure technical and environmental performance. This chapter introduces the integrated monitoring strategy, which combines vegetation assessment through spectral indices (e.g., NDVI), vegetation field surveys, and root system evolution analysis through different techniques (direct and indirect relev  ), focusing on instrumental and technical application in SWBE monitoring. The second published paper focuses on the long-term evaluation of slope stability, addressing the technical performance of SWBE interventions through SSAP software slope stability modelling, validating that ecological recovery doesn't come at the cost of geotechnical safety. This chapter aims to assess whether ecological restoration trajectories are supported by sustained mechanical effectiveness over time, thereby linking bioengineering design with hydrogeological risk reduction. The third submitted paper describes the multi-taxon sampling design adopted to compare a landslide restored using SWBE techniques with two naturally evolved landslides. The chapter focuses on the analysis of alpha diversity and ecosystem functionality, integrating

data on vegetation, soil fauna, and soil microorganisms to evaluate biodiversity patterns and ecological processes across contrasting restoration scenarios.

Beyond the specific technical and methodological assessments, this research is conceptually anchored within the broader scientific field of landslide ecology. By framing landslides as significant natural disturbances rather than mere geological hazards, this study highlights their role in creating unique habitats and driving ecological renewal. Within this perspective, naturally evolving landslides serve as critical ecological benchmarks. By using these undisturbed successional pathways as reference conditions, Soil and Water Bioengineering (SWBE) techniques can move beyond traditional stabilisation toward a more nature-mimicking approach. This alignment with natural processes is essential for optimising design and management strategies, ultimately increasing the effectiveness of SWBE interventions in fostering stable, resilient, and biodiverse communities that are functionally integrated into the surrounding landscape.

3. FLOWCHART



4. PAPERS

4.1. *Manuscript I*

Root System Evolution Survey in a Multi Approach Method for SWBE Monitoring: A Case Study in Tuscany (Italy)

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Abstract

Land degradation and soil erosion, intensified by frequent intense hydro-meteorological events, pose significant threats to ecological processes. In response to the environmental challenges, there is a growing emphasis on employing Nature-Based Solutions (NBS), such as Soil and Water Bioengineering (SWBE) techniques, which promote a sustainable approach and materials for the restoration of natural areas damaged by climate events, unlike traditional “grey” engineering works. However, the effective implementation of SWBE interventions requires a multidisciplinary monitoring approach, considering engineering, geological, ecological, biological, and landscape aspects. The success of these interventions depends on evaluating both short-term stabilities provided by the non-living supporting structure and the long-term development of vegetation introduced during the work. Monitoring should regard structural integrity assessments, vegetation evolution studies, and analyses of root system efficiency (distribution, mechanical characteristics, etc.). This study wants to fill the research gap in SWBE management by proposing a comparison of two study techniques for a root system development evaluation, within a multi-approach methodology for the assessment of these interventions in terms of soil stability and natural evolution. The paper provides insights into geotechnical analysis within a shallow landslide, comparing two different methods for the evaluation of root system evolution. Direct methods (RAR) and indirect methods (ERT) were used for root development monitoring and then compared. Vegetation development was assessed by NDVI parameter by analysing Landsat satellite images. An overall analysis of the data obtained from monitoring the study area shows good plant development, thanks to the SWBE intervention, which in addition to the slope stability effect, contributes to better water regulation and initiates a natural ecological succession. The findings contribute to advancing the understanding of the effectiveness of SWBE techniques, offering valuable information for future bioengineering projects and environmental conservation efforts, and promoting them as sustainable techniques for natural recovery.

1. Introduction

Land degradation and soil erosion, due to increasingly frequent extreme hydrometeorological events, have negative consequences on ecological processes, making the environment, particularly rural and mountain areas, more susceptible to biodiversity loss [1]. Nowadays, the use of plants as a building material transfers the plant's multifunctionality within engineering structures and meets the demand rising from society for more environmentally friendly approaches to structure design [2]. European strategies (EU Green Deal, EU Adaptation strategy, Biodiversity strategy for 2030), research policy (Horizon Europe 21-27, European Biodiversity Partnership-Biodiversa+, etc.) [3-7], and regulations promote the employment of Nature-Based Solutions, such as Soil and Water Bioengineering techniques (SWBE) [8]. In contrast to conventional "hard" civil engineering structures, the idea of SWBE structures is the use of biological components in the engineering structure not just to consider a technical function but also ecological and aesthetic values [9-11].

Soil and Water Bioengineering (SWBE) techniques are applied worldwide, achieving great results for slope and streambank stabilisation, water regulation, soil reinforcement, and mitigation of environmental impacts. SWBE techniques manage natural hazard control using plants as living material in combination with inert natural material, achieving two main goals: on the one hand, the technical function stabilising the soil, thanks to the development of the root systems; on the other hand, the mitigation of environmental damage, initiating natural ecological processes [12-15]. Designing SWBE structures, being multi-functionality techniques, requires considering engineering, geological, ecological, biological, and landscape aspects, to carry out an intervention that can respond to technical and environmental needs. Despite the increasing importance of SWBE techniques worldwide, there is a need to reconcile natural hazard control and ecological restoration by posing new applied research questions aimed at meeting this purpose, particularly by considering a multidisciplinary approach, establishing practical guidelines for SWBE design [16-19], implementing monitoring stages in bioengineering projects, and analysing existing SWBE works in terms of performance, success, and failures [20].

To evaluate the success of soil bioengineering work, it is necessary to conduct investigations related to all kinds of parameters considered during the design phase [21,22]. In the short and medium term, it will be essential for the non-living supporting structure to be sufficiently stable and ensure the stability of the slope or embankment subject to work. The stability provided by the structure, whether made of wood, stones, or other mixed solutions, will allow for the development of vegetation introduced through the work (seeding, cuttings, or rooted plants), which will be responsible for the future stability of the slope, as it is expected that the initial structure

will degrade over time. In the long term, it will be necessary to monitor the development of this vegetation and the induced, para-natural, or natural successions that will occur. The use of plants as a building material transfers the plant's multifunctionality within engineering structures and meets the demand rising from society for more environmentally friendly approaches to structure design, like Nature-Based Solutions [2,23]. The effectiveness of the soil bioengineering work should be evaluated through periodic assessments of the supporting elements' structural integrity and the slope's overall stability. The evolution of vegetation established within the structure and its surroundings should be analysed, in different periods, through studies and surveys related to dimensional and quantitative characteristics, the level of biodiversity, root system development evaluation, and the physiological capacity of the existing plants.

Analysis of root system distribution allows us to understand how plant stands evolution proceeds as a function of slope stability concerning surface movements and instabilities, those most affected by extreme weather events, consequently understanding the susceptibility of stands to climate change [24-27]. Given the previous considerations, the study aims to present a field survey on root system evaluation, related to slope stability, in multi-approach monitoring to evaluate the technical and ecological efficiency of SWBE work, giving insights into the results of vegetation monitoring methodologies. Particularly, the paper will describe and provide an overview of our first results on comparing direct and indirect root system surveys, and how tree root system evolution changes concerning tree position and soil characteristics, in a shallow landslide restored by SWBE techniques. The authors of this work are applying a multi-criteria approach to monitor a landslide in Tuscany, which occurred during one of the most catastrophic events in Tuscany. This study brings a notable scientific contribution as it has the advantage of being a long-term monitoring (30 years).

2. Materials and Methods

2.1. Meteorological Event Description

On 19 June 1996, a localised thunderstorm phenomenon of extreme violence (474 mm/12 h, with maximum peaks of 158 mm/1 h) struck the southern Apuan Alps, triggering in the mountainous areas of Versilia many surface landslide phenomena. The affected area includes the entire regional catchment area of the Versilia River, about 98 km². The most affected areas were, on the Garfagnana side, the built-up area of Fornovolasco, while on the Tyrrhenian side, the towns of Pomezzana, Farnocchia, Stazzema, Cardoso, Levigliani, and Saravezza. The most significant damage can be attributed to the numerous and extensive shallow landslides that, in the upland part of the affected area, obstructed communication routes by interrupting power and telephone lines and affected inhabited buildings. The landslides, mainly attributable to earth

and debris slides, evolved into flows (soil slip–debris flows), which were very rapid in initiation and evolution, partially or obstructed riverbeds, aggravating the effects of floods. This marked soil collapse susceptibility is to be ascribed not only to the exceptional rainfall but also to the geological and morphological characteristics of the area, which has a rock formation of sandstone and shale (called Cardoso stone) covered by a thick blanket of particularly unstable and landslide-prone debris.

2.2. Study Area

The study area is a hillslope located in the Apuan Alps, in northern Lucca province, Northern Tuscany (latitude: 43°98'78.36" N, longitude: 10°31'47.41"E) affected in 1996 by a shallow landslide process that occurred consequent of the meteorological event described in the previous section. The area of the landslide is approximately 12.000 m² and is located at an elevation between 450 and 600 m.a.s.l. (Figure 1). The average gradient of the slope is around 70% with a North–West exposure.

The area of landslide (Figure 1) could be classified in the European Forest class “8- Thermophilous deciduous forest” type 8.7 “Chestnut forests” [28]. The area is an abandoned sweet chestnut forest (*Castanea sativa* L.), in the past managed for chestnut production and in which some other species were present, such as *Ostrya carpinifolia* Scop., *Ilex aquifolium* L., *Ficus carica* L., *Alnus glutinosa* L., *Carpinus betulus* L., and *Acer* spp. L. It can be noted that the abandoned sweet chestnut forests have a stem density of 100 specimens per hectare, increased by several basal suckers with different ages compared to the main stem. The landslide was stabilised between 1998 and 1999 through Soil and Water Bioengineering techniques to prevent further soil erosion processes and shallow landslide events. Locally available building materials (stones, chestnut woods, and cuttings) were collected and used to build the bioengineering structures. The engineering stabilisation interventions mainly focused on the use of live wooden crib walls and living palisades in combination with trapezoidal wooden open channels to drain slope water (Figure 2). In detail, the stabilisation carried out consisted of vegetated crib walls made of chestnut wood, with the introduction of *Salix* species cuttings (*Salix purpurea*, *S. eleagnos*, *S. triandra*), while soil surface stabilisation was carried out employing live stakes with cuttings, live bundles and hydroseeding of herbaceous species and, in the intermediate part, with shrub species (mainly *Cytisus scoparius* L.). From the technical report, potted plants belonging to species with high water demand were used in areas characterised by high water percentage: *Fraxinus excelsior*, *Acer pseudoplatanus*, *Acer platanoides*, *Alnus incana*, *Frangula alnus*, *Laburnum* sp., *Cornus* sp.pl, *Euonymus europaeus*, *Crataegus monogyna*, and *Prunus spinosa*.

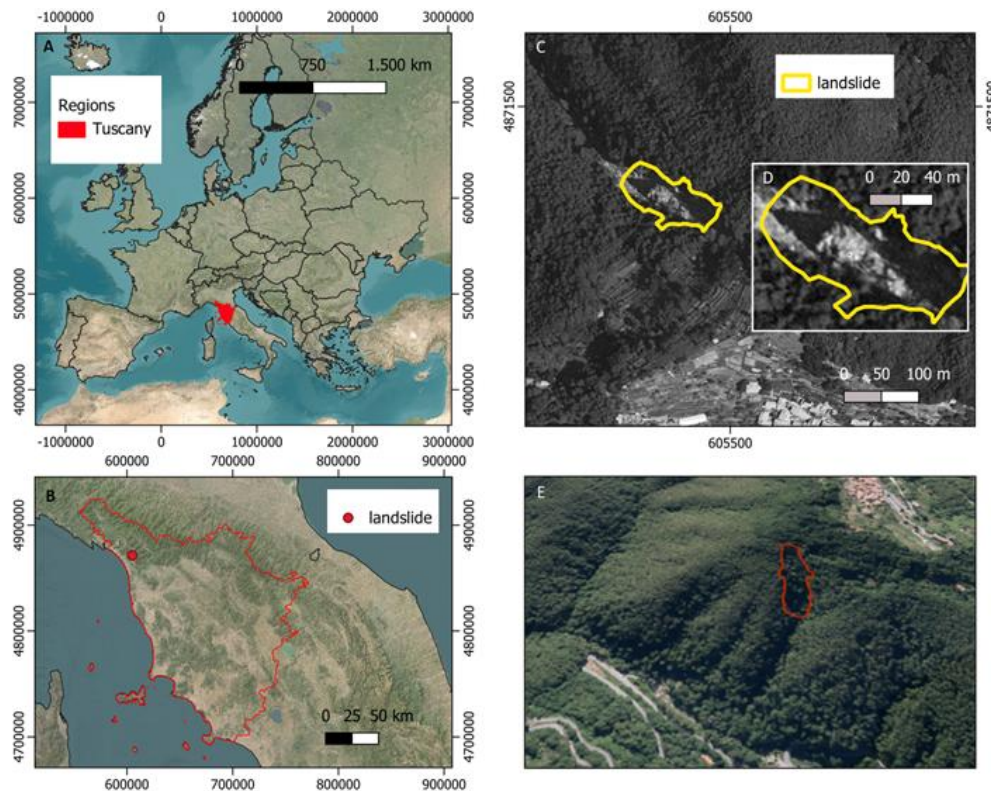


Figure 1. Panel (A) displays the location of the Tuscany Region within Europe. Panel (B) indicates the specific locations of landslides within the Tuscany Region. Panel (C) presents the landslide locations overlaid on the regional orthophoto acquired by the Tuscany Administration in 2016. Meanwhile, Panel (D) provides a zoomed-in view of the landslide area. Additionally, Panel (E) exhibits a 3D Google Earth image from 2023, highlighting the landslide perimeter in red, and it is possible to see that this landslide is situated on the mountain slope at the foot of the village of Pomezzana (LU) –coordinates system WGS84-UTM32N.

DEFINITIVE PROJECT FOR LANDSLIDE RESTORATION IN loc. POMEZZANA

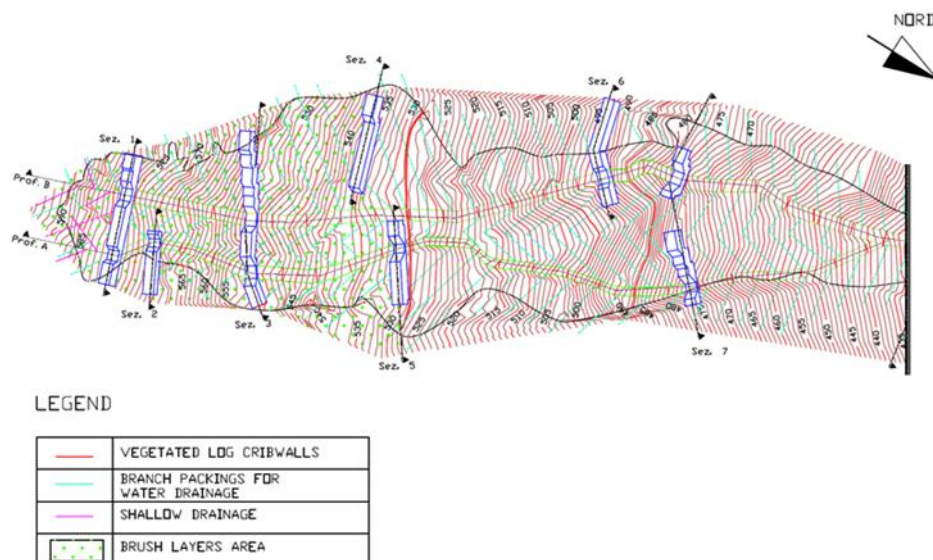


Figure 2. Final project plan of the forest hydraulic technique landslide restoration with different techniques of SWBE.

After the work was completed in 1999, no maintenance activities were conducted on the structures, because the implementation of SWBE required no additional interventions, and allowed the restored area to naturally evolve. In fact, during the recent monitoring years, none of the artificially introduced species were found, except for sporadic maples (*Acer pseudoplatanus* L.) and a few individuals of willow (*Salix caprea* L.). Nearly, all the cuttings were found to have dried up due to shading and competition from other species that entered the landslide area. Now, the forest stand consists of black alder (*Alnus glutinosa* L.) even-aged stand of about 23 years old that appears with high density. Additionally, others tree species not introduced by the SBWE were found such as black locust (*Robinia pseudoacacia* L.), black hornbeam (*Ostrya carpinifolia* Scop.), manna ash (*Fraxinus ornus* L.), elderberry (*Sambucus nigra* L.), chestnut (*Castanea sativa* Mill.), holly (*Ilex aquifolium* L.), and white hornbeam (*Carpinus betulus* L.). The undergrowth is composed of hygrophilous and nitrophilous species, the main ones being bramble (*Rubus ulmifolius* Schott) and nettle (*Urtica dioica* L.) [29].

2.3. Sampling Design and Data Collection

A multi-parameter sampling design is set to make a comprehensive study of the landslide evolution; in the present research, vegetation evolution rate and root system growth are analysed. The first vegetation survey was carried out in 2000, after the realisation of the SWBE intervention was completed, evaluating the percentage number of willow cuttings rooted post-intervention, obtaining a good result of more than 90% of the cuttings rooted. In 2013 and 2023, field surveys were conducted to monitor vegetation development in the restored area and the effects of the SWBE arrangement on slope stability, using a multiapproach monitoring method. The surveys included forest dendrometric measurements, geotechnical surveys on root systems, botanical surveys, and soil samplings. Table 1 shows the parameters collected and the year in which they were taken.

Table 1. Collected parameters are divided into macro areas and years of sampling. Sample and data collection in the survey years (2013 and 2023) were taken using the same techniques and methodologies for vegetation, soil, and geotechnical surveys.

Parameters	Description	2013	2023
Vegetation development	Tree and shrub species	X	X
	Tree density (n/area)	X	X
	Tree breast height diameter (cm)	X	X
	Tree height (m)	X	X
	Tree basal area (m ²)	X	X
	Remote Sensing - NDVI analysis	X	X
Slope stability and SWBE durability	Soil microorganism analysis	/	X
	Soil characteristics analysis	X	X
	RAR direct measurements	X	X
	Analysis of stable soil aggregates	X	/
	RAR indirect measurements - ERT	X	/

	Resistograph analysis	X	X
Ecological process	Botanic sampling	/	X
	Braun-Blanquet sampling	/	X

Vegetation development survey

The most structured and comprehensive vegetation development surveys were completed 13 (2013) and 24 (2023) years after the SWBE restoration project. For both the survey years of 2013 and 2023, traditional forest/shrub vegetation stand data, i.e., diameter at breast height, tree height, and plant species, for each tree were collected. Field surveys were conducted in a study area on the landslide site, roughly half of the total area (5000 m²). In addition to the forestry data of the stand, with the use of a GPS, the position of each tree and shrub was collected. Vegetation survey aims to assess the para-natural evolution of plant species in the landslide area. The first data collected refers to vegetation evolution observation over time, from the front side of the mountain (near the village of Stazzema), where the entire landslide area can be seen (Figure 3). This is useful for comparing the observed evolution with satellite data.



Figure 3. Time series of vegetation evolution (from 19 May 1998 to 19 September 2023). Along the timeline, we report the succession of plant species.

For that reason, a monitoring system of vegetation dynamics was conducted using the Normalised Vegetation Index (NDVI) to evaluate the vegetation recovery after the landslide [30]. The study of the NDVI index was completed through a script operated on the Google Earth Engine platform (GEE), where Landsat 05 and 07 satellites were used to evaluate the historical series of data in the landslide area. The NDVI values were subsequently processed by averaging the NDVI values for June, the month in which the landslide occurred. Furthermore, for the Mediterranean areas, in June, we tend to have the highest NDVI values [31], which is why we consider the average of this month as significant data for a synthetic comparison for a time series. NDVI calculation presents some issues, mainly because the resolution of the Landsat satellite is not very high about the shape and width of the landslide area. This is a long strip of land with lateral forest cover on both sides. In each pixel of 30 x 30 m, we have the

interference of lateral vegetation. However, at the time of the landslide, the Sentinel-2 data that provided some bands at 10 m resolution were not available and could not be used to reconstruct the time series.

Slope stability and root system analysis

The distribution of root systems is carried out through direct measurements by making localised excavations around the tree being measured (Figure 4). Thanks to this methodology, a summary parameter of the distribution, the root area ratio (RAR),

$$(1) RAR(Z) = \frac{Ar(z)}{Ars}$$

Is obtained from the ratio of roots area $Ar(z)$ at z depth and rooted soil area Ars . Through the $Ar(z)$ equation, other useful parameters can be derived for inclusion in slope stability estimation models. The b - factor is expressed in the formula:

$$(2) Ar(z) = Ar0 e^{\frac{-z}{b}}$$

Where $Ar0$ is the root area at $z = 0$ (extrapolated) and represents a scaling factor for $Ar(z)$, while b is the average rooting depth, the expected value of the plant's root depths as the average of a probability density function [26,27,32,33]. It is seen that the b factor is determined by climatic and pedological values in a water-limited ecosystem and that, simplifying, the ratio $1/b$ determines the average rooting depth. In the case study of Pomezzana, two trees were the subject of RAR measurement in 2013, and the other four trees were during this year's surveys; the procedure performed is the same as that applied in other works [26,34].

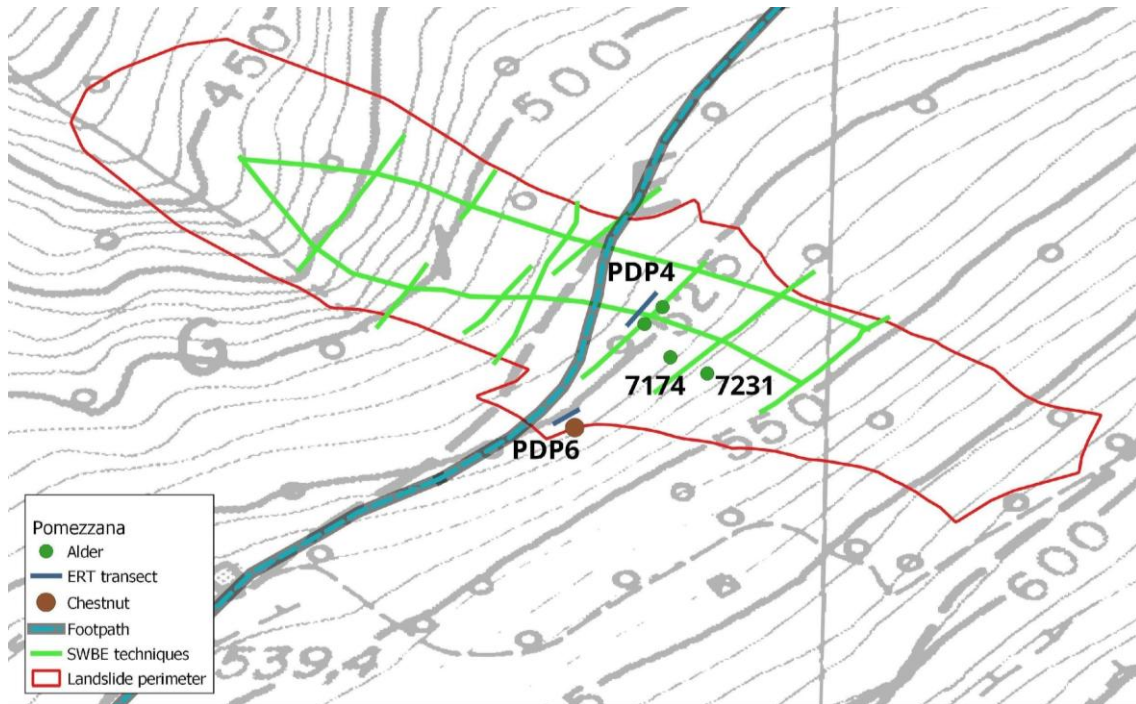


Figure 4: Outline of the 2013 surveys: location of survey points of RAR values and ERT geoelectric analysis.

In the 2013 survey, indirect techniques, using geophysical instruments, were tested to investigate an indirect methodology that could provide indications of the distribution of the root system in depth. The analysis of the geoelectrical tests is based on the processing of several vertical transects of conductivity values, obtaining the distribution of values at depth, following an exponential trend. Two geoelectrical resistivity tomographies (ERTs) were carried out, along two transects, which were going to intercept the root systems of two black Alders for the PDP4 profile and a Chestnut tree stump in PDP6. Each transect identifies a case study (Tree and No-Tree) and is made up of central and adjacent transects. The transect is chosen for the case study they identify, and the analysis includes almost the entire assessment of the electrical tomography portion. The electrical tomographies were carried out with a Polo-Dipole device, along a 4,8 m transect from 24 electrodes placed 20 cm apart. The measured apparent-resistivity data sets have been processed with the specific software RES2DINV c, by Geotomo Ltd. (Houston, TX, USA) [35,36]. The measured alders were part of the stand of para-natural origin, established on the landslide after the restoration works, while the Chestnut tree stump was already present before the landslide and was coppiced during the works. The comparison of these two cases is useful to understand whether the alders have root system development comparable with those of the neighbouring plants, which were not affected by the hydrogeological disruption.

3. Results

The multi-approach methodology for monitoring SWBE works presented attempts to bring together various techniques and protocols to evaluate the technical and vegetative effectiveness of interventions. Not having processed all the data together yet, the research focused on data from direct (Figure 5) and indirect surveys on the RAR and ERT root systems, conducted in 2013.



Figures 5: Images of the two explored root systems: plant 7174 on the (left) and the plant 7231 on the (right).

Root investigation: RAR is described according to how it is distributed in depth. The trend of RAR in depth follows a negative exponential curve due to its development in a semiarid water-limited environment [19]; deviation from the curve often occurs when the root system

encounters physical or chemical obstacles to its development, so it tends to develop an irregular architecture or flatten out in the more superficial layers.

As can be seen in the pictures in Figure 5, the root systems of the two Alder plants investigated have different morphology and development. Therefore, we have represented (Figure 6) a longitudinal section at the area central to the landslide body, where RAR analysis was carried out for plants 7231 and 7174 and ERT transect at the PDP4 point. Alder 7174 is located immediately downstream of the log crib wall, unlike 7231, which is positioned above the second set of log crib walls.

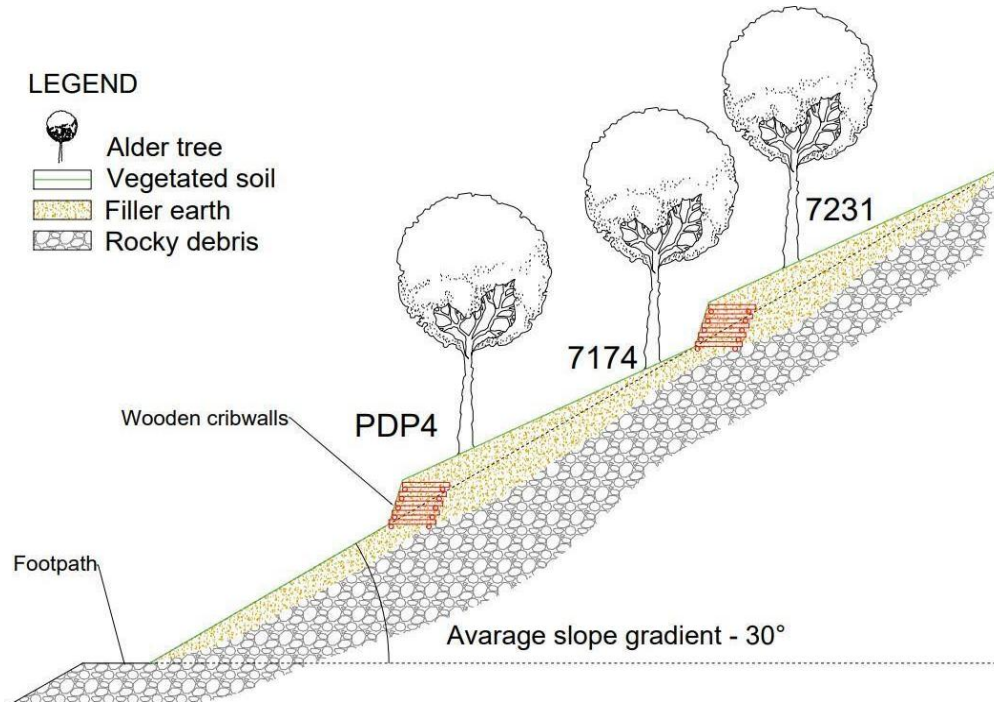


Figure 6. Longitudinal section scheme of the ERT and RAR trees distribution.

In Figure 7, the RAR values with soil depth show an exponential negative trend. In fact, for plant 7174, we find $R^2 = 0,8071$, while for 7231, we have $R^2 = 0,9226$. From the distribution, we find that the slope of the negative exponential is 0,054 and 0,011, respectively, which correspond to an average rooting depth (MRD) of -18 cm for plant 7174 and -90 cm for plant 7231 (Figure 5).

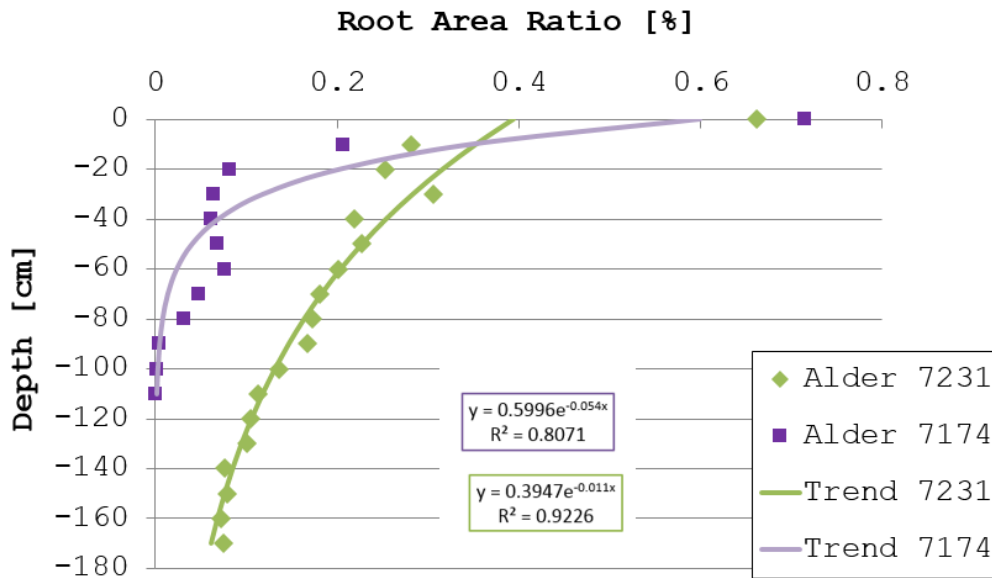


Figure 7: Percentage root area ratio for the two Alders explored.

By processing the data obtained from root system evaluation on Alder species, results show different root development between plants 7231 and 7174; root growth is influenced by the position of the plants (uphill and downhill) with respect to the SWBE wooden techniques [37]. From the trend of the exponential curves of the percentage values of RAR, it is possible to extract the values of the b-factor, with which, thanks to the correlation described in the studies of Preti et al., 2010, the average rooting depth (MRD) is derived. Plant 7174 appears to have a shallow root system, as it is placed at the crib wall foot where there appears to be less loose soil. In contrast, the roots of Alder 7231, being located above the crib wall went deeper, given a greater presence of loose filler earth. Therefore, we obtain for plant 7174 a b-factor value equal to $-0,054$, which corresponds to an MRD value of 19 cm; for the plant identified with 7231, the b-factor is equal to $-0,011$; therefore, the average root depth is approximately 90 cm. Also, in the ERT PDP4 analyses, the b-factor values obtained follow the value of plant 7231; the sampled alders also being placed above the log crib wall. Terraced slope reprofiling using SWBE techniques promotes deep-root system growth with positive effects on soil erosion and loss of organic matter.

Geophysical investigation. The results of geoelectric investigations are represented by a tomography for each transect, and it shows how ERT analysis can be considered a valid tool for monitoring vegetation root development, given the values in line with those obtained by RAR [38]. The graphical representation shows the distribution of soil resistivity in the PDP4 and the PDP6 transects (Figures 4 and 8).

Raw resistivity data collected in the field are processed (inversion); from these, it is possible to derive the conductivity of the medium investigated (reciprocal of resistivity). As demonstrated in another study [34], it is possible to estimate the distribution directly from

observation of conductivity trends at depth for resistive soils under dry conditions. Graphical data elaboration (Figures 9 and 10) shows where a tree is present (Alders and Chestnut coppice); the exponential trend fits well with a significance coefficient ($R^2 > 0,5$). On the other hand, where there are no trees, the exponential trend does not fit conductivity values, with low significant coefficients for PDP4 ($R^2 < 0,2$) and medium significance coefficients for PDP6 ($R^2 < 0,5$). Inverting the raw data gives us a resistivity/conductivity data matrix with a spatial resolution of approximately 7,5 cm (vertical) x 20 cm (horizontal). Corresponding to each plant investigated, we consider the central, left, and right vertical (Vert 1, 2, and 3) conductivity values and calculate the trend in depth to extract the angular coefficient of the exponential. It shows a very similar exponential trend between resistivity and rooted area (Ar), so conductivity values are considered Ar values, as seen in other research [26,39]. The same operation is carried out for the treeless portion of the transect analysed with geoelectrics.

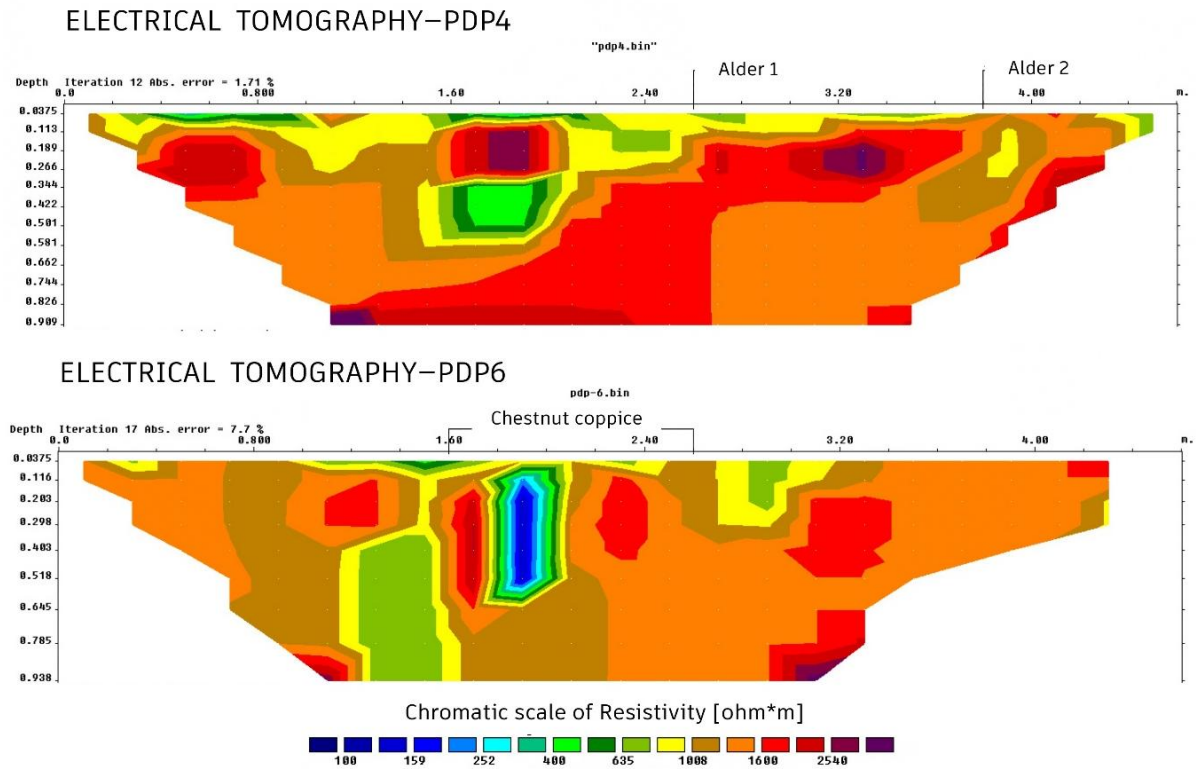


Figure 8. ERT: Electrical tomography graphical results for transect PDP-4 and transect PDP-6.

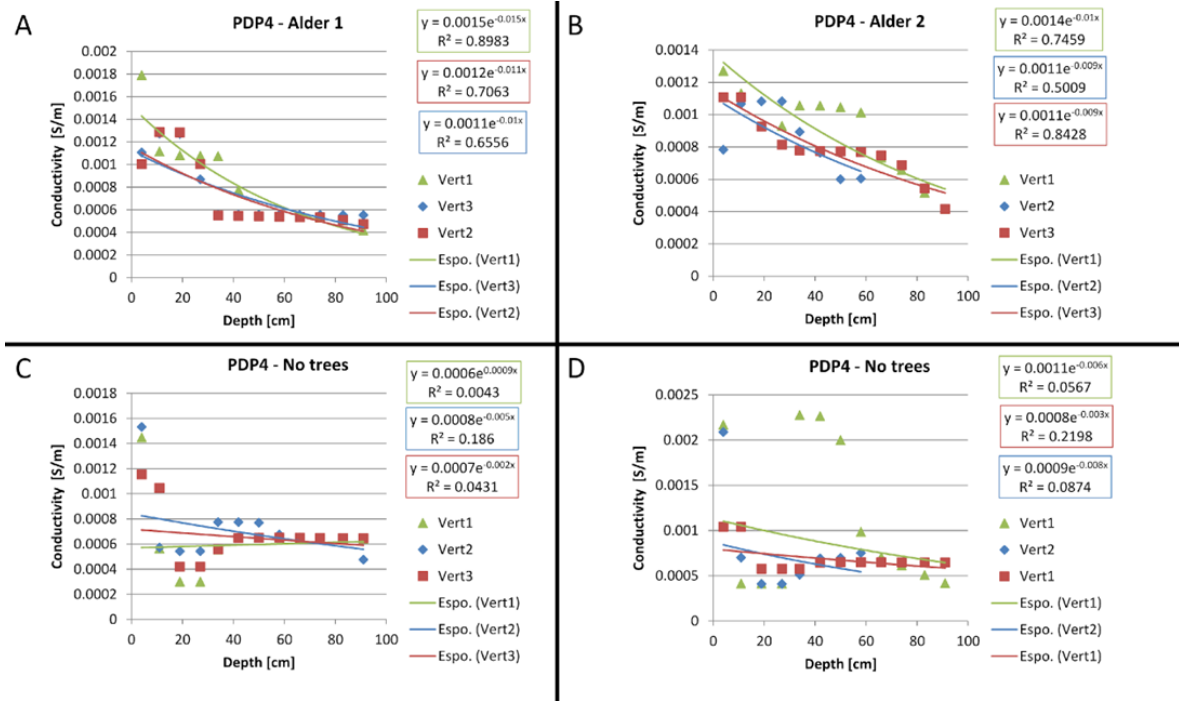


Figure 9. ERT graphical results in PDP-4: Correlation between conductivity and depth for Alder 1 (A) and Alder 2 (B). (C, D) The trend of conductivity values in depth in portions of the transect where there are no trees.

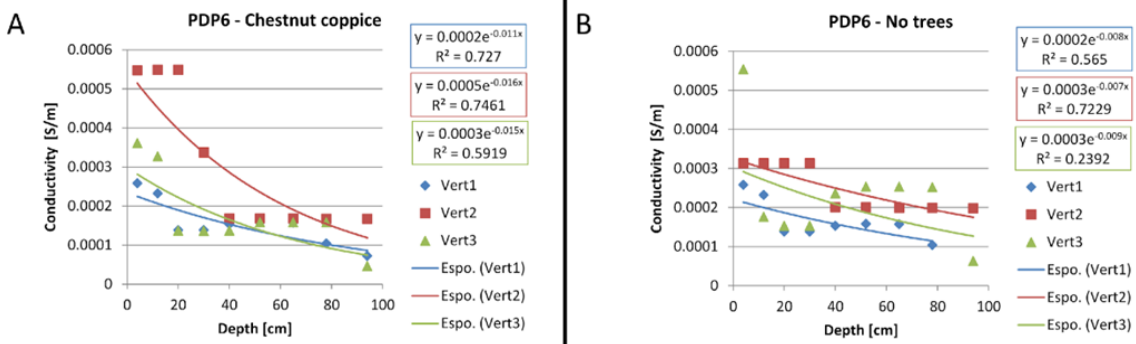


Figure 10: ERT graphical results in PDP-6. Correlation between conductivity and depth in Chestnut coppice (A) and no trees portion.

The conductivity (S/m) and depth (cm) relation can be verified from these graphs, in vegetated and non-vegetated conditions. The distribution of conductivity, correlated with RAR values, is well comparable with the distribution estimated by geoelectrical surveys when trees are present. With the electrical tomographs, it is evident that the depth distribution trends are significant and well comparable between the alders and the chestnut stump present before the disruption; b values (so MRD values) of Alder PDP4 are in accordance with b values of Alder 7231.

Vegetation evolution: The study of satellite images, considering the variation in NDVI values, allowed us to have an evolutionary trend recovery of the vegetation on the landslide, after the restoration work. Through NDVI processing, vegetation development is verified to be stopped when the landslide has occurred, and when remediation works are underway. Then, a para-natural succession was started without interruption and grew with a significative increase

in the highest value of the NDVI index. Plotting all NDVI data over time does not appreciate this trend well (Figure 11). The interference of lateral vegetation to the landslide area leads to noise, while this is shown by isolating only June data each year (Figure 12). From Figure 12, it is possible to note that 3 years after the landslide, thanks to the restoration work, the photosynthetic activities of vegetation are also higher than the one observed the years before the landslide occurred.

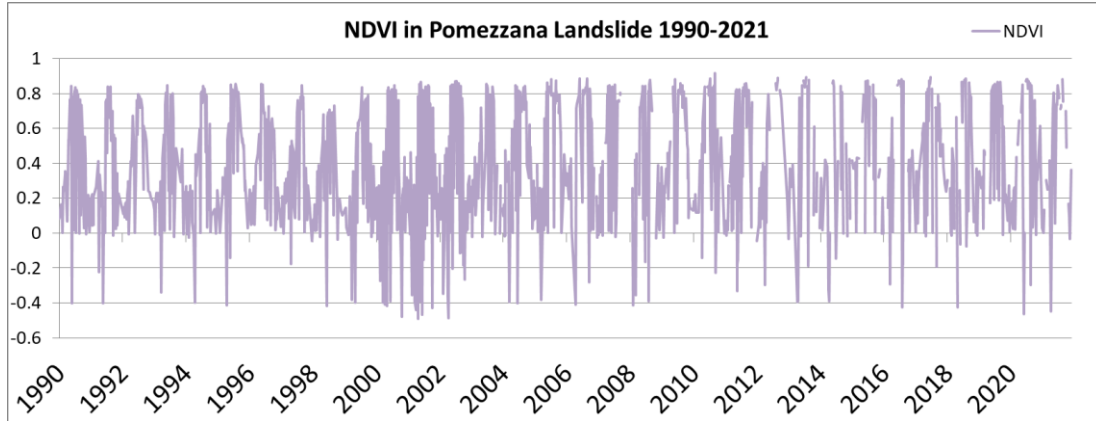


Figure 11: All NDVI data in the period observed.

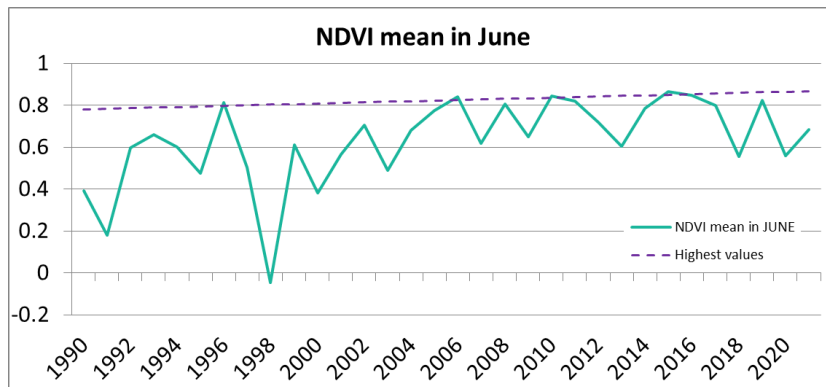


Figure 12: NDVI mean value of June of each year.

4. Discussion

The monitoring of bioengineering works for the restoration of collapsed slopes allows us to verify the effectiveness of the choices made in the design, realisation and execution phase. The multidisciplinary approach is necessary as these interventions are complex and involve experts and technicians with different knowledge. The restoration of a landslide must consider numerous elements such as soil characteristics, morphology, water regulation, vegetation development, structure-material natural degradation, and ecological and economic sustainability.

With this study, we present some of the first results obtained from innovative analyses and with an indirect approach (remote sensing and geophysical investigations) to observe the dynamics of vegetation evolution after the restoration works [38,40] and to verify the functionality of the intervention from an ecological point of view. The main results concern the elaboration

of the NDVI and the execution of geoelectrical tomography to verify the development of the vegetation, both the epigeal portion and the hypogeal portion (root distribution). The NDVI trend allows us to analyse the development of vegetation in terms of photosynthetic functionality. The results show that from the total absence of vegetation (average negative NDVI values), we quickly move to high values (0,8) with an increasing trend. This can be explained by the fact that herbaceous plants colonise the landslide, resulting in greater photosynthetic activity compared to the forest plants that were there before the landslide. Using indicators such as NDVI is promising, but since most of the time it is localised interventions in disturbed areas, the use of drones with specific sensors could be a solution for higher image resolution. Moreover, the results are consistent with what is observed in coppice-managed forests in Tuscany, where the same trend in vegetation recovery was observed following a cutting that can be assimilated with the para-natural landslide recovery [30].

Geoelectrical investigations prove to be a valid technique to indirectly analyse the root system of a tree, with estimated depth distribution values very close to the control values. From the results obtained, the root systems of the plants that have settled in the area subject to disruption are well-developed. When the thickness of the soil allows it, they are found to be even deeper than the neighbouring chestnut trees—this happens due to conflicts between the chestnut tree and the calcareous matrix of this territory [41]. Monitoring the evolution of root systems is important in assessing the effectiveness of SWBE interventions, even more so in the accommodation of mountain slopes with a strong propensity for falling. As we said at the beginning, the Apuan Alps are characterised by steep slopes and unstable soils, and it is in these geomorphological situations where soil erosion and slope stability need to be kept under control. Understanding the evolution of root systems over time, especially in areas restored with SWBE techniques, is important to understand the health of the vegetation and plan management interventions to maintain the work [42,43]. It was one of the first SWBE interventions in Tuscany to restore a large landslide; the implementation was effective and successful, without requiring any kind of supplementary intervention, but leaving the restored area to evolve naturally.

The measurements carried out and field analysis confirm that the stand of paranatural origin is developing normally and that the SWBE engineering intervention has made possible the spontaneous establishment of a tree stand, accelerating the ecological succession, thus quickly restoring the conditions before the hydrogeological disruption and ensuring a high functionality of the vegetation formation in terms of ecosystem services (biomass, CO₂ storage, soil protection, stormwater regulation, etc.). A direct technique (RAR) and an indirect technique (ERT) were chosen based on their use in monitoring bioengineering works: The former was chosen for its widespread use, while the latter was an already promising technique for assessing

geotechnical aspects of soil and roots [44]. Direct and indirect field surveys were completed to assess the technical characteristics and development of the root systems of the forest stand, both turned out to be valid methodologies for root monitoring, on which to deepen studies on their use depending on the various factors affecting root growth: vegetation type, soil, climate, morphology, etc. Although the results of indirect ERT analysis differ in some places from the RAR values obtained from direct surveys, we can assume that at transects, an ecohydrological anomaly (topsoil, plant species, adverse conditions, etc.) could influence the b-factor values, at least in our specific research experience.

As already pointed out in the results, the value of the b-factor, which influences the trend of exponential trend, turns out to be different for plant 7174 than for 7231, but also for the root development data obtained from ERT processing. The values obtained for plant 7174, b-factor 0,054 and MRD 18 cm, are justified by its position on the slope, as being at the foot of the log crib wall the loose filler earth is shallow. This results in a low average root depth value (about 20 cm) in contrast to the other plants, which all have b-factor values around 0,01, and are found to have average root depths of about 90 cm. From initial data processing on the latest RAR tests performed, b-factor values of about 0,035 (average root depth 30 cm) are found, which roughly correspond to the average b-factor values found in 2013. Considering ERT processing, the analysis verifies a good correlation between conductivity and depth according to a negative exponential trend; how values are distributed in depth is verified by observing the variability of the angular coefficient (factor b in logarithmic transformation $Ar(z) = e^{bz} \Rightarrow \ln(z) = bz$). In PDP4, below the Alders, the angular coefficient of the exponential trend is found around $-0,01$ (Max $-0,009$, Min $-0,015$) which is comparable with the exponential trend angular coefficient of distribution of 7231 Alder root system, measured by direct analysis (RAR). In PDP6, similar behaviour for the chestnut coppice is found; although in the “no-trees” case study, coefficients are similar to the root development values obtained by RAR direct tests.

As already pointed out in other research [26,45–48], RAR values have much variability depending on soil, depth, species, and local climatic conditions; in general, RAR decreases as depth increases [48,49]. As general considerations on vegetation root system monitoring techniques, it is also necessary to specify the limitations of these techniques, which would also need to be applied to other case studies and for other types of SWBE interventions. It would be interesting to evaluate the indirect ERT technique at other sites, how it varies according to the main variables (soil, species, and local climatic conditions), and how these influence the accuracy of the instrument. From the comparison between the two species examined, no significant differences, except for 7174 for microclimate differences, were seen in root system development, which, even in the second monitoring, are fully comparable with the chestnut stump

outside the landslide body, or anyway, the trend of b values indicates that the root system is developing by increasing soil cohesion. The results from root system surveys emphasise the key role played by natural vegetation development, which not only benefits the ecosystem but also increases slope stability.

5. Conclusions and Outlook

The para-natural succession started with the SWBE works in 1998, with the introduction of *Salix alba* cuttings, leading to a stable and well-developed topsoil. This is a fact that can be observed simply by visiting the place. With this study, we wanted to adopt innovative techniques for monitoring SWBE works to define and introduce analyses that could in the future translate into good practices for professionals and companies in the sector. We believe that the initial objectives have been achieved, as the techniques have shown the expected results, although it is essential to deepen and improve these techniques. The use of vegetation indices, such as NDVI, is a common practice in many sectors. Its application to the SWBE sector will allow the evolution of interventions to be monitored with benefits for possible maintenance, improvements, and forecasts. The use of geoelectric shows a high potential for evaluating the development of root systems, although this application is still not widespread. Soon, research will go into the monitoring of vegetation, and more generally the ecological processes promoted by SWBE techniques, and the monitoring of structures made of wood. The effects of NBSs on biodiversity and ecological evolution are still under-researched, but it is increasingly necessary to promote them as major techniques for climate change mitigation. On the other hand, we need to better understand the durability of the structures concerning the type of vegetation that develops during the restoration intervention. In conclusion, the data and considerations made in this research increase the knowledge on root area ratio in forest stands established on landslide areas recovered using Soil and Water Bioengineering techniques. The study also promotes a multi-approach monitoring methodology for forest hydraulic system interventions, which will surely be further explored in future projects. The research aims to promote the use of innovative techniques for monitoring bioengineering works, with the ultimate goal of helping to increase the effectiveness and performance of these techniques. Together, these innovative techniques have allowed us to verify the good progress of the para-natural succession and the technical efficiency of SWBE techniques.

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References

1. Kumar, R.; Devrani, R.; Dangwal, A.; Deshmukh, B.; Dutt, S. Extreme Hydrological Event-Induced Temporal Variation in Soil Erosion of the Assiganga River Basin, NW Himalaya. In *Advances in Remote Sensing Technology and the Three Poles*; Wiley: Hoboken, NJ, USA, 2022; pp. 230–246. [CrossRef]
2. Bischetti, G.B.; De Cesare, G.; Mickovski, S.B.; Rauch, H.P.; Schwarz, M.; Stangl, R. Design and temporal issues in Soil Bioengineering structures for the stabilisation of shallow soil movements. *Ecol. Eng.* 2021, 169, 106309. [CrossRef]
3. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 28 January 2024).
4. Available online: https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en (accessed on 2 February 2024).
5. Available online: https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en (accessed on 28 January 2024).
6. Available online: <https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/programmes/horizon> (accessed on 9 February 2024).
7. Available online: <https://www.biodiversa.eu/> (accessed on 10 February 2024).

8. Debele, S.E.; Leo, L.S.; Kumar, P.; Sahani, J.; Ommer, J.; Bucchignani, E.; Vranić, S.; Kalas, M.; Amirzada, Z.; Pavlova, I.; et al. Nature-based solutions can help reduce the impact of natural hazards: A global analysis of NBS case studies. *Sci. Total Environ.* 2023, 902, 165824. [CrossRef]
9. Rauch, H.P.; von der Thannen, M.; Raymond, P.; Mira, E.; Evette, A. Ecological challenges* for the use of soil and water bioengineering techniques in river and coastal engineering projects. *Ecol. Eng.* 2022, 176, 106539. [CrossRef]
10. Giupponi, L.; Bischetti, G.B.; Giorgi, A. A proposal for assessing the success of soil bioengineering work by analysing vegetation: Results of two case studies in the Italian Alps. *Landsc. Ecol. Eng.* 2017, 13, 305–318. [CrossRef]
11. Giupponi, L.; Borgonovo, G.; Giorgi, A.; Bischetti, G.B. How to renew soil bioengineering for slope stabilization: Some proposals. *Landsc. Ecol. Eng.* 2019, 15, 37–50. [CrossRef]
12. Rey, F.; Bifulco, C.; Bischetti, G.B.; Bourrier, F.; De Cesare, G.; Florineth, F.; Graf, F.; Marden, M.; Mickovski, S.B.; Phillips, C.; et al. Soil and water bioengineering: Practice and research needs for reconciling natural hazard control and ecological restoration. *Sci. Total Environ.* 2019, 648, 1210–1218. [CrossRef]
13. Mickovski, S.B.; Waterlot, C. Sustainability Re-Thinking Soil Bioengineering to Address Climate Change Challenges. *Sustainability* 2021, 6, 3338. [CrossRef]
14. Mickovski, S.B.; Gonzalez-Ollauri, A.; Thomson, C.; Gallagher, C.; Tardio, G. Assessment of the Sustainability Performance of Eco-Engineering Measures in the Mediterranean Region. *Land* 2022, 11, 533. [CrossRef]
15. Vianna, V.F.; Fleury, M.P.; Menezes, G.B.; Coelho, A.T.; Bueno, C.; Lins da Silva, J.; Luz, M.P. Bioengineering techniques adopted for controlling riverbanks' superficial erosion of the Simplicio Hydroelectric Power Plant, Brazil. *Sustainability* 2020, 12, 7886. [CrossRef]
16. Associazione Italiana per l'Ingegneria Naturalistica. Manuale IN 2.0: Innovazioni in Ingegneria Naturalistica; Collana Fiumi e Territorio—Regione Toscana; Associazione Italiana per l'Ingegneria Naturalistica: Trieste, Italy, 2022; Volume 1.
17. Florineth, F. *Pflanzen Statt Beton: Sicherer und Gestalten Mit Pflanzen*, 2nd ed.; Hannover: Berlin, Germany, 2012.
18. Lazio, R. *Manuale di Ingegneria Naturalistica: Sistemazione dei Versanti*. Roma: Assessorato all'Ambiente e Cooperazione tra i popoli Direzione Regionale Ambiente e Cooperazione tra i popoli. 2006. Available online: https://www.aipin.it/wp-content/uploads/2020/10/Manuale_Lazio_Vol-3_versanti_compressed2.pdf (accessed on 22 January 2024).
19. Ormerod, S.; Schiechl, H.M.; Stern, R. Water Bioengineering Techniques for Watercourse, Bank and Shoreline Protection. *J. Appl. Ecol.* 1997, 34, 1110. [CrossRef]
20. Stokes, A.; Douglas, G.B.; Fourcaud, T.; Giadrossich, F.; Gillies, C.; Hubble, T.; Kim, J.H.; Loades, K.W.; Mao, Z.; McIvor, I.J.; et al. Ecological mitigation of hillslope instability: Ten key issues facing researchers and practitioners. *Plant Soil* 2014, 377, 1–23. [CrossRef]
21. Zaimes, G.N.; Tardio, G.; Iakovoglou, V.; Gimenez, M.; Luis Garcia-Rodriguez, J.; Sangalli, P. New tools and approaches to promote soil and water bioengineering in the Mediterranean. *Sci. Total Environ.* 2019, 693, 133677. [CrossRef]

22. Mickovski, S.B.; Wallace, M.; Papic, J.B.; Simeonovski, I. Modelling and monitoring behavior of vegetated slopes in variable weather conditions. In *Smart Geotechnics for Smart Societies*; CRC Press: Boca Raton, FL, USA, 2023; pp. 1876–1880. [CrossRef]
23. Sorolla, A.; Piera, E.; Mota-Freixas, B.; Sorolla Salvans, G.; Rueda, I.; Lochner Prats, A.; Unzeta, C. Improvement of the plantation success in a crib wall in a mediterranean hydro-meteorological risks scenario—Practical results. *Sustainability* 2021, 13, 11785. [CrossRef]
24. Gonzalez-Ollauri, A.; Hudek, C.; Mickovski, S.B.; Viglietti, D.; Ceretto, N.; Freppaz, M. Describing the vertical root distribution of alpine plants with simple climate, soil, and plant attributes. *Catena* 2021, 203, 105305. [CrossRef]
25. Tardío, G.; González-Ollauri, A.; Mickovski, S.B. A non-invasive preferential root distribution analysis methodology from a slope stability approach. *Ecol. Eng.* 2016, 97, 46–57. [CrossRef]
26. Preti, F.; Dani, A.; Laio, F. Root profile assessment by means of hydrological, pedological and above-ground vegetation information for bio-engineering purposes. *Ecol. Eng.* 2010, 36, 305–316. [CrossRef]
27. Laio, F.; D’Odorico, P.; Ridolfi, L. An analytical model to relate the vertical root distribution to climate and soil properties. *Geophys. Res. Lett.* 2006, 33, L18401. [CrossRef]
28. Barbati, A.; Marchetti, M.; Chirici, G.; Corona, P. European Forest Types and Forest Europe SFM indicators: Tools for monitoring progress on forest biodiversity conservation. *For. Ecol. Manag.* 2014, 321, 145–157. [CrossRef]
29. Guastini, E.; Preti, F.; Dani, A. Living Part on Soil Bioengineering Structures in Appennino Tosco-Emiliano; EGU General Assembly: Wien, Austria, 2014.
30. Chirici, G.; Giannetti, F.; Mazza, E.; Francini, S.; Travaglini, D.; Pegna, R.; White, J.C. Monitoring clearcutting and subsequent rapid recovery in Mediterranean coppice forests with Landsat time series. *Ann. For. Sci.* 2020, 77, 40. [CrossRef]
31. Maselli, F.; Amparo Gilabert, M.; Conese, C. Integration of High and Low Resolution NDVI Data for Monitoring Vegetation in Mediterranean Environments. *Remote Sens. Environ.* 1998, 63, 208–218. [CrossRef]
32. Arnone, E.; Caracciolo, D.; Noto, L.V.; Preti, F.; Bras, R.L. Modeling the hydrological and mechanical effect of roots on shallow landslides. *Water Resour. Res.* 2016, 52, 8590–8612. [CrossRef]
33. Gonzalez-Ollauri, A.; Mickovski, S.B. Plant-soil reinforcement response under different soil hydrological regimes. *Geoderma* 2017, 285, 141–150. [CrossRef]
34. Battista Bischetti, G.; Antonio Chiaradia, E.; Epis, T.; Morlotti, E. Root cohesion of forest species in the Italian Alps. *Plant Soil* 2009, 324, 71–89. [CrossRef]
35. Hojat, A.; Arosio, D.; Ivanov, V.I.; Loke, M.H.; Longoni, L.; Papini, M.; Tresoldi, G.; Zanzi, L. Quantifying seasonal 3D effects for a permanent electrical resistivity tomography monitoring system along the embankment of an irrigation canal. *Near Surf. Geophys.* 2020, 18, 427–443. [CrossRef]
36. Hruška, J.; Kuda, F.; Holík, L.; Vranová, V. Assessment of slope stability on logged forest-hill slopes using ground-penetrating radar and electrical resistivity tomography. *Geol. J.* 2023, 58, 247–263. [CrossRef]

37. Tron, S.; Dani, A.; Laio, F.; Preti, F.; Ridolfi, L. Mean root depth estimation at landslide slopes. *Ecol. Eng.* 2014, 69, 118–125. [CrossRef]
38. Giambastiani, Y.; Errico, A.; Preti, F.; Guastini, E.; Censini, G. Indirect root distribution characterization using electrical resistivity tomography in different soil conditions. *Urban For. Urban Green.* 2022, 67, 127442. [CrossRef]
39. Mattia, C.; Bischetti, G.B.; Gentile, F. Biotechnical characteristics of root systems of typical Mediterranean species. *Plant Soil* 2005, 278, 23–32. [CrossRef]
40. Forzieri, G.; Guarnieri, L.; Vivoni, E.R.; Castelli, F.; Preti, F. Spectral-ALS data fusion for different roughness parameterizations of forested floodplains. *River Res. Appl.* 2011, 27, 826–840. [CrossRef]
41. D’Amato Avanzi, G.; Giannecchini, R.; Puccinelli, A. The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: The June 19, 1996 event in northwestern Tuscany (Italy). *Eng. Geol.* 2004, 73, 215–228. [CrossRef]
42. Zhang, H.; Zhao, Z.; Ma, G.; Sun, L. Quantitative evaluation of soil anti-erodibility in riverbank slope remediated with nature-based soil bioengineering in Liaohe River, Northeast China. *Ecol. Eng.* 2020, 151, 105840. [CrossRef]
43. Zhang, Z.; Cao, L.; Zhu, Z.; He, C.; Xiang, H.; Xu, L.; Sun, C.; Lin, C.; Yang, H.; Li, K. Evaluation on soil bioengineering measures in agricultural areas: Poorer durability of wooden structures and better aboveground habitat improvements. *Ecol. Eng.* 2019, 129, 1–10. [CrossRef]
44. Delgado-Gonzalez, L.; Forquet, N.; Choubert, J.M.; Boutin, C.; Moreau, M.; Moreau, S.; Clement, R. Flow path monitoring by discontinuous time-lapse ERT: An application to survey relationships between secondary effluent infiltration and roots distribution. *J. Environ. Manag.* 2023, 326, 116839. [CrossRef]
45. Bischetti, G.B.; Chiaradia, E.A.; Simonato, T.; Speziali, B.; Vitali, B.; Vullo, P.; Zocco, A. Root strength and root area ratio of forest species in Lombardy (Northern Italy). *Plant Soil* 2005, 278, 11–22. [CrossRef]
46. Schmidt, K.M.; Roering, J.J.; Stock, J.D.; Dietrich, W.E.; Montgomery, D.R.; Schaub, T. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. *Can. Geotech. J.* 2001, 38, 995–1024. [CrossRef]
47. Marzini, L.; D’Addario, E.; Papasidero, M.P.; Chianucci, F.; Disperati, L. Influence of Root Reinforcement on Shallow Landslide Distribution: A Case Study in Garfagnana (Northern Tuscany, Italy). *Geosciences* 2023, 13, 326. [CrossRef]
48. Chiaradia, E.A.; Vergani, C.; Bischetti, G.B. Evaluation of the effects of three European forest types on slope stability by field and probabilistic analyses and their implications for forest management. *For. Ecol. Manag.* 2016, 370, 114–129. [CrossRef]
49. Giadrossich, F.; Cohen, D.; Schwarz, M.; Ganga, A.; Marrosu, R.; Pirastru, M.; Capra, G.F. Large roots dominate the contribution of trees to slope stability. *Earth Surf. Process Landf.* 2019, 44, 1602–1609. [CrossRef]

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Slope stability time evolution of a shallow landslide restored by Soil and Water Bioengineering (SWBE) techniques: A case study in Northwest Tuscany (Italy)

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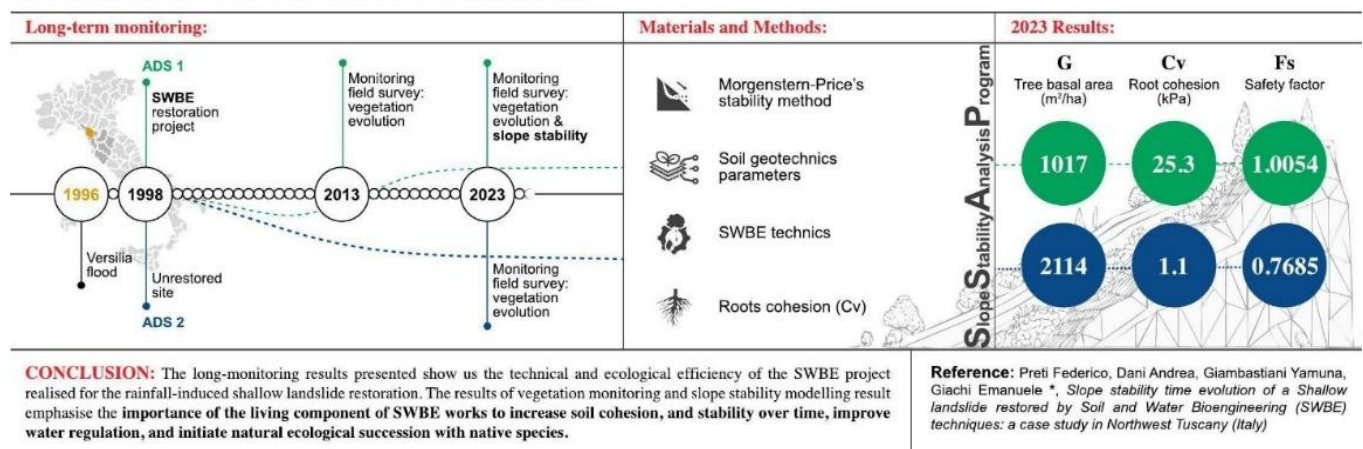
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Graphical Abstract:

Soil and Water BioEngineering (SWBE) effects on slope stability A site-specific study in northwest Tuscany (Italy)



Abstract

The well-known extreme flood event occurred on 19 June 1996 in Versilia, north-western Tuscany, Italy, causing an impressive number of landslides and debris flows, dramatic floods and 15 fatalities. The Tuscany Region financed Soil and Water Bioengineering (SWBE) interventions to restore slope stability and mitigate soil erosion. The Pomezzana landslide was the greatest one restored by such kind of Nature-Based Solutions (NBS) in 1998, applied in Tuscany for the first time.

The study presents the 2023 landslide monitoring surveys, concerning the vegetation evolution state and the slope stability conditions of two different situations: AdS1-SWBE restored landslide and AdS2-unrestored landslide. The root systems of the main tree species present (chestnut, alder, and hornbeam) have been characterised and used to evaluate the effects of vegetation on slope stability according to the historical monitoring 1998–2013–2023.

The Root Area Ratio (RAR) values obtained in the field, and therefore soil cohesion values, also considering the deterioration of the wooden crib wall, drove us to calculate the Factor of Safety (FS) through SSAP 2010™ software. Various scenarios of slope stability were evaluated with the infiltration depth obtained with the landslide back analysis, with the event rainfall, obtaining the time evolution of the slope stability. The study confirms the technical effectiveness of the slope stabilisation of the SWBE interventions, as in the restoration of superficial landslides triggered by rainfall, the research also shows the positive effects of vegetation evolution over slope stability and ecological succession, triggering natural native species succession with increasing soil reinforcement. The results show the SWBE restoration project hastened the slope stabilisation process through the combination of vegetation development and SWBE techniques.

1. Introduction

Landslides are natural phenomena of soil and/or rock movement on slopes, occurring when instability forces exceed the stability ones. The main reason for shallow landslides is excessive water infiltration caused by intense rainfall events, combined with soil water accumulation. Globally, these phenomena are also considered among the main causes of soil and organic matter loss (Sidle and Bogaard, 2016; Walker and Shiels, 2013). At the same time, the actual trend of climate change increases the occurrence of intense or extreme hydrometeorological events that significantly damage the environment and the territory and consequently human infrastructures near the slopes or floodable areas (Igwe and Una, 2019). These phenomena cause significant damage to ecological processes and potential biodiversity, mainly affecting the first states of the soil, rich in organic material, nutrients, and soil microorganisms. The landscape is more susceptible to extreme events, also exacerbated by the change in land use and management practices, especially in fragile territories such as agricultural and forestry areas; the abandonment of these areas has meant the loss of widespread management of the territory, in particular, the water and vegetation management (e.g. dry-stone walls, channels, drains, drainages, etc.) which were of fundamental importance in areas subject to instability (Tarolli et al., 2014). Shallow landslide phenomena are linked to the effect of intense rainfall events on usually unsaturated soils often related to hydrological conditions present, also accentuated by the almost total absence of vegetation management and monitoring in the areas (Gonzalez-Ollauri and Mickovski, 2017; Miele et al., 2021).

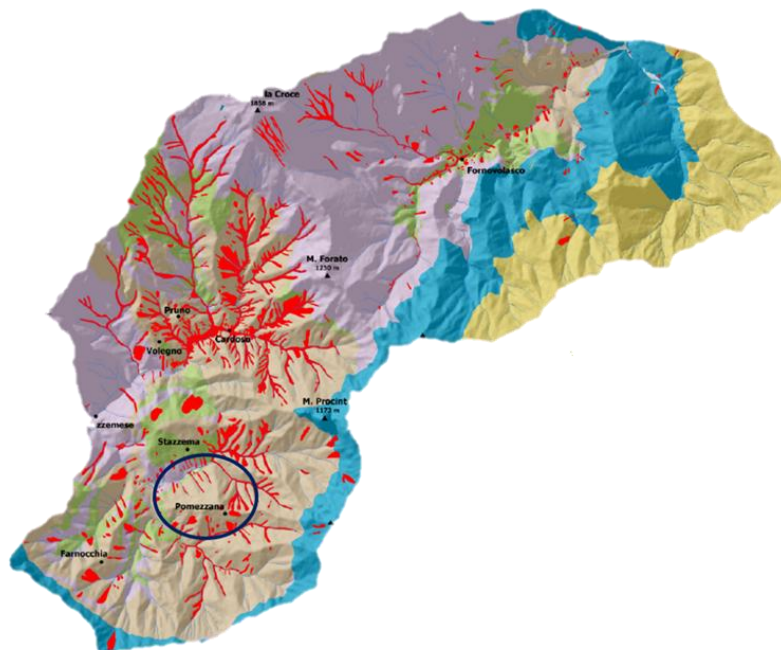


Figure 1: Landslide map of the Versilia flood event in 1996. The black circle indicates the geographical study area between the Stazzema and Pomezana villages (Apuan Alps Park and Toscana Region).

Nature-based solutions (NBS) are technical solutions to reconstitute the naturalness of places, increasing biodiversity and supporting ecosystem services (Debele et al., 2023). The use of NBS solutions, in particular the use of plants as building material in engineering structures meets society's growing demand for more environmentally friendly approaches in the design of structures; greater attention to the environment also reflects the desire for financing plans and European practices to promote green policies, as well as at a global level with the Global Goals for Sustainable Development (Fernandes and Guiomar, 2018; Ruangpan et al., 2019). The greater environmental awareness and the promotion of NBS projects have also seen a worldwide diffusion and knowledge of Soil and Water Bioengineering (SWBE) techniques, which have been studied and applied for the restoration of landscapes and territories long before the definition of NBS (Federico Preti et al., 2022). SWBEs are technical solutions that are part of ecological engineering and can provide nature-based solutions as alternative or complementary measures to the traditional or hydraulic engineering approach (Bischetti et al., 2021). SWBEs use plants as a building material in combination with inert materials (wood and stones), to make the most of the multifunctionality of plants and in the mitigation of natural risks. These techniques, in addition to performing a technical and landscape function, are effective in promoting ecological processes, low cost of implementation and socio-cultural function, always linked to the aspect of preservation of the natural territory. There are numerous examples of ecological engineering techniques designed and implemented for the recovery of landslides on slopes, but also in freshwater environments (Andreu et al., 2008; Böll et al., 2009; Burri et al., 2009; Cavaillé et al., 2015). Many recent studies have focused on the design performance of SWBE structures, trying to consider the multifunctionality of the work through an interdisciplinary methodology (Janssen et al., 2019; Kettenhuber et al., 2023).

Despite the growing importance of SWBE techniques worldwide, it is necessary to reconcile natural hazard control and ecological restoration by posing new applied research questions and, in particular: considering a multidisciplinary approach, establishing practical guidelines for designing SWBEs, implementing monitoring phases in bioengineering projects, analysing existing SWBE works in terms of performance, successes and failures (Mickovski et al., 2022; Rey et al., 2019; Stokes et al., 2014). Since SWBE techniques work with degradable and living materials, monitoring of the two main components is necessary; the wood used for structures deteriorates and decreases its resistance over time. On the other hand, plants propagate and increase their root system, creating favourable conditions for the growth of biodiversity in a pseudo-natural evolution; the growth of the root system increases the resistance and cohesion of the soil over time (DiBiagio et al., 2024; Preti et al., 2010). Eco-engineering measures are considered nature-based technical solutions capable of providing multiple benefits for

sustainability: from land restoration limiting soil erosion in the short term, and stabilisation due to root systems in the long term (Mickovski and Thomson, 2017; Qin et al., 2022). The biological and ecological aspects linked to the implementation of SWBE techniques have been studied for a long time, particularly regarding the choice of plants, best planting periods, and the effectiveness of the root systems on soil stability (Evette et al., 2011; Fattet et al., 2011; Giupponi et al., 2017; Zaimes et al., 2019). Scientific insights into the long-term effects of vegetation development in SWBE interventions are lacking regarding technical aspects of slope stability, as well as environmental issues regarding ecological restoration in the intervention sites (Rauch et al., 2022). The scientific gap addressed in this study involves demonstrating that the paratural succession of vegetation initiated by SWBE techniques is essential for achieving slope stability and contributing to forest renaturalization. Additionally, this work aims to present an investigative methodology that serves as a preparatory step for the comprehensive monitoring of analogous cases, contingent on the boundary conditions at the initial time (t_0).

The present study aims to analyse the functional and ecological temporal evolution of a SWBE-restored slope and to define a survey methodology in a specific case study. Investigations were conducted in the Versilia catchment (Pomezzana, north-western Tuscany), where an extreme meteorological event occurred in 1996, in two different sites: AdS1 a SWBE restored landslide and AdS2 a naturally evolved/unrestored landslide. The vegetation surveys and the SWBE interventions were carried out in two years, 2013 and 2023 respectively, allowing us to have a time series of 25 years (NBS intervention realised in 1998) from the restoration of the shallow landslide. Long-term monitoring has permitted us to have historical data for an in-depth knowledge of the area, thus compared also to a non-restored similar situation. The sampling carried out included: forest dendrometric parameters to quantify the growth rates of the forest, soil sampling for geotechniques characterisation, and study of the root systems of the most significant tree species (Chestnut, Alder, and Hornbeam). The Root Area Ratio (RAR) values, obtained from the analysis of the root systems with a simplified method together with the soil characteristics, were used to identify the soil cohesion values at various depths.

Residual Mechanical log strength in live wooden crib walls has been used for residual efficiency evaluation in the stability degree of the slope; this last was calculated by methods of the safety factor F_s , based on the Limit Equilibrium Method (LEM) verification techniques (Deng et al., 2017; Murgia et al., 2022).

The objective of the research is long-term monitoring and modelling of SWBE efficiency at slope scale with a multidisciplinary approach, by 1) monitoring the present vegetation; 2) verifying the evolution of the SWBE works carried out for the restoration of the landslide slope; 3) evaluate the temporal evolution of the slope stability factor in different scenarios. The study

tests the slope stability of the different scenarios, assuming a rainfall event comparable to the one that occurred in 1996 with a measured rainfall intensity of 478 mm/12 h (Tr 300 years). Field survey data elaboration permits us to implement back analysis for slope stability analysis.

2. *Materials and methods*

2.1 *Study site*

An extreme meteorological event occurred in northwestern Tuscany in June 1996. The extreme event particularly affected the municipalities of Stazzema and Saravezza (Lucca province), concentrated in an area of approximately 150 km² had a maximum intensity recorded of 478 mm recorded in 12 h with a maximum rate of 158 mm/h in the Pomezzana village area (Preti et al., 1999). The rainfall event was classified with a return time greater than 100 years, up to 300–550 years, and was the first convective supercell (or “v-shaped” storm) recognised in Italy. The scale of the event, in addition to causing extensive damage to inhabited areas (Cardoso and Fornovolasco), triggered numerous shallow landslides (Fig. 1), debris flows and flooding in various waterways (D’Amato Avanzi and Giannecchini, 2003).

Most landslide phenomena can be traced back to linear translational flow phenomena, which developed in partially saturated flows or waterlogged materials, to which the linear erosive action of watercourses in river courses and the slope runoff action must be added. The exceptional rainfall intensity on the ground deposits and saturated soils led to the development of debris flows. In the Pomezzana study area, an important triggering factor for landslides was impermeable rock outcrops (metasandstone, siltstone and phyllite) that promote hydric saturation of the soil from the first layers of soil. These instabilities mainly affected less than 3 m depths on slopes with an inclination up to 35°, localized on Pseudomacigno formation soil (D’Amato Avanzi and Giannecchini, 2003; Giannecchini and Avanzi, 2012). The landslides investigated in the present study are in Pomezzana and are included in the municipality of Stazzema (LU) (latitude: 43°98′78.36″ N, longitude: 10°31′47.41″E). It is approximately 200 m long and 70 m wide, covering an approximate surface area of 1,3 ha; more detailed information about the study sites in Giachi et al., 2024. The study site is located between 450 and 600 m.a.s.l. with a North-West exposure, and the slope is on average 65 %. A naturally evolved landslide, that occurred in the same event, was identified on the same slope to have comparable data on natural vegetation evolution compared with the restored one (Fig. 2).

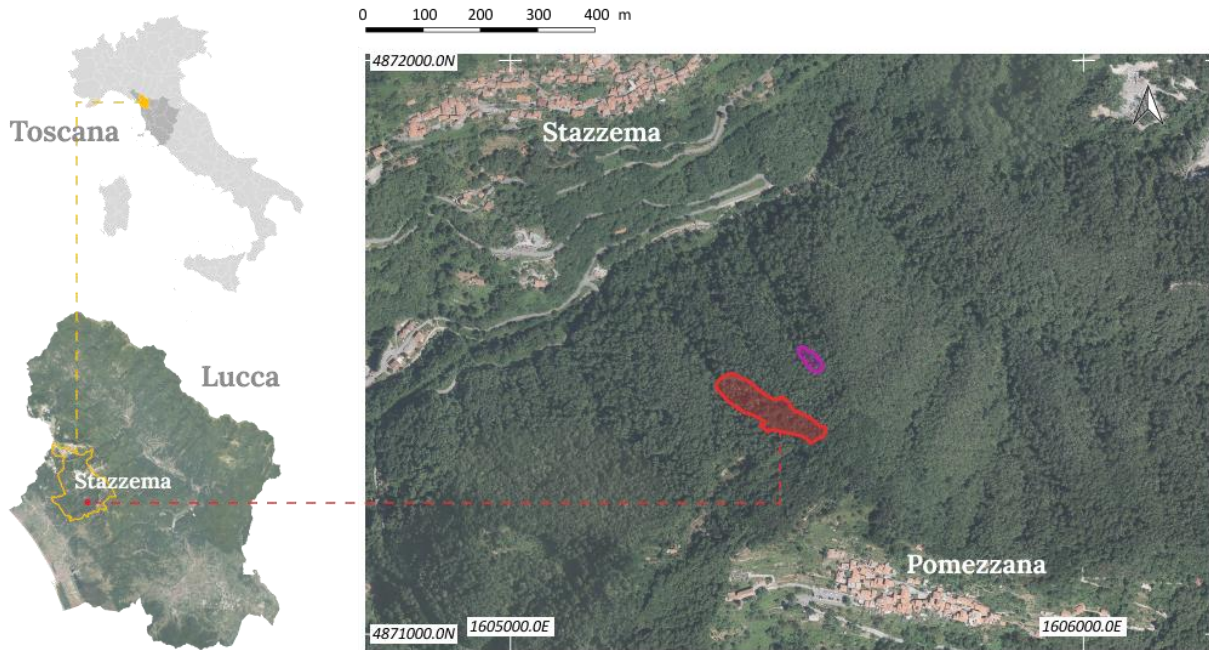


Figure 2: Location of the study site. In red AdS1-SWBE Restored landslide; in violet-AdS2-Unrestored landslide. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The study site belongs to Apuan Alps Regional Natural Park. Before the landslide occurred, forest type was, according to the classes of European forests: Class 8: Thermophilic deciduous forest, typology 8.7 “Chestnut Forests” and still cultivated until the 80s in the last century. Locally the average slope is 65 %, North-West exposure and belongs to a 0,06 km² catchment (20 % of total area). The site is characterised by a Pseudomacigno formation, with sandy/loamy soil (Soil cohesion C_s is 5–15 kPa).

The slope arrangement intervention, realised in 1998–99, permits correct water runoff management, thanks to the terracement and realisation of live crib-wall and ditches, that break slope continuity and control the erosion process. The landslide restoration in Pomezzana was possible due to the exceptional public financing within the natural park area and used various Soil and Water BioEngineering (SWBE) techniques including double live wooden crib walls with willow cuttings, live palisades, wooden and stone ditches, and hydroseeding. The SWBE project was useful to stabilise the collapsed slope and regulate slope water runoff and in-site naturalization (Fig. 3).

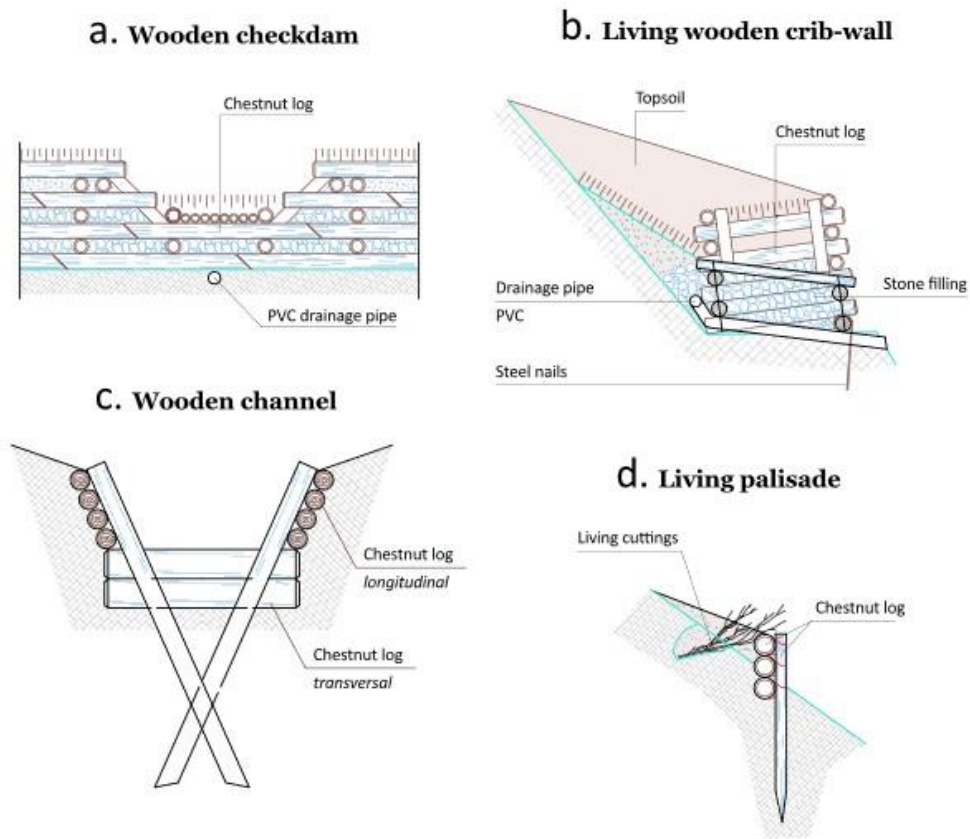


Figure 3: SWBE techniques were implemented in 1998/99 to restore the rainfall-induced shallow landslide (from the technical design of Arch. Bonaldi, 1997/99).



Figure 4: Live wooden crib wall during a 2023 field survey (pH. Emanuele Giachi)

The live wooden crib walls were made with chestnut logs and filled with soil, earth, and stones (Fig. 4); cuttings of *Salix purpurea*, *S. eleagnos*, and *S. triandra*, endemic plants found locally along the streams were then used in the structure (10 plants/m) to allow a fast soil cover and trigger a natural evolution of vegetation (mandatory requirements by the park authority). In the years following the landslide restoration, the vegetation, mainly composed of *Salix* spp., was already fulfilling its soil-protective and stabilisation function. Monitoring surveys from the early 2000s (Fig. 5) showed a gradual shift from willow to naturally renewed plant species (Alder and Hornbeam). The same monitoring methodology has been applied in the naturally evolved landslide for vegetation field survey.



Figure 5: Pomezzana landslide evolution over time.

2.2. Vegetation field survey

The surveys carried out in 2023 on the naturally evolving landslide (AdS2) also allow us to assess how the vegetation cover of the landslide would have been if the SWBE restoration had not been carried out. In 2023, the same vegetation analysis was then conducted in 2 study areas: AdS1-SWBE Restored landslide, and AdS2-Unrestored/naturally evolved landslide. In AdS1, a complete vegetation survey (arboreal and shrub component) was carried out within the representative study area of 5000 m² (38 % of total landslide surface) same forestry survey was conducted in 2013 (Errico et al., 2014; Giachi et al., 2024; Hofmann et al., 2015) and 2023, to evaluate temporal evolution of ecological process and species composition. Since the landslide was of considerable size, we conducted field surveys on 0,5 ha, considered a representative area for the type of vegetation that ecological engineering works on; the study area was the same in both the 2013 and 2023 field surveys (Fig. 6).

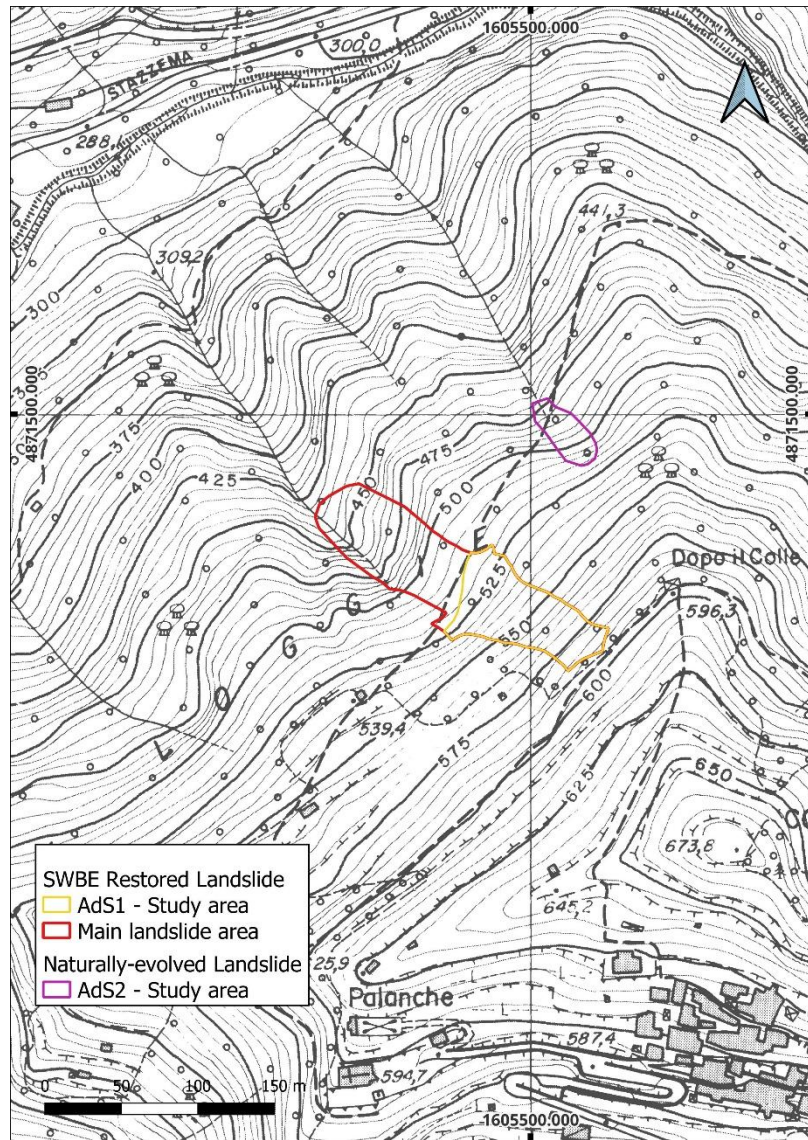


Figure 6: Pomezzana study areas: AdS1 field survey and sampling were made in 5000 m² representative areas; the AdS2 field survey was conducted on the entire surface (around 500 m²) of the naturally evolved landslide.

In AdS2, the same vegetation survey was performed on the naturally evolved landslide site at 500 m² (45 % of landslide surface) vegetation species and age have been detected in all the area because of its smaller dimensions. (Fig. 6). AdS1 and AdS2 field surveys have been conducted to make comprehensive forest vegetation monitoring; we derive values for the number of plants and the tree basal area per hectare, which allows us to make a feasible comparison between the two. The main comparative parameter used is tree basal area (G), which represents the sum of the areas occupied by the logs per unit area (ha), measured using the circle formula, where the diameter equals the average plant diameter at 1,30 cm height (DBHm).

The breast height diameters (DBH) of all individuals and the average height of the stand have been measured for tree and shrub species. For the arboreal and shrubby component, DBH of all the plants present, GPS position, height and average age were measured for the three most representative species: *Alnus incana*, *Castanea sativa*, *Ostrya carpinifolia*. For growth rating

curve analysis, tree age has been measured with Pressler's gimlet on the 3 most representative species Alder, Hornbeam and Chestnut.

Ads2 was chosen to be comparable with Ads1 taking into consideration the natural vegetation of surrounding areas. This is fundamental for the natural revegetation process: due to the principal plant propagation system of the arboreal plant, by seeds, it is mandatory to have surrounding vegetation, slope, exposition, quote, and comparable can suppose analogy in vegetation developing process. Other unrestored areas have been surveyed but with unequivocal differences in the seedling process (e.g. areas with black locusts, are almost absent in AdS1 and AdS2 areas).

For a complete characterisation of the slope vegetation, the growth of the root systems was also investigated to assess root cohesion; given the conditions of the study site, surveys were carried out on the three most prevalent species, as indicated by the tree species surveys. The Root Area $Ar(z)$ of the main species has been measured by excavating 60-70 cm of soil to the tree bases (Fig. 7). Root diameters have been measured and classified at significant depth, based on the plant characteristics in the Mediterranean area (Giachi et al., 2024; Giambastiani et al., 2017; Giambastiani et al., 2022; Preti et al., 2010).



Figure 7: Root system field survey in AdS1-SWBE restored landslide, for Ar and RAR value detection, for the representative tree species: *Alnus incana*, *Castanea sativa* and *Ostrya carpinifolia*.

Root system pictures have been taken during the 2023 field survey. These images were processed using CAD software to measure root areas at progressive depths (Dani and Preti, 2007). The collected data were then used to calculate the RAR regression function (exponential) and to extend the evaluation across different depth ranges (0-30 cm, 30-50 cm, 50-70 cm, 70-

100 cm). Cr values were derived from the combination of tree basal area (G) and b factor for root average depth (Giovanni Battista Chirico et al., 2013b).

2.3. Soil characterisation

During 2023 extensive field survey, soil samplings were detected in the AdS1 study site: six soil samplings have been taken for soil characterisation of surface layers. Laboratory analysis identified values for bulk density (BD) and Soil texture. Data elaboration permits us to defined geotechniques values of soil cohesion (Cs) and porosity, important for back analysis hypothesis. Although the site-specific values are reasonable, further investigations into the geological nature of the area were carried out. Recent geotechnical research on steep slopes in Northwestern Tuscany (Tofani et al., 2017), shows soil cohesion values for surface layers of $6 \text{ kPa} < C_s < 8 \text{ kPa}$. Given the site-specific soil samples and insights from other studies, the chosen value of soil cohesion $C_s = 9 \text{ kPa}$ (for soil depths between 0 and 100 cm) can be considered reliable for terrain modelling.

2.4. Slope stability data and modelling

The variation of the slope stability factor (FS) was evaluated in the 1998-2013-2023 discretised ranges, in AdS1 based on the monitoring field data. Hypothetical scenarios, through back analysis, for the pre-landslide situation (abandoned chestnut forest of 300 years), Unrestored landslide in 2023 and para-natural ecological succession forest (until future 300 years) have been considered from field data elaboration and literature data from the specific study site.

	Vegetation data		Roots cohesion data						SSAP model	
	Nr. Plants	G	b fac- tor	Cv_0	Cv_0- 30	Cv_30- 50	Cv_50- 70	Cv_70- 100	Cwcr	Profile type
	nr/ha	(m ² /ha)	\	kPa	kPa	kPa	kPa	kPa	kPa	\
Pre-Event	100	29.1	-0.07	43.6	24.3	3.0	0.7	0.1		B
Y1	18178	1	-0.04	1.5	1.0	0.3	0.1	0.1	50.8	A
Y15	1592	13.9	-0.04	21.5	14.0	4.7	2.1	0.9	45.4	A
Y25	1017	17.4	-0.04	25.3	16.4	5.5	2.5	1.0	41.9	A
Y50	515	20.3	-0.04	30.4	19.8	6.6	3.0	1.2	34.3	A
Y300	100	29.1	-0.04	43.6	28.4	9.5	4.3	1.7		B
UN-Y25	2114	0.74	-0.04	1.1	0.7	0.2	0.1	0.0		B

Table 1: Schematic resume of data for AdS1 and AdS2 in different temporal scenarios used in SSAP modelling simulations. Root cohesion values at different representative depths and wooden crib wall cohesion contribute to SWBE restore scenarios and the 2 different slope profiles.

The methodology applied to analyse slope stability is the limit equilibrium method (LEM) integrated with the SSAP2010TM program (release 5.2.3.- 2023), used for soil stability research. SSAP2010 is a freeware software for stability evaluation of natural and artificial slopes, or with reinforcing elements like eco-engineering and conventional engineering techniques. The

software allows the input of data for specific characterisation of the studied slope, for the identification of slip surface and the safety factor (FS): morphology, geotechnical parameters, stratigraphy, pre-and post-event topography, hydrological values, and slope reinforcement works. In LEM methods, the calculation of the safety factor (FS) is carried out on a specific slip surface defined within a slope. We therefore define Fs as:

$$(1) F_s = \frac{\tau_f}{\tau_m}$$

Where τ_f is the average shear resistance available along the sliding surface, and τ_m the average mobilised shear resistance. Among the computational methods available in SSAP, the solution chosen to carry out the back analysis of the Pomezzana landslide was the one proposed by Morgenstern and Price (1965); it uses an arbitrary function to define the direction of the resultant of the interface forces. This solution represents a fully balanced method (<https://www.ssap.eu/>). Morgenstern and Price (1965) developed a solution in which the relationship between vertical and horizontal interface forces is expressed through an unknown function, whose parameters are derived from the global mass balance, of the single sliding surface: it doesn't have a simple final formula, but a system of non-linear equations to be solved by iterations. The solution is fully balanced and can be used to study any failure surface with any shape (Innocenti et al., 2023). Geotechnical parameters are needed to obtain an SSAP simulation of slope stability.

In the simulation, we used Morgenstern and Price, 1965 method is due for different reasons. First, all the equilibrium conditions are satisfied in circular slip surface, it can be used with the method of slices; second the condition that there be no rotation of the slice is satisfied if the sum of the moments about the centre of the base of the slice is equal to zero: in the adopted method is computed and comprehended this case and the alternative. Semicircular slip surfaces are typical in non-foot-supported slopes, especially due to localised water accumulation due to upslope morphology convergence and in multilayer soil configuration, since our study began with a back analysis of an occurred landslide, it is the shape that was observed in the specific case in 1996. Slip surface research was performed through the RANDOM algorithm by using a numerical convergence algorithm described by A concise algorithm for computing the factor of safety using the Morgenstern Price method (Zhu et al., 2005).

According to other studies (Lann et al., 2024; Mao, 2022; Murgia et al., 2022), the total cohesion value of in ground with the presence of plants can be expressed as the amount of soil cohesion C_s and the additional cohesion given by the roots C_r :

$$(2) C' = C_s + C_r$$

For stability factor calculation, the effects of the plants must be computed (Chirico et al., 2013a): on the one hand, the development of the root systems increases the cohesion values in

the first layers of the soil, on the other hand, overloading and overturning by wind are negative factors for the slope's stability. To evaluate the mechanical effects of the roots RAR values were measured, according to the formula:

$$(3) RAR(Z) = \frac{Ar(z)}{Ars}$$

Where $Ar(z)$ is the root area function for z depth and Ars is explored soil area. $Ar(z)$, in water-limited ecosystems, can be expressed as z depth function:

$$(4) Ars = Ar0 e^{\frac{-z}{b}}$$

$Ar0$ ($z = 0$ depth) root area can be assumed as a scale factor and in a good approximation, corresponding to the tree-collar area (Preti et al., 2010; Schwarz et al., 2010a). In the case of stand forest, $RAR0$ could be estimated as $G/10.000$, where G (m^2/ha) is the tree basal area (Chirico et al., 2013b; Preti and Giadrossich, 2009). The b factor is sloping scaling for that environment (soil, climate term average condition) and corresponding geometrically to the root area average depth. RAR calculation is necessary (Schwarz et al., 2010a)(in the Wu-Waldron Incremental cohesion scheme) for vegetation cohesion calculation as:

$$(5) Cv = k RAR Tr$$

$$(6) Cv = k Tr (RAR_0) e^{\frac{-z}{b}} = k Tr G e^{\frac{-z}{b}}$$

The RAR parameter has been calculated as an average in all the slopes considering the different species and ages of the tree species (Bischetti et al., 2009). Tr is the average (Unique value for root diameter distribution uncertainty) maximum tensile strength considered as $Tr = 30$ Mpa, as a cautionary value; $k = 0,5$ is the reduction coefficient including geometrical root disposition and overestimation due to uncertainty.

Tr considered is the average value considering root diameter distribution in gauged plants and pre-landslide situations (Vergani et al., 2017; Vergani et al., 2012). For slope stability analysis specific root system distribution would be descriptive of sampled plants but does not reduce uncertainty on overall root distribution in the analysed slope. Let's note that this coefficient increases confidence in FS calculation. According to discussions on various methods for root reinforcement (Mao, 2022; Murgia et al., 2022), in SSAP simulations reference is made to the SWWM-Wu-Preti scheme (consider $k = k'k'' = 0,5$), which has been extensively tested and validated.

Slope stability temporal evolution has been analysed with different scenarios (Fig. 6), respectively:

- Pre-Event (1996): abandoned chestnut tree forest.
- Y1 - Year 1 (1998): restored landslide with SWBE project and willows cuttings renewal.
- Y15 - Year 15 (2013): evolved slope, with alder trees.
- Y25 - Year 25 (2023): evolved slope, with alder, chestnut, and hornbeams trees.

- Y50 – Year 50: evolved slope (restoration project's life) from data extrapolation.
- Y300 – Year 300: evolved slope to natural vegetation – from data extrapolation
- UN-Y25 (2023) – Unrestored Landslide

For SSAP simulation, two slope surface models were used: Profile A - valid for the simulations of the Pre-Event, Y300 and UN-Y25 scenarios, natural soil profile without SWBE techniques; Profile B - used for the Y1, Y15, Y25, and Y50 scenarios, terraced slope profile due to the presence of live wooden crib walls. To assess the contribution of wooden crib walls to slope stability, the cohesion values of the structures, defined as C_{wcr} , were associated with values found in the literature (Uzielli et al., 2025). In Table 1, vegetation data input for C_v estimation, C_{v0} and C_v values at different depth ranges and SSAP modelling characteristics profiles have been resumed.

In all scenarios, SSAP modelling runs considered a fully saturated zone from ground level to critical soil saturation, equivalent to 1,2 m. The critical soil depth value of 1,2 m is consistent with the rainfall data (more than 400 mm, considering the inflow concentration is equivalent to the surface runoff from upstream plus the contribution of inflows to the catchment sides) recorded during the 1996 event; with a soil porosity of 40 %, we obtain an average depth of 1,2 m on the slopes. The post-flood surveys confirm, as mentioned above, that particularly in the chestnut groves the shallow landslides did not deepen more than 2–3 m. This fact can be associated with poor root growth beyond a depth of 50–60 cm, given the calcareous subsoil (Toscana, 1998).

3. Results and discussion

3.1. Vegetation evolution

Vegetation evolution monitoring and management of shallow landslide events are very important (DiBiagio et al., 2024; Qin et al., 2022; Wang et al., 2019), especially in SWBE projects that use plants within their biotechnical value, that replace the structural function of the wooden crib wall (which instead degrades) over time. In addition to the increased stability of the restored slope, evaluating the type of plant species is useful for making considerations on possible ecological processes (para-natural succession triggered by SWBE) of environmental-induced self-regeneration.

Regarding AdS1, the entire restored area has evolved into a black alder forest (*Alnus glutinosa*, although it seems unlikely to be climax vegetation), in filled density, about 23 years old. Other tree species found include black locust (*Robinia pseudoacacia*), black hornbeam (*Ostrya carpinifolia*), manna ash (*Fraxinus ornus*), elderberry (*Sambucus nigra*), chestnut (*Castanea sativa*), and holly (*Ilex agrifolium*). The success of the alder in the restored area can be traced

back to the presence of seed plants uphill, which are able to disseminate (via wind and water) over long distances. Unlike the alder, the chestnut tree adopts gravity dissemination results in slower regeneration. Sporadic individuals of willow have developed from cuttings along the wooden crib walls, despite practically 100 % rooting of the cuttings, but most plants dried due to shading after alder diffusion. A few chestnut trees grew at the landslide's borders. In AdS2, the same plant species as AdS1 have been found, mainly black alder, chestnut, and hornbeam. The naturally evolved landslide shows a lower growth rate compared to the SWBE-restored landslide, with small 13-year-old alder plants averaging a diameter of 2 cm ($G = 0,74 \text{ m}^2/\text{ha}$).

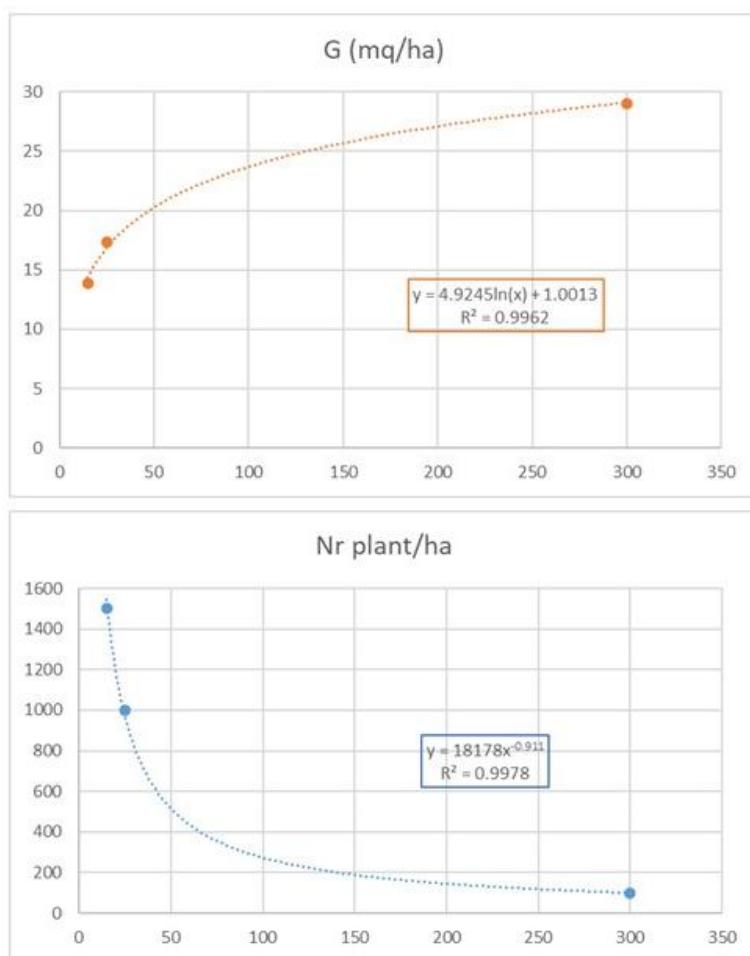


Figure 8: Number of plants/ha and tree basal area G (m^2/ha) - time evolution in AdS1 SWBE Restored landslide

Trees and Shrub species	UNRESTORED LANDSLIDE	SWBE RESTORED LANDSLIDE	
	2023 Nr. Plants/ha	2013 Nr. Plants/ha	2023 Nr. Plants/ha
Acer campestre	\	2	\
Acer pseudoplatanus	\	9	29.8
Alnus glutinosa	1628.6	1345	712.8
Castanea sativa	257.1	34	40.4
Corylus avellana	\	15	4.3
Fraxinus ornus	28.6	2	8.5
Ilex aquifolium	\	\	6.4
Ostrya carpinifolia	171.4	62	95.7
Populus alba	\	4	\
Robinia pseudoacacia	\	45	59.6
Salix alba	\	43	4.3
Salix caprea	\	9	\
Salix cinerea	\	6	\
Sambucus nigra	28.6	15	55.3
Sorbus aria	\	2	\
TOT	2114.3	1591.5	1017
Dm (cm)	1.9	9.7	13.0
G tot (m²/ha)	0.74	13.9	17.38

Table 2: Trees and shrubs vegetation 2023 field survey in AdS1 and AdS2 - species composition, Nr. Plants/ha and tree basal area (G).

The vegetation development (Fig. 8) survey confirmed that the SWBE technique acts as a slope stability support and an ecological starter, promoting native plant succession. The initial value of around 18,000 plants per hectare compares well with a number of willow cuttings used of around 20,000 plants in the initial phase of the project. As surveys over time have shown (Table 2), the willow was naturally replaced by other species indigenous to the area. These findings align with previous studies (Bischetti et al., 2021; Janssen et al., 2019; Kettenhuber et al., 2023) that observed SWBE's role in enhancing habitat quality by accelerating native species colonisation and increasing ecological succession. The observed forest composition suggests a transition toward a more stable vegetation association, with hornbeam and manna ash becoming dominant. In the specific case study, restoration with SWBE techniques (water regulation and terraced profile) allowed the establishment and growth of tree vegetation, initially also assisted by hydroseeding as an additional factor against surface soil erosion. The presence of Robinia pseudoacacia, a competitive alien species, requires forest management efforts, although native species' shading effect is mitigating its development.

3.2. Soil analysis

Soil sampling field survey has been conducted along the restored and un-restored landslide. The bulk density values are around 1 (g/cm³) with SD = 0,1. From these, the porosity of the 40 % soil was derived, also considering the geological nature of the study area. Soil texture formation in the study site, have a percentage contribution from the three components as follows: sand 42 %, silt 42 %, clay 17 %. The soil cohesion value used for the soil slope profile is 9 kPa, obtained by soil samplings in the area, that referring also to recent geotechnical research (Tofani et al., 2017) can be considered reliable.

Cohesion values were also verified on regional geological maps (<https://www.regione.toscana.it/-/geoscopio>). Bibliographic research found post-event geological studies from 1996 event (D'Amato Avanzi and Giannecchini, 2003; D' Amato Avanzi et al., 2004; Giannecchini and Avanzi, 2012) conducted in Cardoso and Stazzema villages, have the same soil formation as the Pomezzana area. The site-specific data are also valid from the comparison of other sources mentioned above.

3.3. Slope Stability Modelling

Based on the analysis of four excavated root systems, an exponential RAR function was derived, and root cohesion was calculated, according to formula 6 (Fig. 9).

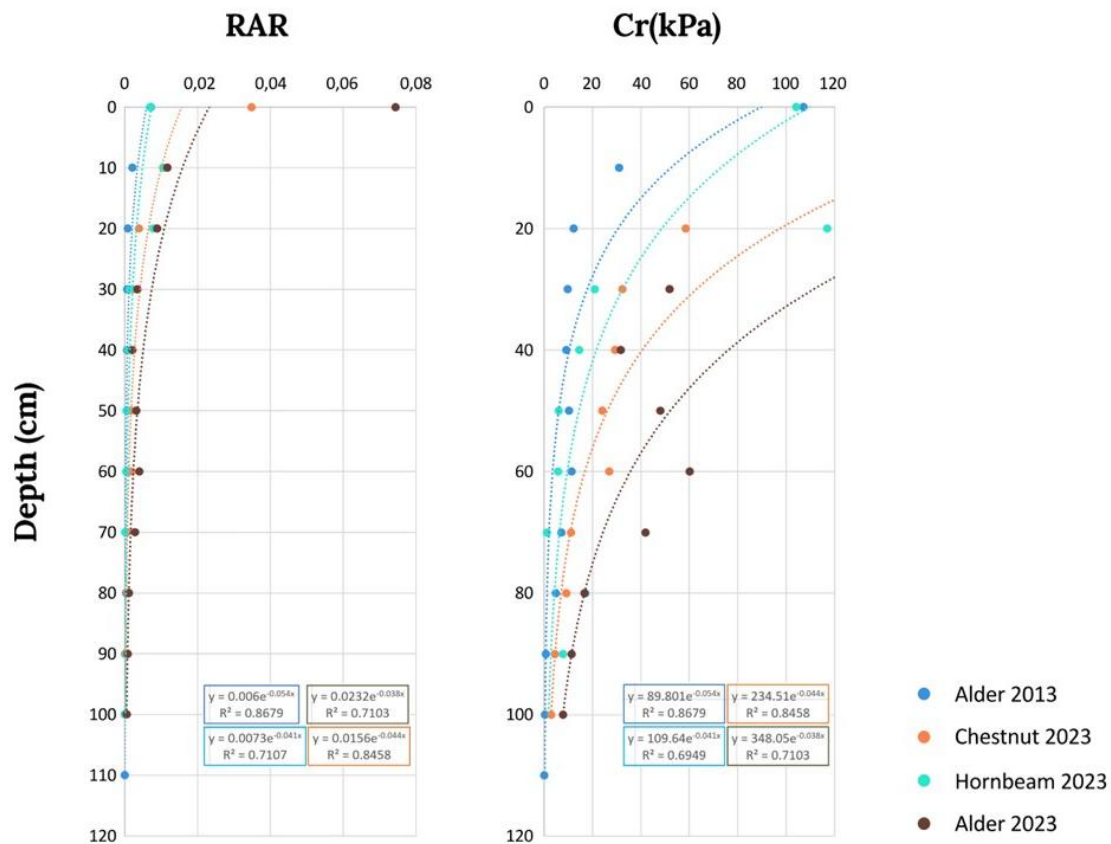


Figure 9: RAR and Cr values as a function of depth for the four plants measured in field surveys in 2013 and 2023, in the landslide area

RAR and root cohesion values follow an exponential trend, reflecting species characteristics, age, and size. A comparison of two alder plants 10 years apart (2013 and 2023) shows an increase in RAR and Cr values with vegetation growth. Analyses of the root systems allowed us to identify parameter b, the average rooting depth, which is influenced by the species and climate of the site; 3b approximates the maximum rooting depth (Preti et al., 2010; Tron et al., 2014). The average b value is detected as 0,04; with variable values of G (m^2/ha) according to formula 6, it was possible to identify Cr values in different temporal scenarios for SSAP simulation. According to the initial assumptions of the study conducted, the vegetation data, root system data and soil characterisation were used to create the SSAP model for slope stability assessment. All values taken are site-specific and cautelative. A fundamental assumption for the SSAP simulations was the choice of the critical depth of soil saturation. Considering an event equivalent to 478 mm rainfall, knowing soil porosity of 40 %, in the worst situation, the soil is saturated to 1,2 m. This is a plausible condition given the effects of the 1996 event, where a large proportion of the surface landslides occurred at tributaries. The SSAP simulations at a critical soil saturation depth of 1,2 m yielded results for different scenarios (Figs. 10-13).

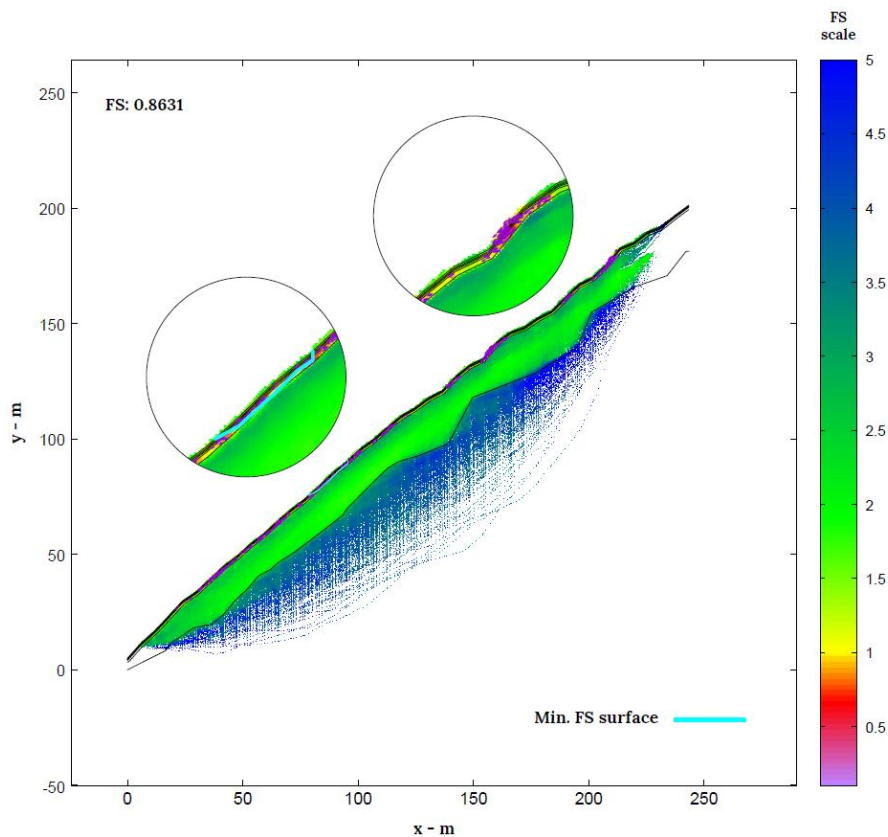


Figure 10: SSAP simulation for Pre-Event scenarios.

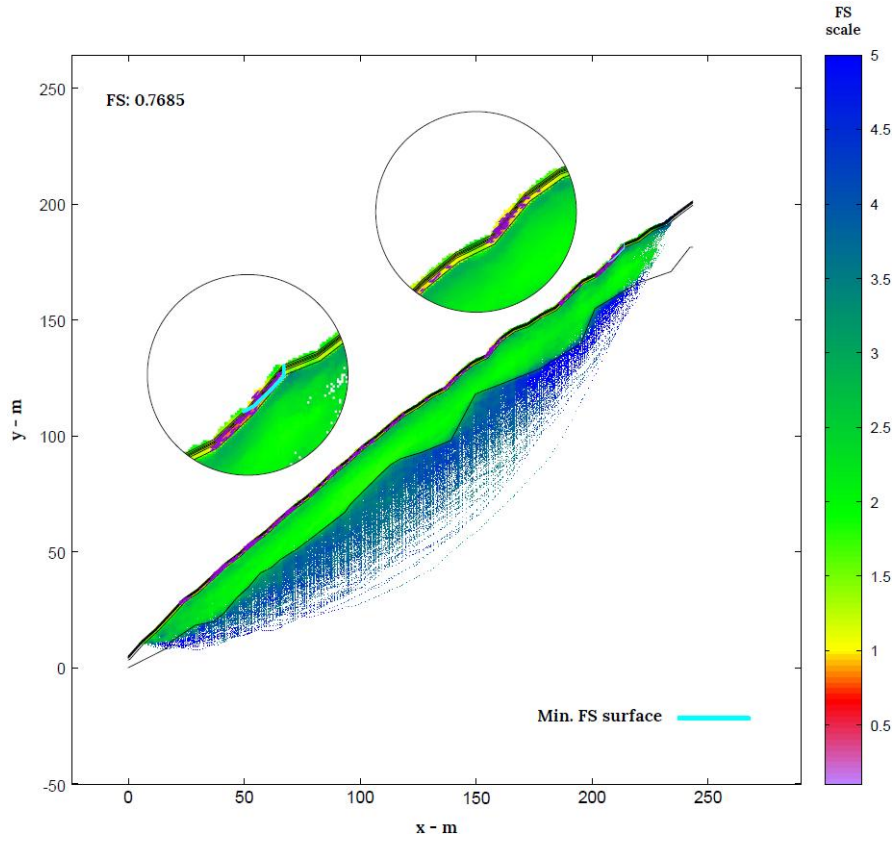


Figure 11: SSAP simulation for UN-Y25 scenarios of AdS2-unrestored landslide.

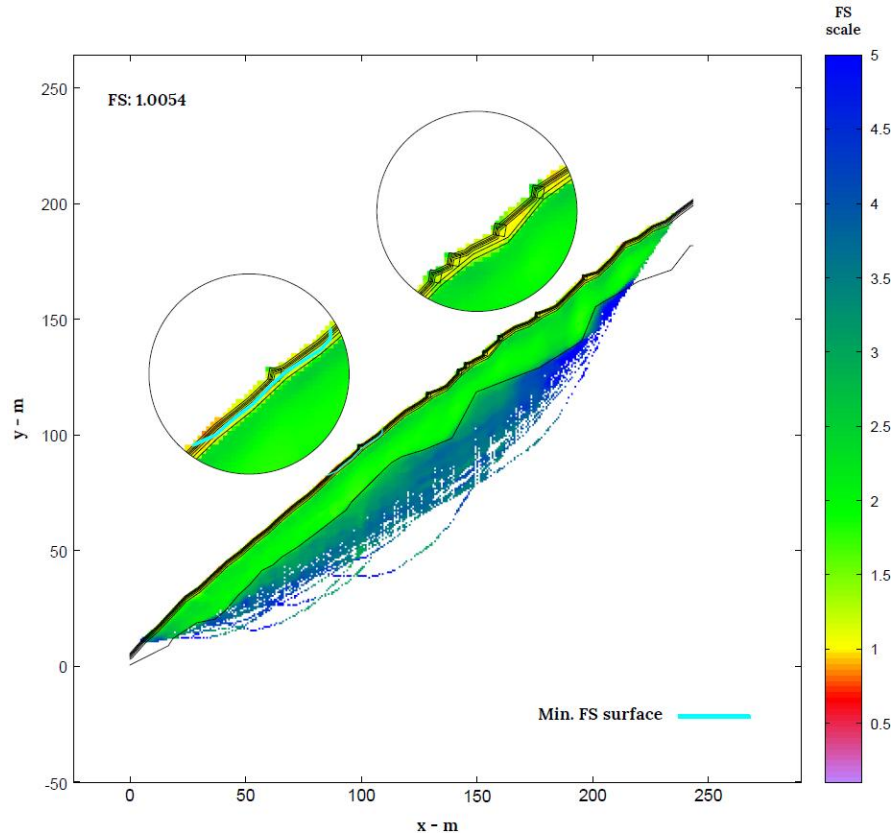


Figure 12: SSAP simulation for Y-25 scenarios for AdS1-SWBE restored landslide.

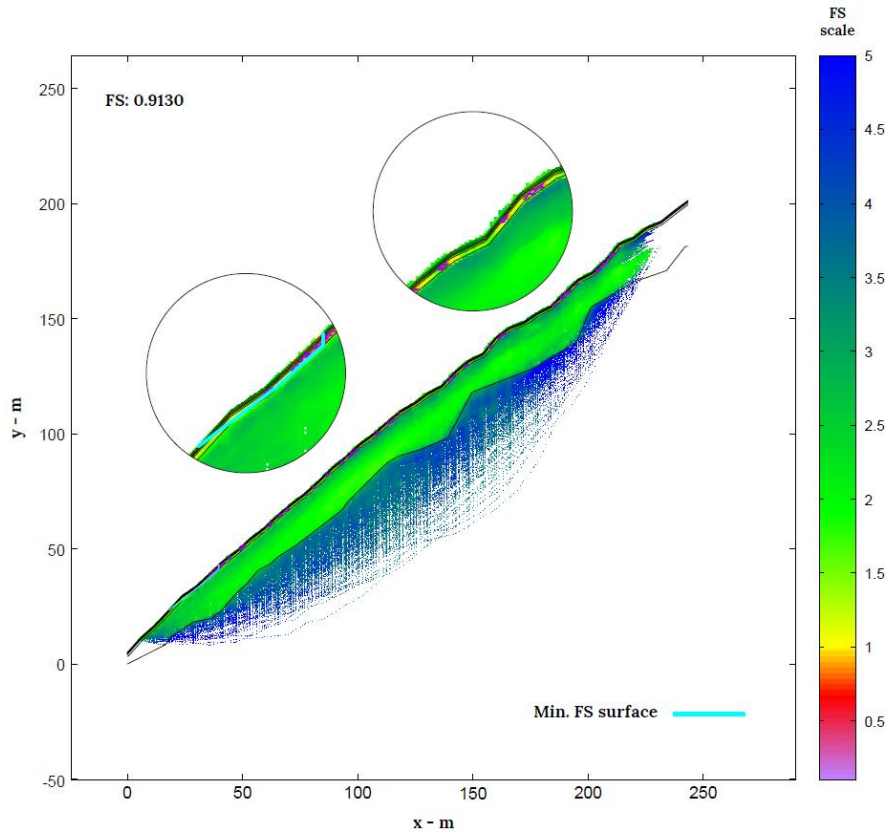


Figure 13: SSAP simulation for Y300 scenarios obtained from data extrapolation on vegetation evolution rate.

According to AdS1 (SWBE-restored landslide), FS values are greater than 1 already a few years post-restoration. This correlates with a decrease in plant density and an increase in stand size (Fig. 8), contributing to higher root cohesion over time. Conversely, wooden crib wall cohesion follows a downward trend, as expected and as already shown in different studies (Uzielli et al., 2025). Regarding AdS2 (naturally evolved landslide, unrestored), FS values remain below 1 at simulation time, highlighting the importance of SWBE techniques in stabilising the upper soil layers. The Pre-Event scenario, assuming 100 plants per hectare (chestnut grove), confirmed that during the 1996 flood event (>300-year return period), critical soil saturation depth was around 1,2 m (see Fig. 14).

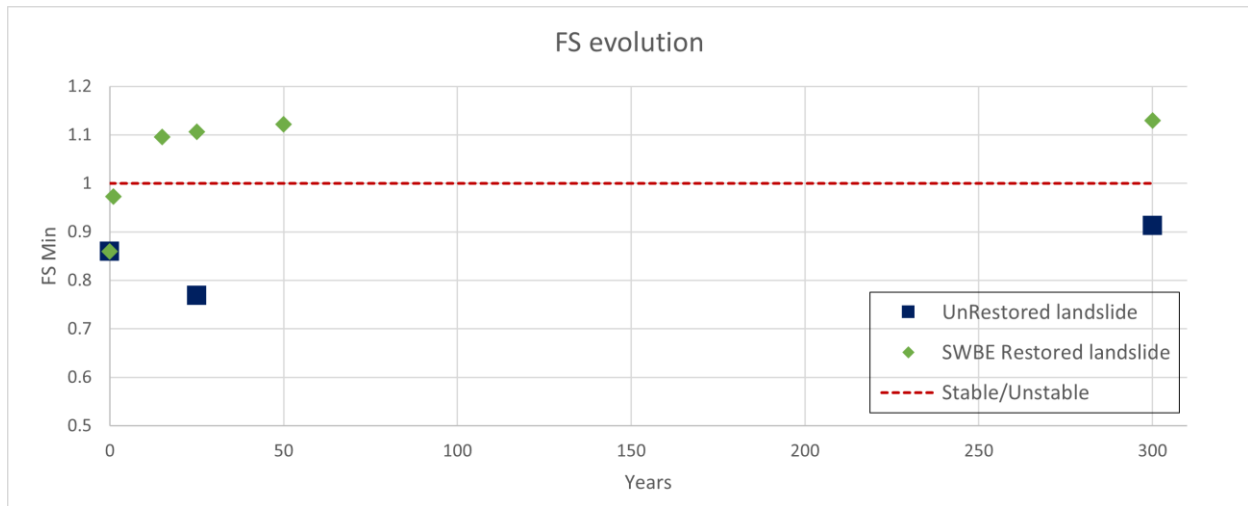


Figure 14: FS value trend for AdS1-SWBE restored landslide and AdS2-Unrestored landslide.

SSAP simulations confirm that vegetation evolution contributes to slope stability by increasing soil cohesion and reducing surface infiltration. The total plant overload in the landslide area (1,5 ha) was calculated as 21 kg/m², a negligible factor in slope stability measurements (Gray and Sotir, 1996; Preti, 2013). The positive effect of vegetation is not only that of soil reinforcement but also that of water uptake, the role of vegetation on slope stability under transient unsaturated conditions (Chirico et al., 2013a). The RAR trend was discretised for stability modelling (Dani and Preti, 2007; Preti et al., 2022; Preti, 2013). Despite a reduction in plant numbers between 2013 and 2023 (Table 2) from around 1500 plants/ha to 1017 plants/ha, RAR values remained high due to multi-species forest composition and tree growth. The para-natural evolution of the vegetation has led to a decrease in the number of plants with a consequent increase in the distance between individuals: since the average plant distance is greater, lateral cohesion may not be influent (Schwarz et al., 2010b) The decrease in tree cover was offset by increased herbaceous cover, leading to improved slope stability through para-natural vegetation succession. The monitoring data suggest that similar trends occurred from 2003 to 2013, where willows were replaced by alder, improving spatial tree cover and increasing slope cohesion.

For slope stability monitoring, the Wu-Waldron modified model was selected over RBM and FBM; Wu and Waldron's method, according to the SWWM-Wu-Preti scheme (Mao, 2022) seemed more feasible than the RBM or FBM methods, which require knowledge of an excessive number of parameters (Schwarz et al., 2010a; Preti, 2013). The approach used is to be considered reliable (tried and tested) and consistent with the data from the field surveys (already numerous, though challenging due to the slope and accessibility situation). Given the relevance of cohesion values in SSAP simulations, the Morgenstern calculation method was chosen for its reliability (Murgia et al., 2022), even in complex soil stratigraphies and reinforced slopes.

Digital terrain and forest models have further allowed long-term management evaluations (Errico et al., 2014; Giachi et al., 2024; Giadrossich et al., 2017; Preti, 2013). The research conducted in the two test areas presents interesting results, even if they must be considered site-specific. The historical data set provides an opportunity to evaluate the long-term effects of a SWBE project for shallow landslide restoration. Cautionary values in line with the measured data of geotechnical parameters and soil saturation levels were used in the SSAP simulations. The FS values are therefore to be considered reliable.

4. Conclusions

The long-monitoring results show the technical and ecological efficiency of the SWBE project realised for the rainfall-induced shallow landslide restoration. The vegetation developed quite rapidly compared to the period of 25 years, which probably would have taken longer to establish itself in unrestored conditions, left to natural evolution.

Comparing the 2013 and 2023 data in AdS1, the number of plants/ha has decreased by 1/3, and tree basal area (G) increased as the soil reinforcement, thus contributes, even with crib walls degradation over time, slope stability even in the hypothetical case of an event comparable to that of 1996, with a critical soil saturation depth of 1,2 m.

Thanks to vegetation structural stability and development, the soil-bolstering function of root systems in the study site has been increasing. The SSAP2010 software, which is free-ware and proposes numerous calculation methods for Fs, can be considered a valuable tool for slope stability assessment in this specific case study. The SWBE restoration project hastened the slope stabilisation process through the combination of vegetation development and SWBE techniques.

The results of vegetation monitoring and slope stability modelling result emphasize the importance of the living component of SWBE works to increase soil cohesion, and stability over time, improve water regulation, and initiate natural ecological succession with native species. Further research will be performed on the study site, site-specific wooden crib wall degradation rate, and ecological and biodiversity enhancement, triggered by SWBE restoration projects. The research aims to promote the monitoring of this type of intervention for the mitigation of natural risks and slope instability, trying to encourage future studies on the long-term technical and ecological effects of SWBE works.

CRedit authorship contribution statement

Federico Preti: Writing - review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrea Dani:** Writing - review & editing, Visualization, Software, Investigation, Data curation. **Yamuna Giambastiani:** Resources, Data curation. **Emanuele Giachi:** Writing - review & editing, Writing - original draft, Visualization, Resources, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Emanuele Giachi reports financial support was provided by the National Biodiversity Future Centre. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Will be made available on request.

References

- Andreu, Vicente, Khuder, Hayfa, Mickovski, Slobodan B., Spanos, Ioannis A., Rubio, Luís, Jouneau, Luc, Berger, Frédéric, Norris, Joanne E., Dorren, Luuk K.A., Nicoll, Bruce C., Achim, Alexis, 2008. Slope Stability and Erosion Control: Ecotechnological Solutions. https://doi.org/10.1007/978-1-4020-6676-4_7.
- Avanzi, D'Amato, Giacomo, Roberto Gianecchini, Puccinelli, Alberto, 2004. The Influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in Northwestern Tuscany (Italy). *Eng. Geol.* 73 (3-4), 215-228. <https://doi.org/10.1016/j.enggeo.2004.01.005>.
- Bischetti, Gian Battista, Chiaradia, Enrico Antonio, Epis, Thomas, Morlotti, Emanuele, 2009. Root cohesion of forest species in the Italian Alps. *Plant Soil* 324 (1), 71-89. <https://doi.org/10.1007/s11104-009-9941-0>.
- Bischetti, Gian Battista, De Cesare, Giovanni, Mickovski, Slobodan B., Rauch, Hans Peter, Schwarz, Massimiliano, Stangl, Rosemarie, 2021. Design and temporal issues in soil bioengineering structures for the stabilisation of shallow soil movements. *Ecol. Eng.* 169, 106309. <https://doi.org/10.1016/j.ecoleng.2021.106309>.
- Boll, Albert, Burri, Katrin, Gerber, Werner, Graf, Frank, 2009. Long-Term Studies of Joint Technical and Biological Measures, 82.
- Burri, Katrin, Graf, Frank, Böll, Albert, 2009. Revegetation Measures Improve Soil Aggregate Stability: A Case Study of a Landslide Area in Central Switzerland, 82.
- Cavaillé, Paul, Ducasse, Léon, Breton, Vincent, Dommange, Fanny, Tabacchi, Eric, Evette, André, 2015. Functional and taxonomic plant diversity for riverbank protection works: bioengineering techniques close to natural banks and beyond hard engineering. *J. Environ. Manag.* 151, 65-75. <https://doi.org/10.1016/j.jenvman.2014.09.028>.
- Chirico, Giovanni B., Borga, Marco, Tarolli, Paolo, Rigon, Riccardo, Preti, Federico, 2013a. Role of vegetation on slope stability under transient unsaturated conditions. *Procedia Environ. Sci.* 19, 932-941. <https://doi.org/10.1016/j.proenv.2013.06.103>.
- Chirico, Giovanni Battista, Dani, Andrea, Preti, Federico, 2013b. Coupling Root Reinforcement and Subsurface Flow Modeling in Shallow Landslides Triggering Assessment Forest Protection and Protection Forest: Tree Root Degradation over Hydrological Shallow Landslides-triggering View Project OPERA Civil Protection from Floods View Project. <https://doi.org/10.1007/978-3-642-31319-6-97>.

Dani, Andrea, Preti, Federico, 2007. Sulla Stima Del Rinforzo Radicale Del Terreno: Andamenti Temporalmente Ed Effetti Sulla Stabilità Di Versante Con Trattamenti Selvicolturali. In: Quaderni Di Idronomia Montana, 27.

Debele, Sisay E., Leo, Laura S., Kumar, Prashant, Sahani, Jeetendra, Ommer, Joy, Buchignani, Edoardo, Vranić, Saša, Kalas, Milan, Amirzada, Zahra, Pavlova, Irina, Shah, Mohammad Aminur Rahman, Gonzalez-Ollauri, Alejandro, Di Sabatino, Silvana, 2023. Nature-based Solutions can help reduce the impact of natural hazards: a global analysis of NBS case studies. *Sci. Total Environ.* 902, 165824. <https://doi.org/10.1016/j.scitotenv.2023.165824>.

Deng, Dong Ping, Li, Liang, Zhao, Lian Heng, 2017. Limit Equilibrium Method (LEM) of slope stability and calculation of comprehensive factor of safety with double strength-reduction technique. *J. Mt. Sci.* 14 (11), 2311-2324. <https://doi.org/10.1007/s11629-017-4537-2>.

DiBiagio, Amanda, Capobianco, Vittoria, Oen, Amy, Tallaksen, Lena M., 2024. State-of-the-art: parametrization of hydrological and mechanical reinforcement effects of vegetation in slope stability models for shallow landslides. *Landslides* 21 (10), 2417-2446.

Errico, Alessandro, Giambastiani, Yamuna, Guastini, Enrico, Dani, Andrea, 2014. Monitoring of a Landslide Stabilized with Bioengineering Techniques in 1997, Northern Tuscany. Vegetation Development Analysis and State of Preservation of Wood. EGU General Assembly 2014, Wien.

Evette, A., Balique, C., Lavaine, C., Rey, F., Prunier, P., 2011. Using ecological and biogeographical features to produce a typology of the plant species used in bioengineering for Riverbank protection in Europe. *River Res. Appl.* <https://doi.org/10.1002/rra.1560>.

Fattet, M., Fu, Y., Ghestem, M., Ma, W., Foulonneau, M., Nespoulous, J., Le Bissonnais, Y., Stokes, A., 2011. Effects of vegetation type on soil resistance to erosion: relationship between aggregate stability and shear strength. *Catena* 87 (1), 60-69. <https://doi.org/10.1016/j.catena.2011.05.006>.

Fernandes, João Paulo, Guiomar, Nuno, 2018. Nature-based solutions: the need to increase the knowledge on their potentialities and limits. *Land Degrad. Dev.* 29 (6), 1925-1939. <https://doi.org/10.1002/ldr.2935>.

Giachi, Emanuele, Giambastiani, Yamuna, Giannetti, Francesca, Dani, Andrea, Preti, Federico, 2024. Root system evolution survey in a multi-approach method for SWBE monitoring: a case study in Tuscany (Italy). *Sustainability* 16 (10), 4022. <https://doi.org/10.3390/su16104022>.

Giacomo, D'Amato Avanzi, Gianecchini, Roberto, 2003. Eventi Alluvionali e Fenomeni Franosi Nelle Alpi Apuane (Toscana) Primi Risultati Di Un'indagine Retrospettiva Nel Bacino Del Fiume Versilia.

Giadrossich, F., Schwarz, M., Cohen, D., Cislighi, A., Vergani, C., Hubble, T., Phillips, C., Stokes, A., 2017. Methods to measure the mechanical behaviour of tree roots: a review. *Ecol. Eng.* 109, 256-271. <https://doi.org/10.1016/j.ecoleng.2017.08.032>.

Giambastiani, Y., Errico, A., Preti, F., Guastini, E., Censini, G., 2022. Indirect root distribution characterization using electrical resistivity tomography in different soil conditions. *Urban Forestry & Urban Greening* 127442. <https://doi.org/10.1016/j.ufug.2021.127442>.

Giambastiani, Yamuna, Preti, Federico, Errico, Alessandro, Sani, Luigi, 2017. On the Tree Stability: Pulling Tests and Modelling to Assess the Root Anchorage*, vol. 4.

Giannecchini, Roberto, Avanzi, Giacomo D' Amato, 2012. Historical research as a tool in estimating hydrogeological hazard in a typical small alpine-like area: the example of the Versilia River Basin (Apuan Alps, Italy). *Phys. Chem. Earth* 49, 32-43. <https://doi.org/10.1016/j.pce.2011.12.005>.

Giupponi, Luca, Bischetti, Gian Battista, Giorgi, Annamaria, 2017. A proposal for assessing the success of soil bioengineering work by analysing vegetation: results of two case studies in the Italian Alps. *Landsc. Ecol. Eng.* 13 (2), 305-318. <https://doi.org/10.1007/s11355-016-0323-5>.

Gonzalez-Ollauri, Alejandro, Mickovski, Slobodan B., 2017. Hydrological effect of vegetation against rainfall-induced landslides. *J. Hydrol.* 549, 374-387. <https://doi.org/10.1016/j.jhydrol.2017.04.014>.

Gray, Donald H., Sotir, Robbin B., 1996. Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control. J. W. & S. Inc. Wiley Inter- Science Publication.

Hofmann, Amerigo, Guastini, Enrico, Bresci, Elena, Preti, Federico, 2015. Learning from the roots of mountain watersheds management. In: *Idronomia Montana*, vol. 34. EdiBios. Igwe, Ogbonnaya, Una, Chuku Okoro, 2019. Landslide impacts and management in nanka area, Southeast Nigeria. *Geoenviron. Disasters* 6 (1). <https://doi.org/10.1186/s40677-019-0122-z>.

Innocenti, Agnese, Pazzi, Veronica, Borselli, Lorenzo, Nocentini, Massimiliano, Lombardi, Luca, Gigli, Giovanni, Fanti, Riccardo, 2023. Reconstruction of the evolution phases of a landslide by using multi-layer back-analysis methods. *Landslides* 20 (1), 189-207. <https://doi.org/10.1007/s10346-022-01971-y>.

Janssen, Philippe, Cavaillé, Paul, Bray, Frédéric, Evette, André, 2019. Soil bioengineering techniques enhance riparian habitat quality and multi-taxonomic diversity in the foothills of the Alps and Jura Mountains. *Ecol. Eng.* 133, 1-9. <https://doi.org/10.1016/j.ecoleng.2019.04.017>.

Kettenhuber, Paula Letícia, Wolff, Rita, dos Santos, Sousa, Dewes, Júnior Joel, Rauch, Hans Peter, Sutili, Fabrício Jaques, Hörbinger, Stephan, 2023. Performance assessment of a soil and water bioengineering work on the basis of the flora development and its associated ecosystem processes. *Ecol. Eng.* 186. <https://doi.org/10.1016/j.ecoleng.2022.106840>.

Lann, Tongsan, Bao, Han, Lan, Hengxing, Zheng, Han, Yan, Changgen, Peng, Jianbing, 2024. Hydro-mechanical effects of vegetation on slope stability: a review. *Sci. Total Environ.* 926, 171691. <https://doi.org/10.1016/j.scitotenv.2024.171691>.

Mao, Zhun, 2022. Root reinforcement models: classification, criticism and perspectives. *Plant Soil* 472 (1-2), 17-28. <https://doi.org/10.1007/s11104-021-05231-1>.

Mickovski, S.B., Thomson, C.S., 2017. Developing a Framework for the Sustainability Assessment of Eco-Engineering Measures. <https://doi.org/10.1016/j.ecoleng.2017.10.004>.

Mickovski, Slobodan B., Gonzalez-Ollauri, Alejandro, Thomson, Craig, Gallagher, Caroline, Tardio, Guillermo, 2022. Assessment of the sustainability performance of eco-engineering measures in the mediterranean region. *Land* 11 (4). <https://doi.org/10.3390/land11040533>.

Miele, Pietro, Di Martire, Diego, Di Napoli, Mariano, Guerriero, Luigi, Calcaterra, Domenico, 2021. Temporal efficiencies of soil bioengineering techniques to mitigate geo-hydrological risks. *Ecol. Eng.* 170. <https://doi.org/10.1016/j.ecoleng.2021.106338>.

Murgia, Ilenia, Giadrossich, Filippo, Mao, Zhun, Cohen, Denis, Capra, Gian Franco, Schwarz, Massimiliano, 2022. Modeling shallow landslides and root reinforcement: a review. *Ecol. Eng.* 181. <https://doi.org/10.1016/j.ecoleng.2022.106671>.

Preti, Federico, 2013. Forest protection and protection forest: tree root degradation over hydrological shallow landslides triggering. *Ecol. Eng.* 61 (1 PARTC), 633-645. <https://doi.org/10.1016/j.ecoleng.2012.11.009>.

Preti, F., Giadrossich, F., 2009. Hydrology and Earth System Sciences Root Reinforcement and Slope Bioengineering Stabilization by Spanish Broom (*Spartium Junceum* L.), 13.

Preti, Federico, Galeotti, Lorenzo, Brugioni, Marcello, 1999. Caratterizzazione Dell'evento Alluvionale Del 19 Giugno 1996 In Versilia e Garfagnana per Gli Interventi Di Sistemazione Idraulico-Forestale.

Preti, F., Dani, A., Laio, F., 2010. Root profile assessment by means of hydrological, pedological and above-ground vegetation information for bio-engineering purposes. *Ecol. Eng.* 36 (3), 305-316. <https://doi.org/10.1016/j.ecoleng.2009.07.010>.

Preti, Federico, Capobianco, Vittoria, Sangalli, Paola, 2022. Soil and Water Bioengineering (SWB) is and has always been a Nature-based solution (NBS): a reasoned comparison of terms and definitions. *Ecol. Eng.* 181. <https://doi.org/10.1016/j.ecoleng.2022.106687>.

Qin, Mingyue, Cui, Peng, Jiang, Yao, Guo, Jian, Zhang, Guotao, Ramzan, Muhammad, 2022. Occurrence of shallow landslides triggered by increased hydraulic conductivity due to tree roots. *Landslides* 19 (11), 2593–2604. <https://doi.org/10.1007/s10346-022-01921-8>.

Rauch, H.P., von der Thannen, M., Raymond, P., Mira, E., Evette, A., 2022. Ecological challenges* for the use of soil and water bioengineering techniques in river and coastal engineering projects. *Ecol. Eng.* 176. <https://doi.org/10.1016/j.ecoleng.2021.106539>.

Rey, F., Bifulco, C., Bischetti, G.B., Bourrier, F., De Cesare, G., Florineth, F., Graf, F., Marden, M., Mickovski, S.B., Phillips, C., Peklo, K., Poesen, J., Polster, D., Preti, F., Rauch, H.P., Raymond, P., Sangalli, P., Tardio, G., Stokes, A., 2019. Soil and water bioengineering: practice and research needs for reconciling natural hazard control and ecological restoration. *Sci. Total Environ.* 648, 1210–1218.

Ruangpan, Laddaporn, Vojinovic, Zoran, Di Sabatino, Silvana, Leo, Laura Sandra, Capobianco, Vittoria, Oen, Amy M.P., McClain, Michael, Lopez-Gunn, Elena, 2019. Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. *Nat. Hazards Earth Syst. Sci. Discuss.* <https://doi.org/10.5194/nhess-2019-128>.

Schwarz, M., Lehmann, P., Or, D., 2010a. quantifying lateral root reinforcement in steep slopes - from a bundle of roots to tree stands. *Earth Surf. Process. Landf.* 35 (3), 354–367. <https://doi.org/10.1002/esp.1927>.

Schwarz, M., Preti, F., Giadrossich, F., Lehmann, P., Or, D., 2010b. Quantifying the role of vegetation in slope stability: a case study in Tuscany (Italy). *Ecol. Eng.* 36 (3), 285–291. <https://doi.org/10.1016/j.ecoleng.2009.06.014>.

Sidele, Roy C., Bogaard, Thom A., 2016. Dynamic earth system and ecological controls of rainfall-initiated landslides. *Earth Sci. Rev.* 159, 275–291.

Stokes, Alexia, Douglas, Grant B., Fourcaud, Thierry, Giadrossich, Filippo, Gillies, Clayton, Hubble, Thomas, Kim, John H., Loades, Kenneth W., Mao, Zhun, McIvor, Ian R., Mickovski, Slobodan B., Mitchell, Stephen, Osman, Normaniza, Phillips, Chris, Poesen, Jean, Polster, Dave, Preti, Federico, Raymond, Pierre, Rey, Freddy, Schwarz, Massimiliano, Walker, Lawrence R., 2014. Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. *Plant Soil* 377 (1–2), 1–23.

Tarolli, Paolo, Preti, Federico, Romano, Nunzio, 2014. Terraced landscapes: from an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene* 6, 10–25.

Tofani, V., Bicocchi, G., Rossi, G., Segoni, S., D'Ambrosio, M., Casagli, N., Catani, F., 2017. soil characterization for shallow landslides modeling: a case study in the Northern Apennines (Central Italy). *Landslides* 14 (2), 755–770. <https://doi.org/10.1007/s10346-017-0809-8>.

Toscana, Regione, 1998. I Tipi Forestali: Boschi e Macchie Di Toscana, 1.

Tron, S., Dani, A., Laio, F., Preti, F., Ridolfi, L., 2014. Mean root depth estimation at landslide slopes. *Ecol. Eng.* 69, 118–125. <https://doi.org/10.1016/j.ecoleng.2014.03.019>.

Uzielli, Marco, Geppetti, Andrea, Borselli, Lorenzo, Renzi, Stefano, Preti, Federico, 2025. comparative geotechnical analysis of slope stabilization through conventional, soil and water bioengineering, and combined solutions. *Ecol. Eng.* 212. <https://doi.org/10.1016/j.ecoleng.2024.107487>.

Vergani, C., Chiaradia, E.A., Bischetti, G.B., 2012. Variability in the tensile resistance of roots in alpine forest tree species. *Ecol. Eng.* 46, 43–56. <https://doi.org/10.1016/j.ecoleng.2012.04.036>.

Vergani, C., Giadrossich, F., Buckley, P., Conedera, M., Pividori, M., Salbitano, F., Rauch, H.S., Lovreglio, R., Schwarz, M., 2017. Root reinforcement dynamics of european coppice woodlands and their effect on shallow landslides: a review. *Earth Sci. Rev.* 167, 88–102.

Walker, Lawrence R., Shiels, Aaron B., 2013. *Landslide Ecology*, 1st ed. Cambridge University Press, Cambridge.

Wang, Xia, Hong, Miao Miao, Huang, Zheng, Zhao, Yun Fei, Yan Sheng, Ou, Jia, Hai Xia, Li, Jia, 2019. Biomechanical properties of plant root systems and their ability to stabilize slopes in geohazard-prone regions. *Soil Tillage Res.* 189, 148–157. <https://doi.org/10.1016/j.still.2019.02.003>.

Zaimas, George N., Tardio, Guillermo, Iakovoglou, Valasia, Gimenez, Martin, Garcia-Rodriguez, Jose Luis, Sangalli, Paola, 2019. New tools and approaches to promote soil and water bioengineering in the mediterranean. *Sci. Total Environ.* 693. <https://doi.org/10.1016/j.scitotenv.2019.133677>.

Zhu, D.Y., Lee, C.F., Qian, Q.H., Chen, G.R., 2005. A concise algorithm for computing the factor of safety using the morgenstern–price method. *Can. Geotech. J.* 42 (1), 272–278. <https://doi.org/10.1139/t04-072>.

4.3. *Manuscript III*

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

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Highlights

SWBE techniques effectively restore shallow landslides; vegetation is the most responsive recovery indicator; SWBE-restored landslide showed higher herbaceous alpha diversity; microbial and soil fauna diversity fully recovered post-landslide; the SWBE approach couples slope stability with biodiversity benefit.

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 in 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 compared to the natural and control sites. Different pedological conditions characterised the three study sites, prompting us to evaluate the ecological dynamics between disturbed and undisturbed plots. 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. 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 enhanced temperature and water stress, which mimic climate change conditions on a habitat level in a natural environment (Walker & Shiels, 2013). Such natural disturbances create unusual vegetation gaps because most of the soil structure is removed, especially in fast 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; 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 stones 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 & 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 performance 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). 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 technique design for landslide restoration, vegetation performs an important role through various paths, including root strength, evaporation and transpiration (Sidle & 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 & 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 very important factor in shallow landslide susceptibility, determining the preferential water pathways and influencing the transpiration rate of the plants (Stokes et al., 2009). Forest canopy and litter layer interception on effective rainfall usually plays a minor role in modifying water and pore pressure propagation in shallow soil (Sidle & 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 “grey” 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 stability 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 hazards control in terms of soil erosion, torrential floods, and shallow landslides (Takaoka, 2024), 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 solutions have been addressed in many studies, highlighting their significant social value and the recovering 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 of native species. Multi-taxon monitoring proved to be an essential tool in investigating the added value of soil and bioengineering techniques in shallow landslide restoration, aiming to reconcile hazard control and ecological restoration through research conducted using 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) against 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 (Latitude: 43°98'78.36" N, Longitude: 10°31'47.41" E; Tuscany). The area lies between 450 and 600 m a.s.l. and is characterised by steep terrain. The slopes exhibit a North-West 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.

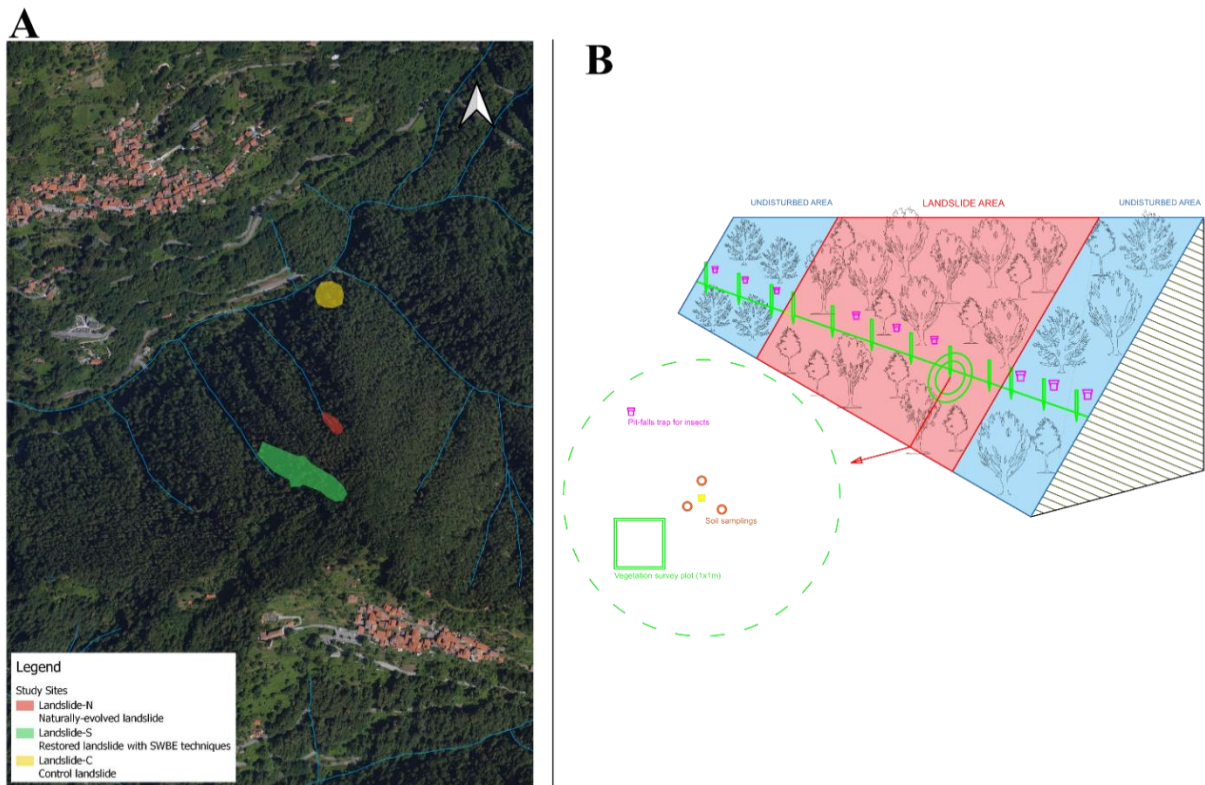


Fig. 1. Location of the three landslides studied. Panel A displays the location of the three landslides: SWBE: restored landslide (green area), natural: naturally evolved landslide (red area), control: control landslide (yellow area). Panel B provides a scheme of the multi-taxon sampling design applied during field trials in the three landslides.

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 Tuscan Region, three comparable landslides occurring during the same 1996 event were identified along the same slope. These sites (Fig. 1A) share consistent pedoclimatic conditions, exposure, and pre-event vegetation, but differ in their post-event management:

- Restored landslide (SWBE): a landslide covering approximately 1,3 ha (200 m long, 70 m wide). In 1998-99, 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, serving as a benchmark for unassisted vegetation recovery.
- Control landslide (*control*): An unrestored site with no subsequent anthropogenic disturbance, located at a slightly 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, *natural*1, *control*1) and in the immediately

adjacent, undisturbed forest (SWBE2, *natural2*, *control2*), as shown in the sampling design (Fig.1B).

2.2.Sampling design for biodiversity assessment

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

In the three landslides, we identified an indicative transect cutting across the study area; along the transect, 12 sampling stations were marked with wooden pickets at fixed intervals, numbered from right to left respectively: 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 diameter). Within each plot, a vegetation survey was conducted on a 1 m² area. In this area, soil samples were taken for physicochemical and microbiological analyses. Arthropod biodiversity has been assessed using pitfall traps, being a well-established method for soil fauna survey (Latella & 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 macro-arthropods have been identified as the three best-fit bio-indicators for biodiversity quality evaluation, for quantifying SWBE restoration projects' evolution 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 m² area (Kent, 2012), repeated for 12 pickets at each study site. To minimise subjective errors, the sampler positioned themselves at each picket and then randomly threw the square within a 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 Shannon index (Eq. 1). From a technical perspective, as demonstrated in various studies within 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. They serve as indicators of habitat quality and help in the assessment of potential vegetation. The species richness and abundance indices have been measured through 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 ($V=174.18 \text{ cm}^3$, $H=12$) to determine bulk density; these 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 ($<2 \text{ mm}$) to remove rock fragments and coarse particulate organic matter. An aliquot of each sample was dried at 105°C to constant weight for measuring pH, on a 1:2.5 (w/v) soil-to-deionised water suspension using an XS PC8 pH meter, and organic matter content, as loss-on-ignition after four hours at 460°C in a muffle furnace. Particle-size distribution was determined in a composite 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 this way were serially diluted up to 10^{-5} in sterile 0.8% NaCl solution. 100 μL of the dilutions 10^{-3} , 10^{-4} , 10^{-5} was spread over the surface of Tryptic Soy Agar medium (Pancreatic digest of casein 15.0 g/L, peptic digest of soybean meal 5 g/L, sodium chloride 5.0 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 evaluated for each dilution, and the CFU/g expressed with respect to the dry weight of the soil was calculated.

Community level physiological profile (CLPP) of the soils was evaluated using 100 μL of a thousandfold diluted soil to inoculate Ecoplates (Biolog TM, 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 uncoloured to violet in the presence of metabolically active cells. Wells containing carbon sources that can be metabolised by the inoculated microbial community become gradually 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 Omilog-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 = sum species richness (for soil fauna and vegetation species) and 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.

(Equation 1)
$$H' = - \sum p_i * \ln p_i$$

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 & Gobbi, 2015). The monitoring was conducted during 2024, from June to November, when macroinvertebrates are most active in terms of foraging and reproduction. Traps have been serviced every 15 days, and caught specimens have been 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 at the order or family taxonomic level. Taxonomic richness has been evaluated for alpha diversity comparisons between 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). 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 & 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). A Non-Metric Multidimensional Scaling

(NMDS) ordination, based on Bray-Curtis's 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 physical-chemical 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).

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 physical-chemical profiles between 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 main PCA components that contribute to site differences are soil pH, texture fraction and bulk density.

Multivariate analysis records significant differences between the internal (disturbed) and external (undisturbed) positions at all sites: SWBE ($p = 0.001$), *control* ($p = 0.003$), and *natural* ($p = 0.004$). 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 axis explained 53,3% of the total variance, driven mainly by silt, clay, sand and bulk density; the second axis explained 25,7%. In the *control* site (Fig. 2B), the first axis 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 axis explains 22,8% of the variance. In the *natural* site (Fig. 2C), the first axis explains 59,3% of the total variance and shows that clay rate 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 driving variables in site different conditions. This multivariate evidence confirms that the geomorphological event causes an ecological disturbance in the three sites.

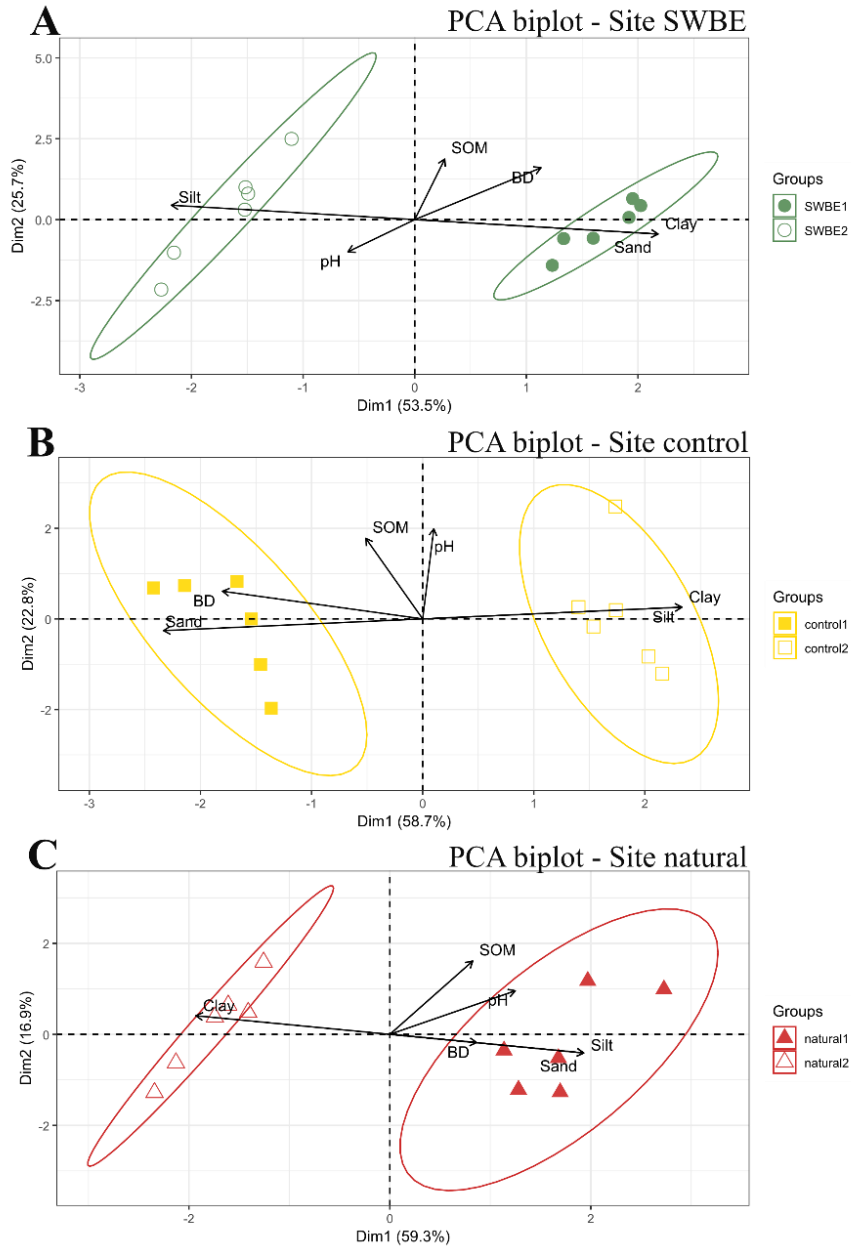


Figure 2: PCA biplot analyses for each study site. A SWBE site restored landslide (green); **B** Control site (yellow); **C** Natural site (red). The solid symbols represent the internal plot, while the empty symbols represent the external plot. The axes indicate the explained percentage of the total variance.

3.2. Composition and alpha diversity for herbaceous vegetation

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

Multivariate analyses (NMDS and PERMANOVA) confirmed floristic composition differences between the internal and external plots within each site (Fig. 3A-C). Floristic species communities of internal and external plots result in significant differences in SWBE ($p=0,004$), *control* ($p=0,015$) and *natural* ($p=0,013$). The SWBE site (Fig.3A) showed the highest 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 than external ones. Differently, in the *natural* internal plots, the alpha diversity indices decreased on average by 2 taxa and 0,4 in the Shannon index than in external plots. Instead, in the *control* site, alpha diversity indices displayed similar averages between internal and external plots.

Anova analysis and Tukey test were conducted for both alpha-diversity indices. For the taxa richness index (Fig.3D), no significant difference is detected, except for the SWBE1 and *natural*1 comparison ($p=0,006$). In Shannon index analysis (Fig.3E), results highlight statistically significant differences in three site/position comparisons. At the control site, both internal (*control*1, $p=0,009$) and external (*control*2, $p=0,035$) 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 ($p=0.001$), indicating different recovery dynamics between the SWBE and *natural* sites in the disturbed area. The external plots of the three study sites display comparable mean values of the Shannon index, with no significant difference. The control site maintained intermediate and stable values across both positions.

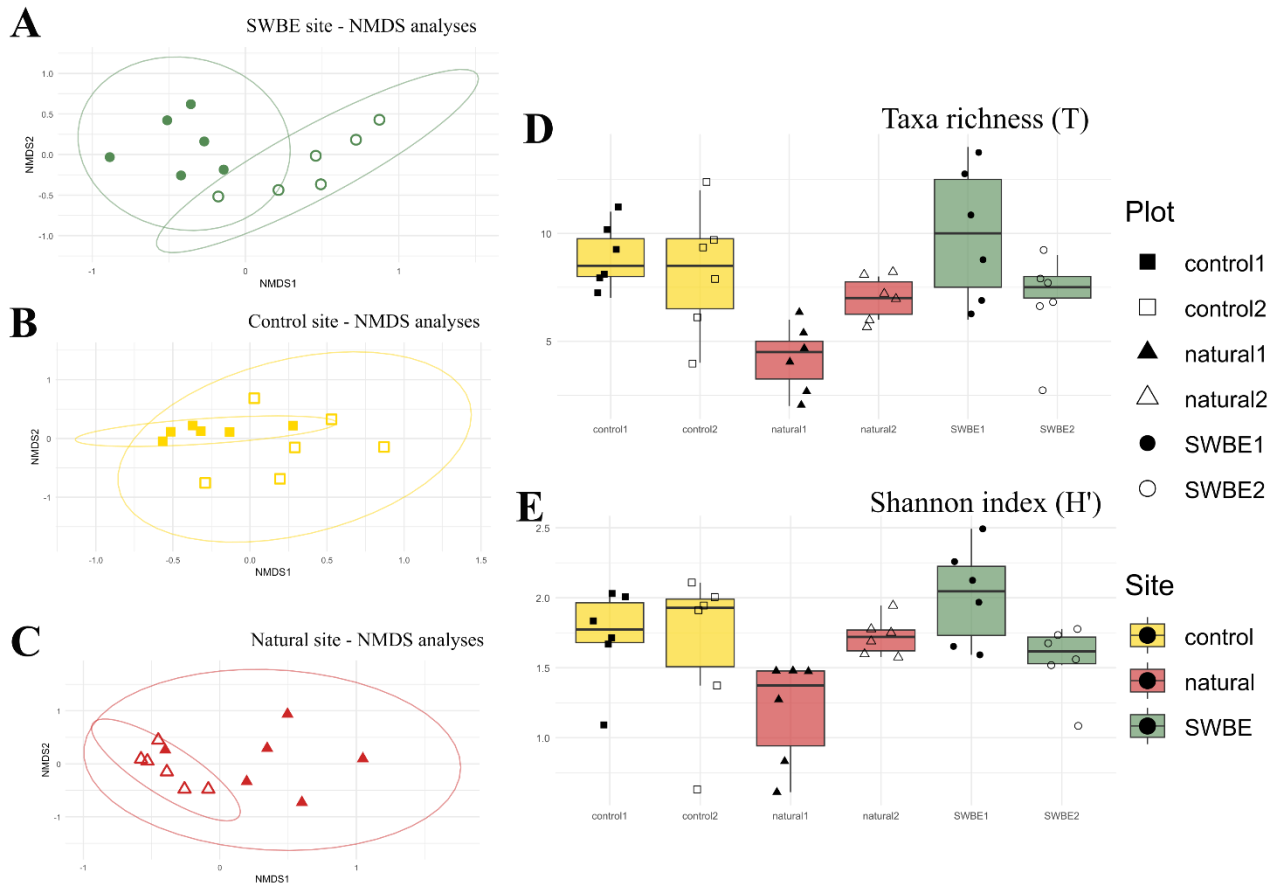


Figure 3: NMDS analyses and boxplot distribution of alpha-diversity indices of herbaceous component. *A.* NMDS analyses in SWBE site; *B.* NMDS analyses in control site; *C.* NMDS analyses in natural site; *D.* Boxplot for taxa richness (T) index; *E.* Boxplot for Shannon index (H'). Boxplot boxes represent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

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 into the below-ground biological compartments (soil microbiota and soil fauna) were specifically focused on the SWBE-restored and control sites. Community-Level Physiological Profiling (CLPP) via Biolog EcoPlates was employed, as it is highly effective at 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. 4). 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 different disturbance regimes. Pairwise comparisons confirmed that the internal landslide bodies exhibited comparable substrate utilisation to their respective undisturbed external sites. These findings indicate a post-disturbance metabolic recovery in both the actively restored (SWBE) and the control sites.

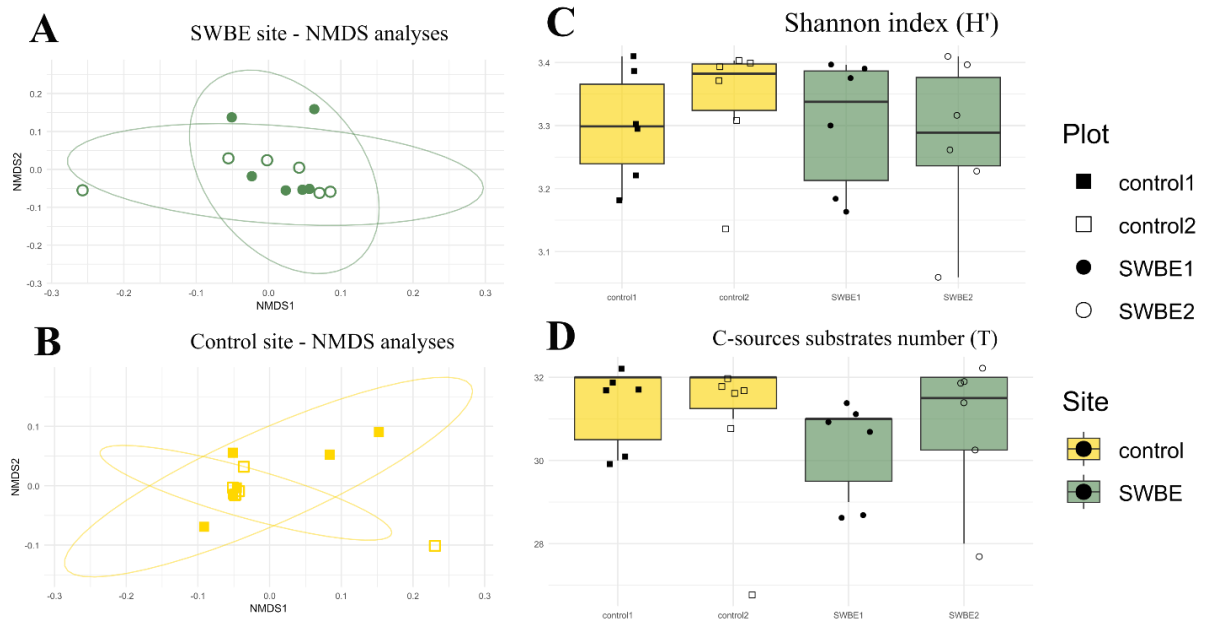


Figure 4: NMDS analyses and boxplot distribution of alpha-diversity indices based on carbon substrate utilisation by microbial communities. *A.* NMDS analyses in SWBE site; *B.* NMDS analyses in control site; *C.* Boxplot for Shannon index (H'); *D.* Boxplot representing the number of c-sources substrates used by microbial communities (T). Boxplot boxes represent the first quartile to the third quartile of observations, with the median indicated by a black horizontal line. The solid symbols represent the internal plot, while the empty symbols represent the external plot. The axes in the NMDS graph indicate the explained total variance percentage.

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 soil fauna resilience 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 indices investigations (Fig. 5D-E). Species richness exhibited no statistical differences between sites and internal/external positions. Similarly, for the Shannon diversity index, the ANOVA revealed no significant effect of site and position (SWBE site, $p=0.539$; control site, $p=0.99$). The boxplot trends (Fig. 5E) 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.

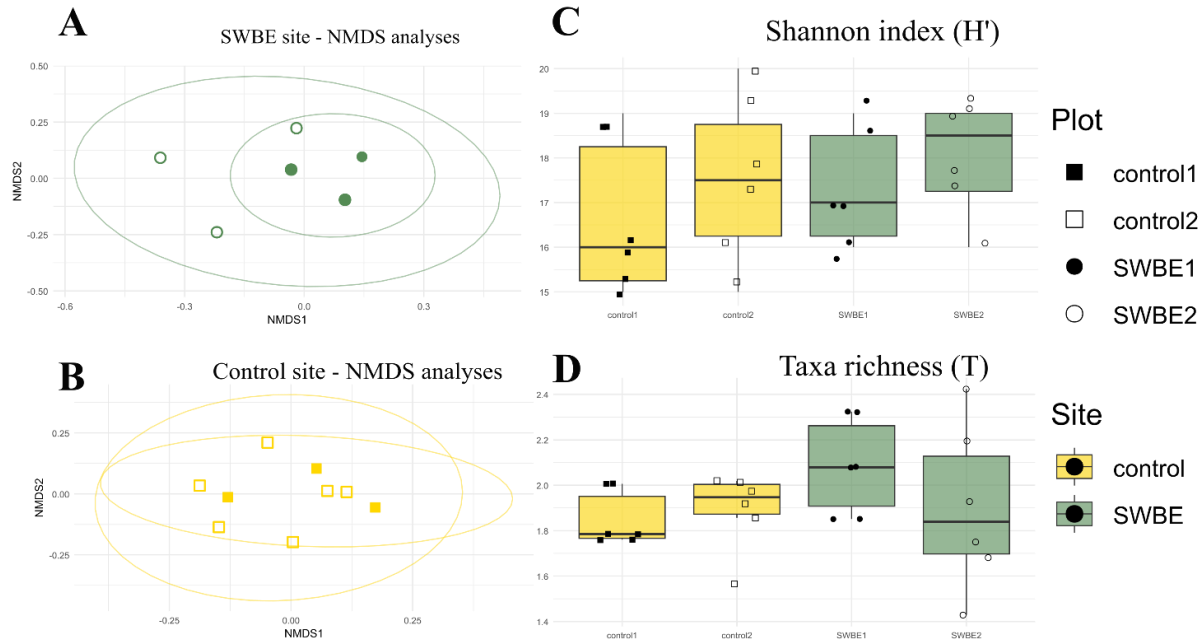


Figure 5: NMDS analyses and boxplot distribution of alpha-diversity indices of soil fauna communities. *A.* NMDS analyses in SWBE site; *B.* NMDS analyses in control site; *C.* Boxplot for Shannon index (H'); *D.* Boxplot for taxa richness (T). Boxplot boxes represent the first quartile to the third quartile of observations, with the median indicated by a black horizontal line. The solid symbols represent the internal plot, while the empty symbols represent the external plot. The axes in the NMDS graph indicate the explained total variance percentage.

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 interesting ecological dynamics in the SWBE restored, *control*, and *natural* sites (Fig.6); soil microorganisms and soil fauna showed interesting trends that deserve further investigation. We recognise that pseudoreplicates present an issue in the broader comparisons of our analyses. To mitigate this and engage in 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. These findings support the idea that the SWBE restoration project activated an ecological process that led to a different species composition, mitigating environmental stress features, specifically through soil erosion control and hydrological regulation (Preti et al., 2025).

Landslide disturbance effect 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 arboreal vegetation homogeneity 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 in the first PCA axis - underscores the impact of the geomorphological event on soil structure. Specifically, the strong influence of silt, clay, 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.



Figure 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 positioning of the sampling transects within each study area.

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) showing different trends within the three studied landslides. The restored site (SWBE) showed an increase in alpha diversity indices in the internal plots compared to the external ones, while there was a decrease in these in the

naturally evolved site (natural) and non-significant differences 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. Differently, the naturally evolved site (natural) displayed a decrease in alpha diversity indices compared to its external plots. In the natural site, the post-landslide regeneration of deeper-rooted trees and shrubs proceeds slowly (Buma & Pawlik, 2021; Preti et al., 2025), leading to conditions of environmental stress that exercise a strong natural selection pressure, reducing both specific richness and overall slope stability (Ata Ollah 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 adapted well 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 shown for the other two sites, suggesting that the increase in alpha diversity indices is due to vegetation fragmented into more communities compared to the lateral areas, similar to what was observed in other landslide vegetation monitoring (Gomes et al., 2020; Walker & 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) because of the bioengineering restoration project, compared to conditions of marked environmental stress in the lateral areas, which determine greater natural selection for species richness. According to other ecological studies (Moi et al., 2020; Sheil & 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 species more than the exclusion of those pre-existing to the disturbing event, increasing specific 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 different ecological dynamic that brings about 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 chestnut tree's root system. The type of vegetation and ground cover that is developing on the SWBE restored site is composed of species (alder and hornbeam) with better geotechnical characteristics (Bischetti et al., 2009), to ensure 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 & Mickovski, 2017; Gray & Sotir, 1996; Löbmann et al., 2020; Stokes et al., 2014), 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.

Ecological recovery of soil fauna and microbial communities

Microbial communities and soil fauna exhibited resilience and functional stability between disturbed and undisturbed areas, both in SWBE and control sites. Given the importance of soil microorganisms in terrestrial ecosystems and their symbiotic relationship with plants (Fagorzi et al., 2025; Philippot et al., 2013, 2021), it is worthwhile to investigate this further through additional analyses. The microbial physiology analyses (CLPP) revealed no significant differences in carbon source utilisation between disturbed and undisturbed plots at both sites. 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). This convergence indicates that microbial communities have fully recovered pre-landslide metabolic diversity, despite the same past disturbances.

Soil fauna displayed a similar response. NMDS ordinations and alpha-diversity metrics confirmed the absence of significant species composition between the internal and external plots in each site. In accordance with our results, previous evidence indicated the effectiveness of the SWBE technique on soil fauna in riparian environments (Calle et al., 2013; Cavaillé et al., 2013). Particularly in SWBE interventions involving the use of live wooden crib walls (Janssen et al., 2019) insects are indicators in terms 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 community managed to restore pre-disturbance conditions at both the restored and control sites, indicating that soil fauna possess effective ecological strategies, adapting even to changes in the composition of plant communities.

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, increasing the availability of trophic resources for plants, subsequently promoting an adaptation of species composition with the possibility of new species establishing. It would be interesting to study 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 undisturbed reference conditions, suggesting a full recovery of soil functional potential. Soil fauna communities successfully restored pre-disturbance conditions at both the SWBE and control sites, indicating their effective ecological adaptation.

Collectively, these findings highlight the ecological benefits of the application of SWBE techniques on shallow landslides, which couple structural stability with the reactivation of ecological dynamics. It would be useful to extend the study to other landslides, covering different climatic and geologic conditions, but also different SWBE techniques. 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.

Credit Authorship contribution statement:

Emanuele Giachi: Conceptualisation, Methodology, Data curation, Formal analysis, Investigation, Writing-original draft, Writing-review, and editing, Visualisation; Agnese Bellabarba: Conceptualisation, Investigation, Methodology, Formal analysis, Visualisation, Writing-Review & Editing; Francesca Decorosi: Methodology, Investigation, Data curation, Writing-Review & Editing; Gergely Ujyari: Investigations, Data curation, Writing-Review & Editing; Marco Cabrucci: Investigations, Data curation, Methodology; Lorenzo Tagliaferri: Investigations, Data curation, Writing-Review & Editing; Matteo Bracalini: Investigations, Data curation, Resources; Patrizia Sacchetti: Resources, Investigations, Data curation, Writing-Review & Editing; Giacomo Certini: Writing-Review & Editing, Resources, Investigations, Data curation, Formal analysis, Methodology, Supervision; Carlo Viti: Resources, Investigations, Methodology, Conceptualisation, Supervision, Writing-Review & Editing; Federico Preti: Conceptualisation, Methodology, Supervision, Project Administration, Funding Acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

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.

Data availability

Will be made available on request.

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References

- Ata Ollah Hosseini, S., Gorgandipour, M., & Abdi, E. (2019). Herbaceous biodiversity and soil properties of stabilised landslide area in northern mountain forest of Iran. *Maejo Int. J. Sci. Technol*, 2019(01), 19–28. www.mijst.mju.ac.th
- Bischetti, G. B., Chiaradia, E. A., Epis, T., & Morlotti, E. (2009). Root cohesion of forest species in the Italian Alps. *Plant and Soil*, 324(1), 71–89. <https://doi.org/10.1007/s11104-009-9941-0>
- Bischetti, G. B., De Cesare, G., Mickovski, S. B., Rauch, H. P., Schwarz, M., & Stangl, R. (2021). Design and temporal issues in Soil Bioengineering structures for the stabilisation of shallow soil movements. *Ecological Engineering*, 169. <https://doi.org/10.1016/j.ecoleng.2021.106309>
- Buma, B., & Pawlik, Ł. (2021). Post-landslide soil and vegetation recovery in a dry, montane system is slow and patchy. *Ecosphere*, 12(1). <https://doi.org/10.1002/ecs2.3346>
- Burrascano, S., Trentanovi, G., Paillet, Y., Heilmann-Clausen, J., Giordani, P., Bagella, S., Bravo-Oviedo, A., Campagnaro, T., Campanaro, A., Chianucci, F., De Smedt, P., Itziar, G. M., Matošević, D., Sitzia, T., Aszalós, R., Brazaitis, G., Andrea, C., Ettore, D. A., Doerfler, I., ... Ódor, P. (2021). Handbook of field sampling for multi-taxon biodiversity studies in European forests. In *Ecological Indicators* (Vol. 132). Elsevier B.V. <https://doi.org/10.1016/j.ecolind.2021.108266>
- Calle, Z., Henao-Gallego, N., Giraldo, C., & Armbrrecht, I. (2013). A Comparison of Vegetation and Ground-Dwelling Ants in Abandoned and Restored Gullies and Landslide Surfaces in the Western Colombian Andes. *Restoration Ecology*, 21(6), 729–735. <https://doi.org/10.1111/rec.12001>
- Cavaillé, P., Dommange, F., Daumergue, N., Loucougaray, G., Spiegelberger, T., Tabacchi, E., & Evette, A. (2013). Biodiversity assessment following a naturalness gradient of riverbank protection structures in French prealps rivers. *Ecological Engineering*, 53, 23–30. <https://doi.org/10.1016/j.ecoleng.2012.12.105>
- Cavaillé, P., Ducasse, L., Breton, V., Dommange, F., Tabacchi, E., & Evette, A. (2015). Functional and taxonomic plant diversity for riverbank protection works: Bioengineering techniques close to natural banks and beyond hard engineering. *Journal of Environmental Management*, 151, 65–75. <https://doi.org/10.1016/j.jenvman.2014.09.028>
- Cavaillé, P., Dumont, B., Van Looy, K., Floury, M., Tabacchi, E., & Evette, A. (2018). Influence of riverbank stabilization techniques on taxonomic and functional macrobenthic communities. *Hydrobiologia*, 807(1), 19–35. <https://doi.org/10.1007/s10750-017-3380-3>

de Jesús Arce-Mojica, T., Nehren, U., Sudmeier-Rieux, K., Miranda, P. J., & Anhuf, D. (2019). Nature-based solutions (NbS) for reducing the risk of shallow landslides: Where do we stand? In *International Journal of Disaster Risk Reduction* (Vol. 41). Elsevier Ltd. <https://doi.org/10.1016/j.ijdrr.2019.101293>

Debele, S. E., Leo, L. S., Kumar, P., Sahani, J., Ommer, J., Bucchignani, E., Vranić, S., Kalas, M., Amirzada, Z., Pavlova, I., Shah, M. A. R., Gonzalez-Ollauri, A., & Di Sabatino, S. (2023). Nature-based solutions can help reduce the impact of natural hazards: A global analysis of NBS case studies. *Science of the Total Environment*, 902, 165824. <https://doi.org/10.1016/j.scitotenv.2023.165824>

Di Nuzzo, L., Vallese, C., Benesperi, R., Giordani, P., Chiarucci, A., Di Cecco, V., Di Martino, L., Di Musciano, M., Gheza, G., Lelli, C., Spitale, D., & Nascimbene, J. (2021). Contrasting multitaxon responses to climate change in Mediterranean mountains. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-83866-x>

Eisenhauer, N., Lanoue, A., Strecker, T., Scheu, S., Steinauer, K., Thakur, M. P., & Mommer, L. (2017). Root biomass and exudates link plant diversity with soil bacterial and fungal biomass. *Scientific Reports*, 7. <https://doi.org/10.1038/srep44641>

Fagorzi, C., Karalija, E., & Bellabarba, A. (2025). Editorial: Climate is changing: harnessing plant-microbe interactions for sustainable agriculture in arid areas. *Frontiers in Microbiology*, 16. <https://doi.org/10.3389/fmicb.2025.1687842>

Fattet, M., Fu, Y., Ghestem, M., Ma, W., Foulonneau, M., Nespoulous, J., Le Bissonnais, Y., & Stokes, A. (2011). Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength. *Catena*, 87(1), 60–69. <https://doi.org/10.1016/j.catena.2011.05.006>

Fox, John., & Weisberg, Sanford. (2019). *An R companion to applied regression*. SAGE Publications, Inc.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soil Analysis* (2nd edn) – Part I. Agronomy Monographs no. 9. American Society of Agronomy and Soil Science of Society of America, Madison, WI, USA, pp. 383–411.

Giachi, E., Giambastiani, Y., Giannetti, F., Dani, A., & Preti, F. (2024). Root System Evolution Survey in a Multi-Approach Method for SWBE Monitoring: A Case Study in Tuscany (Italy). *Sustainability (Switzerland)*, 16(10). <https://doi.org/10.3390/su16104022>

Giupponi, L., Borgonovo, G., Giorgi, A., & Bischetti, G. B. (2019). How to renew soil bioengineering for slope stabilization: some proposals. *Landscape and Ecological Engineering*, 15, 37–50. <https://doi.org/10.1007/s11355-018-0359-9>

Gomes, P. I. A., Aththanayake, U., Deng, W., Li, A., Zhao, W., & Jayathilaka, T. (2020). Ecological fragmentation two years after a major landslide: Correlations between vegetation indices and geo-environmental factors. *Ecological Engineering*, 153. <https://doi.org/10.1016/j.ecoleng.2020.105914>

Gonzalez-Ollauri, A., & Mickovski, S. B. (2017). Shallow landslides as drivers for slope ecosystem evolution and biophysical diversity. *Landslides*, 14(5), 1699–1714. <https://doi.org/10.1007/s10346-017-0822-y>

Gray, D. H., & Sotir, R. B. (1996). *Biotechnical and Soil Bioengineering Slope Stabilization: A practical guide for erosion control* (J. W. & S. Inc. Wiley Inter-science Publication, Ed.).

Grime, J. P. (1998). Benefits of plant diversity to ecosystems: immediate, filter and founder effects. *Journal of Ecology*, 86(6), 902–910. <https://doi.org/10.1046/j.1365-2745.1998.00306.x>

He, Y., Lan, Y., Zhang, H., & Ye, S. (2022). Research characteristics and hotspots of the relationship between soil microorganisms and vegetation: A bibliometric analysis. In *Ecological Indicators* (Vol. 141). Elsevier B.V. <https://doi.org/10.1016/j.ecolind.2022.109145>

Herrick, J. E., Schuman, G. E., & Rango, A. (2006). Monitoring ecological processes for restoration projects. *Journal for Nature Conservation*, 14(3–4), 161–171. <https://doi.org/10.1016/j.jnc.2006.05.001>

IUCN. (2016). *Nature-based solutions to address global societal challenges* (E. Cohen-Shacham, G. Walters, C. Janzen, & S. Maginnis, Eds.). IUCN International Union for Conservation of Nature. <https://doi.org/10.2305/IUCN.CH.2016.13.en>

IUSS Working Group WRB (2022) World Reference Base for soil resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Izquierdo, I., Caravaca, F., Alguacil, M. M., Hernández, G., & Roldán, A. (2005). Use of microbiological indicators for evaluating success in soil restoration after revegetation of a mining area under subtropical conditions. *Applied Soil Ecology*, 30(1), 3–10. <https://doi.org/10.1016/j.apsoil.2005.02.004>

Janssen, P., Cavaillé, P., Bray, F., & Evette, A. (2019). Soil bioengineering techniques enhance riparian habitat quality and multi-taxonomic diversity in the foothills of the Alps and Jura Mountains. *Ecological Engineering*, 133, 1–9. <https://doi.org/10.1016/j.ecoleng.2019.04.017>

Janssen, P., Dommanget, F., Cavaillé, P., & Evette, A. (2021). Does soil bioengineering benefits aquatic biodiversity? An empirical study of the relative influence of local and regional

drivers on benthic macroinvertebrate assemblages. *Ecological Engineering*, 168. <https://doi.org/10.1016/j.ecoleng.2021.106287>

Kakinuma, H., Tsou, C. Y., Higaki, D., Kawakami, R., & Gautum, C. S. (2025). Assessing the long-term effectiveness and socioeconomic benefits associated with ecosystem-based disaster risk reduction measures aimed at mitigating the impact of sediment-related events in Nepal. *Progress in Disaster Science*, 28. <https://doi.org/10.1016/j.pdisas.2025.100464>

Kent, M. . (2012). *Vegetation description and data analysis : a practical approach* (Second). Wiley-Blackwell.

Kettenhuber, P. L. W., dos Santos Sousa, R., Dewes, J. J., Rauch, H. P., Sutili, F. J., & Hörbinger, S. (2023). Performance assessment of a soil and water bioengineering work on the basis of the flora development and its associated ecosystem processes. *Ecological Engineering*, 186. <https://doi.org/10.1016/j.ecoleng.2022.106840>

Latella, L., & Gobbi, M. (2015). *La fauna del suolo. Tassonomia, ecologia e metodi di studio dei principali gruppi di invertebrati terrestri italiani*. (Vol. 2).

Löbmann, M. T., Geitner, C., Wellstein, C., & Zerbe, S. (2020). The influence of herbaceous vegetation on slope stability – A review. In *Earth-Science Reviews* (Vol. 209). Elsevier B.V. <https://doi.org/10.1016/j.earscirev.2020.103328>

Lu, P.-L. (2014). *Using multiple vegetation layers to reduce the risk of rainfall-induced landslides and facilitate post-landslide slope rehabilitation*. 2(2), 13–17. <http://www.access-internationaljournals.org/arbs>

Martin, F. M., Janssen, P., Bergès, L., Dupont, B., & Evette, A. (2021). Higher structural connectivity and resistance against invasions of soil bioengineering over hard-engineering for riverbank stabilisation. *Wetlands Ecology and Management*, 29(1), 27–39. <https://doi.org/10.1007/s11273-020-09765-6>

Mickovski, S. B. (2021). Re-thinking soil bioengineering to address climate change challenges. *Sustainability (Switzerland)*, 13(6). <https://doi.org/10.3390/su13063338>

Moi, D. A., García-Ríos, R., Hong, Z., Daquila, B. V., & Mormul, R. P. (2020). Intermediate Disturbance Hypothesis in Ecology: A Literature Review. *Annales Zoologici Fennici*, 57(1–6), 67. <https://doi.org/10.5735/086.057.0108>

Moreau, C., Cottet, M., Rivière-Honegger, A., François, A., & Evette, A. (2022). Nature-based solutions (NbS): A management paradigm shift in practitioners' perspectives on riverbank soil bioengineering. *Journal of Environmental Management*, 308. <https://doi.org/10.1016/j.jenvman.2022.114638>

Nehren, U., Arce-Mojica, T., Barrett, A. C., Cueto, J., Doswald, N., Janzen, S., Lange, W., Vargas, A. O., Pirazan-Palomar, L., Renaud, F. G., Sandholz, S., Sebesvari, Z., Sudmeier-

Rieux, K., & Walz, Y. (2023). Towards a typology of nature-based solutions for disaster risk reduction. *Nature-Based Solutions*, 3, 100057. <https://doi.org/10.1016/j.nbsj.2023.100057>

Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Kylvik, M., Rey, F., van Dijk, J., Vistad, O. I., Wilkinson, M. E., & Wittmer, H. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. In *Science of the Total Environment* (Vol. 579, pp. 1215–1227). Elsevier B.V. <https://doi.org/10.1016/j.scitotenv.2016.11.106>

Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Borman, T., Carvalho, G., Chirico, M., De Caceres, M., ... Weedon, J. (2001). *vegan: Community Ecology Package*. In *CRAN: Contributed Packages*. <https://doi.org/10.32614/CRAN.package.vegan>

Pérez-Valera, E., Verdú, M., Navarro-Cano, J. A., & Goberna, M. (2020). Soil microbiome drives the recovery of ecosystem functions after fire. *Soil Biology and Biochemistry*, 149. <https://doi.org/10.1016/j.soilbio.2020.107948>

Philippot, L., Griffiths, B. S., & Langenheder, S. (2021). Microbial Community Resilience across Ecosystems and Multiple Disturbances. *Microbiology and Molecular Biology Reviews*, 85(2). <https://doi.org/10.1128/mmbr.00026-20>

Philippot, L., Raaijmakers, J. M., Lemanceau, P., & Van Der Putten, W. H. (2013). Going back to the roots: The microbial ecology of the rhizosphere. In *Nature Reviews Microbiology* (Vol. 11, Number 11, pp. 789–799). <https://doi.org/10.1038/nrmicro3109>

Preti, F., Capobianco, V., & Sangalli, P. (2022). Soil and Water Bioengineering (SWB) is and has always been a nature-based solution (NBS): a reasoned comparison of terms and definitions. *Ecological Engineering*, 181. <https://doi.org/10.1016/j.ecoleng.2022.106687>

Preti, F., Dani, A., Giambastiani, Y., & Giachi, E. (2025). Slope stability time evolution of a shallow landslide restored by Soil and Water Bioengineering (SWBE) techniques: A case study in Northwest Tuscany (Italy). *Ecological Engineering*, 214, 107570. <https://doi.org/10.1016/j.ecoleng.2025.107570>

Punetha, P., Samanta, M., & Sarkar, S. (2019). Bioengineering as an effective and eco-friendly soil slope stabilization method: A review. In *Advances in Natural and Technological Hazards Research* (Vol. 50, pp. 201–224). Springer Netherlands. https://doi.org/10.1007/978-3-319-77377-3_10

R Core Team. (2024). “*R: a language and environment for statistical computing*” *R Foundation for Statistical Computing*.

Rauch, H. P., von der Thannen, M., Raymond, P., Mira, E., & Evette, A. (2022). Ecological challenges* for the use of soil and water bioengineering techniques in river and coastal engineering projects. *Ecological Engineering*, 176. <https://doi.org/10.1016/j.ecoleng.2021.106539>

Rey, F., Bifulco, C., Bischetti, G. B., Bourrier, F., De Cesare, G., Florineth, F., Graf, F., Marden, M., Mickovski, S. B., Phillips, C., Peklo, K., Poesen, J., Polster, D., Preti, F., Rauch, H. P., Raymond, P., Sangalli, P., Tardio, G., & Stokes, A. (2019). Soil and water bioengineering: Practice and research needs for reconciling natural hazard control and ecological restoration. In *Science of the Total Environment* (Vol. 648, pp. 1210–1218). Elsevier B.V. <https://doi.org/10.1016/j.scitotenv.2018.08.217>

Rey, F., Dupire, S., & Berger, F. (2024). Forest-based solutions for reconciling natural hazard reduction with biodiversity benefits. *Nature-Based Solutions*, 5, 100114. <https://doi.org/10.1016/j.nbsj.2024.100114>

Rousset, J., Piton, G., François, A., Didier, M., & Evette, A. (2025). Biogeomorphic assessment of natural streambank structures in the Alps: A step to improve soil and water bioengineering techniques. *Earth Surface Processes and Landforms*, 50(9). <https://doi.org/10.1002/esp.70126>

Sheil, D., & Burslem, D. F. R. P. (2013). Defining and defending Connell's intermediate disturbance hypothesis: a response to Fox. *Trends in Ecology & Evolution*, 28(10), 571–572. <https://doi.org/10.1016/j.tree.2013.07.006>

Sidle, R. C., & Bogaard, T. A. (2016). Dynamic earth system and ecological controls of rainfall-initiated landslides. In *Earth-Science Reviews* (Vol. 159, pp. 275–291). Elsevier B.V. <https://doi.org/10.1016/j.earscirev.2016.05.013>

Smith, D. J., Wynn-Thompson, T. M., Stremler, M. A., Williams, M. A., Seiler, J. R., & Hession, W. C. (2023). Root reinforcement and extracellular products reduce streambank fluvial erosion. *Science of the Total Environment*, 896. <https://doi.org/10.1016/j.scitotenv.2023.165125>

Stokes, A., Atger, C., Bengough, A. G., Fourcaud, T., & Sidle, R. C. (2009). Desirable Plant root traits for protecting natural and engineered slopes against landslides. In *Plant and Soil* (Vol. 324, Number 1, pp. 1–30). <https://doi.org/10.1007/s11104-009-0159-y>

Stokes, A., Douglas, G. B., Fourcaud, T., Giadrossich, F., Gillies, C., Hubble, T., Kim, J. H., Loades, K. W., Mao, Z., McIvor, I. R., Mickovski, S. B., Mitchell, S., Osman, N., Phillips, C., Poesen, J., Polster, D., Preti, F., Raymond, P., Rey, F., ... Walker, L. R. (2014). Ecological mitigation of hillslope instability: Ten key issues facing researchers and practitioners. In *Plant*

and Soil (Vol. 377, Numbers 1–2, pp. 1–23). Kluwer Academic Publishers.
<https://doi.org/10.1007/s11104-014-2044-6>

Su, X., Jia, J., Zhang, J., Li, X., & Zhang, M. (2024). Spatiotemporal evolutionary characteristics of vegetation restoration after historical earthquake landslides from 1985 to 2020: A case study of Tianshui City, China. *Ecological Indicators*, 169. <https://doi.org/10.1016/j.ecolind.2024.112798>

Symmank, L., Natho, S., Scholz, M., Schröder, U., Raupach, K., & Schulz-Zunkel, C. (2020). The impact of bioengineering techniques for riverbank protection on ecosystem services of riparian zones. *Ecological Engineering*, 158. <https://doi.org/10.1016/j.ecoleng.2020.106040>

Takaoka, S. (2024). A landscape-level study on vegetation richness of ancient landslide areas. *Progress in Physical Geography*, 48(1), 45–59. <https://doi.org/10.1177/03091333231206314>

Tisserant, M., Bourgeois, B., González, E., Evette, A., & Poulin, M. (2021). Controlling erosion while fostering plant biodiversity: A comparison of riverbank stabilization techniques. *Ecological Engineering*, 172. <https://doi.org/10.1016/j.ecoleng.2021.106387>

Tisserant, M., González-Sargas, E., Evette, A., Bourgeois, B., & Poulin, M. (2024). A functional characterization of bioengineered plant communities along riverbanks. *Ecological Engineering*, 204. <https://doi.org/10.1016/j.ecoleng.2024.107279>

Walker, L. R., & Shiels, A. B. (2013). *Landslide Ecology* (1st ed.). Cambridge University Press.

Walker, L. R., Velázquez, E., & Shiels, A. B. (2009). Applying lessons from ecological succession to the restoration of landslides. *Plant and Soil*, 324(1), 157–168. <https://doi.org/10.1007/s11104-008-9864-1>

Zuur, A. F., Ieno, E. N., & Elphick, C. S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution*, 1(1), 3–14. <https://doi.org/10.1111/j.2041-210x.2009.00001.x>

5. CONCLUSIONS

This research provides an integrated assessment of Soil and Water Bioengineering (SWBE) interventions applied to shallow landslide restoration, combining long-term slope stability analysis, multidisciplinary monitoring methodologies, and multi-taxon biodiversity assessment. By jointly addressing technical performance and ecological dynamics, the study contributes to bridging the persistent gap between bioengineering hazard mitigation and ecosystem-based restoration approaches.

5.1. *Main Findings*

The results demonstrate that Soil and Water Bioengineering (SWBE) interventions can effectively promote both hydrogeological stability and ecological recovery over medium to long temporal scales. By jointly addressing technical performance and biological dynamics, the findings indicate that SWBE interventions can reactivate native ecological processes while simultaneously ensuring sustainable slope stabilisation in a landslide-affected area.

Empirical evidence for long-term slope stability

The para-natural succession initiated by the SWBE works implemented in 1998 led to the development of a stable and well-structured topsoil, supporting the establishment of native vegetation communities and the progressive enhancement of root-mediated soil reinforcement. Vegetation monitoring revealed structural dynamics consistent with forest maturation processes, including a reduction in stem density accompanied by an increase in basal area, ultimately contributing to improved slope stability.

Slope stability modelling performed using SSAP freeware confirmed that the combined effects of vegetation development and bioengineering structures increased the factor of safety (Fs), even under critical soil saturation scenarios comparable to extreme rainfall events. Crucially, as detailed in Figures 10–13 of Manuscript 3, the quantitative analysis of soil–root reinforcement provides the mechanical evidence for these claims. While structural elements such as wooden crib walls provided immediate post-event stabilisation, they naturally undergo gradual degradation. The data highlight a critical transfer phase: as the inert timber elements decay, the living component—specifically the enhanced root cohesion provided by matured *Salix* and native forest species—progressively assumes the mechanical load. This confirms the fundamental role of vegetation in sustaining long-term mechanical effectiveness, successfully transitioning the slope from an engineered structure to a self-sustaining, reinforced soil-root matrix.

Ecological trajectories and multi-taxon biodiversity

From an ecological perspective, the application of SWBE techniques resulted in enhanced alpha diversity and ecosystem functionality, especially within the herbaceous vegetation layer, which proved to be a sensitive indicator of restoration success. However, a pivotal finding of this research concerns the divergence in successional trajectories between assisted restoration and natural evolution. Non-Metric Multidimensional Scaling (NMDS) ordination, based on Bray–Curtis dissimilarity, revealed a structured compositional separation between the herbaceous communities of the SWBE-restored plots and those of plots undergoing natural succession. The engineered sites exhibited higher internal similarity. Rather than simply accelerating natural succession, bioengineering interventions promote a distinct "para-natural" trajectory, leading to plant assemblages specifically structured for and adapted to the stabilised soil conditions.

Despite this divergence in aboveground beta-diversity, soil microbial communities exhibited a high degree of functional recovery, reaching alpha-diversity levels comparable to undisturbed conditions. This highlights a profound synergistic plant–soil–microbe interaction within the restored sites. The specific root systems of selected pioneering species drive the rhizosphere microbiome, promoting the establishment of functional microbial guilds. These microorganisms play a critical role in producing extracellular polymeric substances that enhance soil aggregation, thereby improving the soil's shear strength and hydraulic conductivity beyond mere mechanical root anchoring (Bardgett & van der Putten, 2014; Fattet et al., 2011).

This functional complementarity indicates that, while the taxonomic composition of the plant communities differs from naturally evolving landslides, the SWBE-restored slope has successfully re-established the belowground machinery necessary for nutrient cycling and organic matter decomposition. While soil fauna displayed intermediate responses influenced by ongoing habitat heterogeneity and microclimatic factors, the integration of aboveground vegetation patterns with belowground microbial profiles reveals that SWBE techniques engineer a highly resilient ecological state. Ultimately, this validates their role as authentic Nature-Based Solutions (NBS) capable of delivering multiple ecosystem services alongside primary hazard mitigation. Overall, the results indicate that SWBE interventions can reactivate native ecological processes while simultaneously ensuring slope stabilisation in a landslide-affected area.

5.2. *Methodological Innovation*

A key contribution of this research lies in the development and application of a multidisciplinary, long-term monitoring framework adapted to SWBE interventions. The main innovative aspect of this methodology concerns the adoption of a comprehensive sampling design,

developed through collaboration with experts in pedology, microbiology, entomology, and botany. The primary objective was to maximise the correlations between soil characteristics and selected biodiversity indicators: vegetation (arboreal, shrubby, and herbaceous), soil microorganisms, and soil fauna. To ensure replicability even in hilly and mountainous environments characterised by steep slopes and complex accessibility, a specific field protocol was established: transects were traced along the slope contour, with stakes placed at regular intervals to mark the centre of virtual circular test areas for sampling and surveys.

While this holistic integration of various disciplines provided a deep understanding of ecosystem recovery, a critical procedural insight emerged regarding the efficiency of the biological indicators. Our field surveys demonstrated that monitoring the herbaceous layer is the most functional and cost-effective approach in terms of survey time and resource allocation, particularly when compared to the demanding sampling protocols required for microbial communities and soil fauna. To identify habitat evolutionary trajectories, herbaceous species proved to be the most highly responsive and sensitive indicators. Due to their rapid life cycles, they reflect environmental shifts and successional dynamics much faster than arboreal species, whose extended growth periods tend to mask short-to-medium-term ecological changes. Consequently, the findings suggest that implementing a standardised, multi-seasonal, and multi-year monitoring protocol focused primarily on herbaceous vegetation dynamics can provide valid, actionable insights into the ecological evolution and overall success of SWBE-restored sites.

Complementing this field-based ecological approach, the integration of remote sensing techniques (e.g., NDVI-based vegetation indices), geoelectrical investigations, and geotechnical modelling provides a robust methodology for assessing both technical performance and vegetation monitoring over time. The use of vegetation indices demonstrated strong potential for monitoring the spatial and temporal evolution of SWBE works, offering an additional cost-effective tool to support maintenance planning and performance forecasting. Similarly, geoelectrical methods, although still underutilised in SWBE monitoring, proved valuable for indirectly assessing root system development and subsurface structure. Together, these approaches move beyond traditional assessments focused solely on structural integrity, aiming to maximise the effects on biodiversity and enabling a more comprehensive evaluation of SWBE effectiveness.

5.3. *Implications for SWBE Design and Management*

The findings of this study have important implications for the design, implementation, and long-term management of SWBE works. The demonstrated synergy between vegetation development and slope stability underscores the necessity of integrating ecological considerations into the very early design phases of bioengineering interventions. Because the long-term safety of these works relies on the critical "handover" phase—where decaying structural elements, such as wooden crib walls, transfer the mechanical load to biological root reinforcement—vegetation cannot be treated as a secondary or merely aesthetic component. Consequently, species selection, planting density, and vegetation management strategies must be explicitly aligned with both strict geotechnical requirements and the desired "para-natural" ecological succession trajectories.

Furthermore, the adoption of the integrated monitoring protocols proposed in this research can significantly enhance the technical performance, functional efficiency, and overall durability of SWBE systems. By employing targeted and cost-effective monitoring strategies—such as tracking the highly responsive herbaceous layer alongside the use of remote sensing indices (e.g., NDVI)—practitioners can efficiently evaluate both ecological health and structural integrity. Continuous, multi-seasonal monitoring allows for the early detection of structural vulnerabilities or ecological stagnation, facilitating timely, adaptive management interventions before critical slope failures occur.

Ultimately, the methodological framework and empirical evidence provided in this thesis offer a practical foundation for developing evidence-based guidelines and best practices. For stakeholders, land managers, and public authorities operating in landslide-prone environments, this research demonstrates how to effectively translate ecological outcomes into quantifiable Ecosystem Services, particularly regulating services such as erosion control, slope stabilisation, and water regulation. By formally recognising and managing SWBE interventions as multi-functional Nature-Based Solutions (NBS), policymakers can promote more resilient and sustainable land management strategies that transcend the limitations of traditional hard-engineering paradigms.

5.4. *Limitations of the study*

Despite the robustness and the multidisciplinary nature of the results obtained, this study is subject to certain genuine limitations, primarily related to its spatial scale, site-specific conditions, and temporal framework. While the findings yield highly interesting and detailed insights into post-disturbance ecological trajectories, they remain inherently case-specific. A

major methodological constraint encountered during the research design was the extreme logistical and geographical difficulty in identifying multiple, strictly comparable paired study sites. Specifically, it proved highly challenging to locate landslides left to natural evolution in close spatial proximity to equivalent landslides restored with SWBE techniques that also shared identical baseline climatic, geological, and geomorphological conditions. Consequently, this scarcity of perfectly paired sites restricted the current investigation to a focused, although in-depth, site comparison. Furthermore, the evaluation is constrained to a specific range of bioengineering techniques (e.g., wooden crib walls).

Equally important is the limitation regarding the temporal scope of the ecological surveys. While the established sampling design is highly structured and replicable, time and resource constraints precluded the repetition of the field campaigns across multiple consecutive years. Relying on contemporary temporal "snapshots" of the ecological communities, rather than a continuous, multi-year monitoring dataset based on the same sampling grid, restricts the ability to precisely track interannual successional shifts and trace the exact timeline of the evolutionary trajectories.

Additionally, although this research successfully initiated a much-needed multi-taxon assessment—addressing an explicitly identified gap in SWBE restoration ecology—the simultaneous and exhaustive collection of data across all biological compartments (vegetation, soil microbiome, and soil fauna) proved to be highly resource- and time-intensive. As a result, the overall volume of the multi-taxon dataset collected was inherently limited. A more extensive and temporally repeated multi-taxon data collection would be required to perform more complex statistical cross-correlations between different trophic levels and to fully unravel the intricate web of plant-soil-microbe interactions.

5.5. *Future Research*

To build upon the foundation established in this thesis and address the limitations, future research should aim to extend the proposed monitoring framework to multiple landslide sites characterised by different climatic, geological, and geomorphological settings, as well as to a broader spectrum of SWBE solutions. Long-term and multi-site monitoring is particularly needed to statistically validate beta-diversity patterns and community assembly processes across contrasting restoration trajectories, including various SWBE-restored and naturally evolving landslides.

Furthermore, deeper investigations into synergistic plant–soil–microorganism interactions (such as functional metagenomic mapping), continuous root system dynamics, and the

exact degradation rates of structural bioengineering elements would provide critical insights into the precise mechanisms underpinning both ecological resilience and mechanical stability. Finally, the development and refinement of standardised ecological and functional indicators would significantly facilitate the comparison of SWBE effectiveness across different independent studies. Translating these ecological metrics into quantifiable Ecosystem Services will ultimately support the wider policy integration and broader adoption of SWBE techniques as scalable Nature-Based Solutions for climate change adaptation and hydrogeological risk mitigation.

In the context of increasing hydrogeological instability driven by climate change, SWBE techniques represent a strategic and multifunctional approach for slope stabilisation and environmental restoration. This research demonstrates that technically efficient SWBE solutions can be compatible with, and even promote, biodiversity enhancement and the establishment of stable and resilient ecosystems. By integrating engineering performance with ecological evaluation, the study contributes to advancing SWBE from a primarily technical intervention towards a holistic, ecosystem-based strategy for sustainable land management. The outcomes of this thesis not only advance scientific understanding of SWBE processes but also provide concrete tools and insights for improving the design, monitoring, and management of bioengineering works. Ultimately, such integrative approaches are essential for maximising the technical, ecological, and socio-environmental benefits of Nature-Based Solutions in mountainous and landslide-prone regions.

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“La montagna più alta rimane sempre dentro di noi.” (Walter Bonatti)

PAPERS

- Giachi, E.; Giambastiani, Y.; Giannetti, F.; Dani, A.; Preti, F. Root System Evolution Survey in a Multi-Approach Method for SWBE Monitoring: A Case Study in Tuscany (Italy). *Sustainability* 2024, 16, 4022. <https://doi.org/10.3390/su16104022>
- Preti F., Dani A., Giambastiani Y., Giachi E. Slope stability time evolution of a shallow landslide restored by Soil and Water Bioengineering (SWBE) techniques: A case study in Northwest Tuscany (Italy), *Ecological Engineering* 2025, 214-107570, ISSN 0925-8574. <https://doi.org/10.1016/j.ecoleng.2025.107570>
- Giachi, E., Bellabarba, A., Decorosi, F., Ujvári, G., Cabrucci, M., Tagliaferri, L., Bracalini, M., Sacchetti, P., Certini, G., Viti, C., Preti, F. Soil and water bioengineering impacts on biodiversity: multi-taxon monitoring in a landslide restoration project, *Ecological Engineering*, submitted in November 2025.

CONFERENCE TALKS AND SEMINARS

- E. Giachi, M. Cabrucci, A. Bellabarba, F. Decorosi, M. Pollastrini, C. Viti, F. Preti. Soil and Water Bioengineering Techniques' Effects on Biodiversity in Tuscany. Full Talk. Convegno “La ricerca nel settore dell’idraulica agraria, dell’irrigazione e delle sistemazioni idraulico-forestali - Giornate di Studio in onore del Prof. Giuseppe Provenzano”, Palermo, Italy, 4-5/12/2023 - Oral presentation.
- Dani, A., Giachi, E., Preti, F., Cabrucci, M., Pollastrini, M., Bellabarba, A., Viti, C., Decorosi, F., and Giambastiani, Y. Long-term landslide ecological monitoring: the case of Pomezana, Tuscany., Poster. EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-20621, <https://doi.org/10.5194/egusphere-egu24-20621>, 2024.
- Giachi, E., Preti, F., Pollastrini, M., Cabrucci, M., Viti, C., Bellabarba, A., Decorosi, F., and Dani, A. Soil and Water BioEngineering (SWBE) techniques effects on Biodiversity, in Tuscany (Italy), Full Talk. EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-19131, <https://doi.org/10.5194/egusphere-egu24-19131>, 2024.
- Giachi E., Cabrucci M., Bellabarba A., Decorosi F., Dani A., Pollastrini M., Viti C., Preti F. Soil and Water Bioengineering (SWBE): biodiversity monitoring in Tuscany (Italy). Poster. AIIA mid-term 2024, Padova, Italy, June 16-17 - Poster presentation.
- Giachi E., Cabrucci M., Decorosi F., Viti C., Dani A., Preti F. Long-term landslide biodiversity monitoring: the case of Pomezana, Tuscany. Poster. NBFC Biodiversity PhD Day, Padova, 3-5 June 2024 - Poster presentation.
- Giachi E.*, Cabrucci M., Bellabarba A., Decorosi F., Dani A., Sacchetti P., Certini G., Viti C., Preti F. Soil and Water Bioengineering shallow landslide restoration project enhances biodiversity conditions: a study case in Tuscany (Italy). EGU General Assembly 2025, Vienna, Austria, 28 Apr –02 Mag 2025 – Poster presentation
- Giachi E.*, Cabrucci M., Bellabarba A., Decorosi F., Dani A., Sacchetti P., Certini G., Viti C., Preti F. Soil and Water Bioengineering (SWBE): Slope Stability Evolution and Multi-

Taxon Diversity Monitoring in a Restored Shallow Landslide in Tuscany. 6th International Conference on Soil Bio- and Eco-Engineering (SBEE25), Xalapa, Mexico, 30 June – 4th July 2025. – Oral presentation

AWARDS

- VIII Edition “Afan de Rivera” award (Cat. C) by Ass. Naz. Consorzi di gestione e tutela del territorio e acque irrigue (ANBI) for the Master thesis “Analisi della stabilità e della qualità del Borro della Suganella a San Casciano in Val di Pesa, per la sistemazione con tecniche di Ingegneria Naturalistica.” Napoli, June 17 2021
- Best talk by a young scientist at the VI International Conference on Soil Bioengineering and Ecoengineering: The Use of Vegetation to Improve Slope Stability, held in Xalapa, Veracruz, México, from June 30 to July 4, 2025.

7. REFERENCES

<i>References</i>	<i>Year</i>	<i>Classification</i>
Andreu, V., Khuder, H., Mickovski, S. B., Spanos, I. A., Rubio, L., Jouneau, L., Berger, F., Norris, J. E., Dorren, L. K., Nicoll, B. C., & Achim, A. (2008). Slope stability and erosion control: Ecotechnological solutions. In Ltd.	2008	Slope stability and root cohesion
Arnone, E., Caracciolo, D., Noto, L. V., Preti, F., & Bras, R. L. (2016). Modeling the hydrological and mechanical effect of roots on shallow landslides. <i>Water Resources Research</i> , 52(11), 8590–8612. https://doi.org/10.1002/2015WR018227	2016	Slope stability and root cohesion
Associazione Italiana per l'Ingegneria Naturalistica - AIPIN. (2022). Manuale IN 2.0: Innovazioni in Ingegneria Naturalistica (Vol. 1). Collana Fiumi e Territorio - Regione Toscana.	2022	Manuals and Guidelines
Ata Ollah Hosseini, S., Gorgandipour, M., & Abdi, E. (n.d.). Herbaceous biodiversity and soil properties of stabilised landslide area in northern mountain forest of Iran. <i>Maejo Int. J. Sci. Technol</i> , 2019(01), 19–28. www.mijst.mju.ac.th	2019	Landslide ecology
Barbati, A., Marchetti, M., Chirici, G., & Corona, P. (2014). European Forest Types and Forest Europe SFM indicators: Tools for monitoring progress on forest biodiversity conservation. <i>Forest Ecology and Management</i> , 321, 145–157. https://doi.org/10.1016/j.foreco.2013.07.004	2014	Ecology
Bardgett, R. D., & Van Der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. In <i>Nature</i> (Vol. 515, Issue 7528, pp. 505–511). Nature Publishing Group. https://doi.org/10.1038/nature13855	2014	Plant/Soil interaction
Bischetti, G. B., Chiaradia, E. A., Epis, T., & Morlotti, E. (2009). Root cohesion of forest species in the Italian Alps. <i>Plant and Soil</i> , 324(1), 71–89. https://doi.org/10.1007/s11104-009-9941-0	2009	Slope stability and root cohesion
Bischetti, G. B., De Cesare, G., Mickovski, S. B., Rauch, H. P., Schwarz, M., & Stangl, R. (2021). Design and temporal issues in Soil Bioengineering structures for the stabilisation of shallow soil movements. <i>Ecological Engineering</i> , 169. https://doi.org/10.1016/j.ecoleng.2021.106309	2021	Soil and Water Bioengineering
Böll, A., Burri, K., Gerber, W., & Graf, F. (2009). Long-term studies of joint technical and biological measures. In <i>For. Snow Landsc. Res</i> (Vol. 82).	2009	Soil and Water Bioengineering
Bordoloi, S., & Ng, C. W. W. (2020). The effects of vegetation traits and their stability functions in bio-engineered slopes: A perspective review. In <i>Engineering Geology</i> (Vol. 275). Elsevier B.V. https://doi.org/10.1016/j.enggeo.2020.105742	2020	Landslide ecology
Bordoni, M., Meisina, C., Valentino, R., Lu, N., Bittelli, M., & Chersich, S. (2015). Hydrological factors affecting rainfall-induced shallow landslides: From the field monitoring to a simplified slope stability analysis. <i>Engineering Geology</i> , 193, 19–37. https://doi.org/10.1016/j.enggeo.2015.04.006	2015	Geotechnics
Brunbjerg, A. K., Bruun, H. H., Moeslund, J. E., Sadler, J. P., Svenning, J. C., & Ejrnæs, R. (2017). Ecospace: A unified framework for understanding variation in terrestrial biodiversity. <i>Basic and Applied Ecology</i> , 18, 86–94. https://doi.org/10.1016/j.baec.2016.09.002	2017	Ecology
Buma, B., & Pawlik, L. (2021). Post-landslide soil and vegetation recovery in a dry, montane system is slow and patchy. <i>Ecosphere</i> , 12(1). https://doi.org/10.1002/ecs2.3346	2021	Landslide ecology
Burrascano, S., Trentanovi, G., Paillet, Y., Heilmann-Clausen, J., Giordani, P., Bagella, S., Bravo-Oviedo, A., Campagnaro, T., Campanaro, A., Chianucci, F., De Smedt, P., Itziar, G. M., Matošević, D., Sitzia, T., Aszalós, R., Brazaitis, G., Andrea, C., Ettore, D. A., Doerfler, I., ... Ódor, P. (2021). Handbook of field sampling for multi-taxon	2021	Ecology

biodiversity studies in European forests. In <i>Ecological Indicators</i> (Vol. 132). Elsevier B.V. https://doi.org/10.1016/j.ecolind.2021.108266		
Burri, K., Graf, F., & Böll, A. (2009). Revegetation measures improve soil aggregate stability: a case study of a landslide area in Central Switzerland. In <i>For. Snow Landsc. Res</i> (Vol. 82).	2009	Slope stability and root cohesion
Cavaillé, P., Dommange, F., Daumergue, N., Loucougaray, G., Spiegelberger, T., Tabacchi, E., & Evette, A. (2013). Biodiversity assessment following a natural gradient of riverbank protection structures in French prealps rivers. <i>Ecological Engineering</i> , 53, 23–30. https://doi.org/10.1016/j.ecoleng.2012.12.105	2013	Soil and Water Bioengineering
Cavaillé, P., Ducasse, L., Breton, V., Dommange, F., Tabacchi, E., & Evette, A. (2015). Functional and taxonomic plant diversity for riverbank protection works: Bioengineering techniques close to natural banks and beyond hard engineering. <i>Journal of Environmental Management</i> , 151, 65–75. https://doi.org/10.1016/j.jenvman.2014.09.028	2015	Soil and Water Bioengineering
Cavaillé, P., Dumont, B., Van Looy, K., Floury, M., Tabacchi, E., & Evette, A. (2018). Influence of riverbank stabilization techniques on taxonomic and functional macrobenthic communities. <i>Hydrobiologia</i> , 807(1), 19–35. https://doi.org/10.1007/s10750-017-3380-3	2018	Soil and Water Bioengineering
Chiaradia, E. A., Vergani, C., & Bischetti, G. B. (2016). Evaluation of the effects of three European forest types on slope stability by field and probabilistic analyses and their implications for forest management. <i>Forest Ecology and Management</i> , 370, 114–129. https://doi.org/10.1016/j.foreco.2016.03.050	2016	Slope stability and root cohesion
Chirici, G., Giannetti, F., Mazza, E., Francini, S., Travaglini, D., Pigna, R., & White, J. C. (n.d.). Monitoring clearcutting and subsequent rapid recovery in Mediterranean coppice forests with Landsat time series. https://doi.org/10.1007/s13595-020-00936-2/Published	2020	Methodology
Chirico, G. B., Borga, M., Tarolli, P., Rigon, R., & Preti, F. (2013). Role of Vegetation on Slope Stability under Transient Unsaturated Conditions. <i>Procedia Environmental Sciences</i> , 19, 932–941. https://doi.org/10.1016/j.proenv.2013.06.103	2013	Slope stability and root cohesion
Chirico, G. B., Dani, A., & Preti, F. (2013). Coupling Root Reinforcement and Subsurface Flow Modeling in Shallow Landslides Triggering Assessment Forest protection and protection forest: Tree root degradation over hydrological shallow landslidetriggering View project OPERA Civil protection from floods View project. https://doi.org/10.1007/978-3-642-31319-6-97	2013	Slope stability and root cohesion
D'Amato Avanzi, G., Falaschi, F., Gianneccchini, R., & Puccinelli, A. (2009). Soil slip susceptibility assessment using mechanical-hydrological approach and GIS techniques: An application in the Apuan Alps (Italy). <i>Natural Hazards</i> , 50(3), 591–603. https://doi.org/10.1007/s11069-009-9357-4	2009	Methodology
D'Amato Avanzi, G., Gianneccchini, R., & Puccinelli, A. (2004). The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: The June 19, 1996 event in northwestern Tuscany (Italy). <i>Engineering Geology</i> , 73(3–4), 215–228. https://doi.org/10.1016/j.enggeo.2004.01.005	2004	Geotechnics
Dani, A., & Preti, F. (2007). Sulla stima del rinforzo radicale del terreno: andamenti temporali ed effetti sulla stabilità di versante con trattamenti selvicolturali. <i>Quaderni Di Idronomia Montana</i> , 27.	2007	Slope stability and root cohesion
de Jesús Arce-Mojica, T., Nehren, U., Sudmeier-Rieux, K., Miranda, P. J., & Anhuf, D. (2019). Nature-based solutions (NbS) for reducing the risk of shallow landslides: Where do we stand? In <i>International Journal of Disaster Risk Reduction</i> (Vol. 41). Elsevier Ltd. https://doi.org/10.1016/j.ijdrr.2019.101293	2019	Nature based Solutions
Debele, S. E., Leo, L. S., Kumar, P., Sahani, J., Ommer, J., Bucchi-gnani, E., Vranić, S., Kalas, M., Amirzada, Z., Pavlova, I., Shah, M. A. R., Gonzalez-Ollauri, A., & Di Sabatino, S. (2023). Nature-based solutions can help reduce the impact of natural hazards: A global analysis	2023	Nature based Solutions

of NBS case studies. <i>Science of the Total Environment</i> , 902, 165824. https://doi.org/10.1016/j.scitotenv.2023.165824		
Delgado-Gonzalez, L., Forquet, N., Choubert, J. M., Boutin, C., Moreau, M., Moreau, S., & Clement, R. (2023). Flow path monitoring by discontinuous time-lapse ERT: An application to survey relationships between secondary effluent infiltration and roots distribution. <i>Journal of Environmental Management</i> , 326. https://doi.org/10.1016/j.jenvman.2022.116839	2023	Methodology
Deng, D. ping, Li, L., & Zhao, L. heng. (2017). Limit equilibrium method (LEM) of slope stability and calculation of comprehensive factor of safety with double strength-reduction technique. <i>Journal of Mountain Science</i> , 14(11), 2311–2324. https://doi.org/10.1007/s11629-017-4537-2	2017	Methodology
Di Nuzzo, L., Vallese, C., Benesperi, R., Giordani, P., Chiarucci, A., Di Cecco, V., Di Martino, L., Di Musciano, M., Gheza, G., Lelli, C., Spitale, D., & Nascimbene, J. (2021). Contrasting multitaxon responses to climate change in Mediterranean mountains. <i>Scientific Reports</i> , 11(1). https://doi.org/10.1038/s41598-021-83866-x	2021	Ecology
DiBiagio, A., Capobianco, V., Oen, A., & Tallaksen, L. M. (2024). State-of-the-art: parametrization of hydrological and mechanical reinforcement effects of vegetation in slope stability models for shallow landslides. In <i>Landslides</i> (Vol. 21, Issue 10, pp. 2417–2446). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s10346-024-02300-1	2024	Slope stability and root cohesion
Eggermont, H., Balian, E., Azevedo, J. M. N., Beumer, V., Brodin, T., Claudet, J., Fady, B., Grube, M., Keune, H., Lamarque, P., Reuter, K., Smith, M., Van Ham, C., Weisser, W. W., & Le Roux, X. (2015). Nature-based solutions: New influence for environmental management and research in Europe. In <i>GAIA - Ecological Perspectives for Science and Society</i> (Vol. 24, Issue 4, pp. 243–248). Oekom Verlag. https://doi.org/10.14512/gaia.24.4.9	2015	Nature based Solutions
Eisenhauer, N., Lanoue, A., Strecker, T., Scheu, S., Steinauer, K., Thakur, M. P., & Mommer, L. (2017). Root biomass and exudates link plant diversity with soil bacterial and fungal biomass. <i>Scientific Reports</i> , 7. https://doi.org/10.1038/srep44641	2017	Plant/Soil interaction
Erktan, A., Cécillon, L., Graf, F., Roumet, C., Legout, C., & Rey, F. (2016). Increase in soil aggregate stability along a Mediterranean successional gradient in severely eroded gully bed ecosystems: combined effects of soil, root traits and plant community characteristics. <i>Plant and Soil</i> , 398(1–2), 121–137. https://doi.org/10.1007/s11104-015-2647-6	2016	Slope stability and root cohesion
Errico, A., Giambastiani, Y., Guastini, E., & Dani, A. (2014). Monitoring of a landslide stabilized with bioengineering techniques in 1997, northern Tuscany. Vegetation development analysis and state of preservation of wood.	2014	Soil and Water Bioengineering
Evette, A., Balique, C., Lavaine, C., Rey, F., & Prunier, A. P. (2011). USING ECOLOGICAL AND BIOGEOGRAPHICAL FEATURES TO PRODUCE A TYPOLOGY OF THE PLANT SPECIES USED IN BIOENGINEERING FOR RIVERBANK PROTECTION IN EUROPE. <i>RIVER RESEARCH AND APPLICATIONS</i> . https://doi.org/10.1002/rra.1560	2011	Soil and Water Bioengineering
Evette, A., Labonne, S., Rey, F., Liebault, F., Jancke, O., & Girel, J. (2009). History of bioengineering techniques for erosion control in rivers in western europe. <i>Environmental Management</i> , 43(6), 972–984. https://doi.org/10.1007/S00267-009-9275-Y	2009	Soil and Water Bioengineering
Fagorzi, C., Karalija, E., & Bellabarba, A. (2025). Editorial: Climate is changing: harnessing plant-microbe interactions for sustainable agriculture in arid areas. <i>Frontiers in Microbiology</i> , 16. https://doi.org/10.3389/fmicb.2025.1687842	2025	Plant/Soil interaction

Fattet, M., Fu, Y., Ghestem, M., Ma, W., Foulonneau, M., Nespoulous, J., Le Bissonnais, Y., & Stokes, A. (2011). Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength. <i>Catena</i> , 87(1), 60–69. https://doi.org/10.1016/j.catena.2011.05.006	2011	Slope stability and root cohesion
Fernandes, J. P., & Guiomar, N. (2018). Nature-based solutions: The need to increase the knowledge on their potentialities and limits. <i>Land Degradation and Development</i> , 29(6), 1925–1939. https://doi.org/10.1002/ldr.2935	2018	Nature based Solutions
Florin Florineth. (2012). <i>Pflanzen statt beton: Sicheren und Gestalten mit Pflanzen</i> (2nd ed.).	2012	Manuals and Guidelines
Forzieri, G., Guarnieri, L., Vivoni, E. R., Castelli, F., & Preti, F. (2011). Spectral-ALS data fusion for different roughness parameterizations of forested floodplains. <i>River Research and Applications</i> , 27(7), 826–840. https://doi.org/10.1002/rra.1398	2011	Methodology
Fox, John., & Weisberg, Sanford. (2019). <i>An R companion to applied regression</i> . SAGE Publications, Inc.	2019	Manuals and Guidelines
Frankl, A., Evrard, O., Cammeraat, E., Tytgat, B., Verleyen, E., & Stokes, A. (2022). Tracing hotspots of soil erosion in high mountain environments: how forensic science based on plant eDNA can lead the way. An opinion. <i>Plant and Soil</i> , 476(1–2), 729–742. https://doi.org/10.1007/s11104-021-05261-9	2022	Soil and Water Bioengineering
Giachi, E., Giambastiani, Y., Giannetti, F., Dani, A., & Preti, F. (2024). Root System Evolution Survey in a Multi-Approach Method for SWBE Monitoring: A Case Study in Tuscany (Italy). <i>Sustainability (Switzerland)</i> , 16(10). https://doi.org/10.3390/su16104022	2024	Methodology
Giadrossich, F., Cohen, D., Schwarz, M., Ganga, A., Marrosu, R., Pirastu, M., & Capra, G. F. (2019). Large roots dominate the contribution of trees to slope stability. <i>Earth Surface Processes and Landforms</i> , 44(8), 1602–1609. https://doi.org/10.1002/esp.4597	2019	Slope stability and root cohesion
Giadrossich, F., Schwarz, M., Cohen, D., Cislighi, A., Vergani, C., Hubble, T., Phillips, C., & Stokes, A. (2017). Methods to measure the mechanical behaviour of tree roots: A review. <i>Ecological Engineering</i> , 109, 256–271. https://doi.org/10.1016/j.ecoleng.2017.08.032	2017	Slope stability and root cohesion
Giambastiani, Y., Preti, F., Errico, A., & Sani, L. (2017). ON THE TREE STABILITY: PULLING TESTS AND MODELLING TO ASSESS THE ROOT ANCHORAGE*. In <i>Procedia Environmental Science, Engineering and Management</i> (Vol. 4, Issue 4). http://www.procedia-esem.eu	2017	Methodology
Giannecchini, R., & D’Amato Avanzi, G. (2012). Historical research as a tool in estimating hydrogeological hazard in a typical small alpine-like area: The example of the Versilia River basin (Apuan Alps, Italy). <i>Physics and Chemistry of the Earth</i> , 49, 32–43. https://doi.org/10.1016/j.pce.2011.12.005	2012	Natural hazard
Giannetti, F., Barbati, A., Mancini, L. D., Travaglini, D., Bastrup-Birk, A., Canullo, R., Nocentini, S., & Chirici, G. (2018). European Forest Types: toward an automated classification. <i>Annals of Forest Science</i> , 75(1). https://doi.org/10.1007/s13595-017-0674-6	2018	Methodology
Giunta Regionale Regione Toscana. (1998). <i>I Tipi Forestali: Boschi e macchie di Toscana</i> (Vol. 1).	1998	Manuals and Guidelines
Giupponi, L., Bischetti, G. B., & Giorgi, A. (2017). A proposal for assessing the success of soil bioengineering work by analysing vegetation: results of two case studies in the Italian Alps. <i>Landscape and Ecological Engineering</i> , 13(2), 305–318. https://doi.org/10.1007/s11355-016-0323-5	2017	Landslide ecology
Giupponi, L., Borgonovo, G., Giorgi, A., & Bischetti, G. B. (2019). How to renew soil bioengineering for slope stabilization: some proposals. <i>Landscape and Ecological Engineering</i> , 15, 37–50. https://doi.org/10.1007/s11355-018-0359-9	2019	Soil and Water Bioengineering

Gonzalez-Ollauri, A., & Mickovski, S. B. (2017a). Hydrological effect of vegetation against rainfall-induced landslides. <i>Journal of Hydrology</i> , 549, 374–387. https://doi.org/10.1016/j.jhydrol.2017.04.014	2017	Slope stability and root cohesion
Gonzalez-Ollauri, A., & Mickovski, S. B. (2017b). Plant-soil reinforcement response under different soil hydrological regimes. <i>Geoderma</i> , 285, 141–150. https://doi.org/10.1016/j.geoderma.2016.10.002	2017	Slope stability and root cohesion
Gonzalez-Ollauri, A., & Mickovski, S. B. (2017c). Shallow landslides as drivers for slope ecosystem evolution and biophysical diversity. <i>Landslides</i> , 14(5), 1699–1714. https://doi.org/10.1007/s10346-017-0822-y	2017	Landslide ecology
Gonzalez-Ollauri, A., Hudek, C., Mickovski, S. B., Viglietti, D., Cretto, N., & Freppaz, M. (2021). Describing the vertical root distribution of alpine plants with simple climate, soil, and plant attributes. <i>Catena</i> , 203. https://doi.org/10.1016/j.catena.2021.105305	2021	Slope stability and root cohesion
Gonzalez-Ollauri, A., Mickovski, S. B., Anderson, C. C., Debele, S., Emmanuel, R., Kumar, P., Loupis, M., Ommer, J., Pfeiffer, J., Panga, D., Pilla, F., Sannigrahi, S., Toth, E., Ukonmaanaho, L., & Zieher, T. (2023). A nature-based solution selection framework: Criteria and processes for addressing hydro-meteorological hazards at open-air laboratories across Europe. <i>Journal of Environmental Management</i> , 331. https://doi.org/10.1016/j.jenvman.2022.117183	2023	Nature based Solutions
Gonzalez-Ollauri, A., Munro, K., Mickovski, S. B., Thomson, C. S., & Emmanuel, R. (2021). The ‘Rocket Framework’: A Novel Framework to Define Key Performance Indicators for Nature-based Solutions Against Shallow Landslides and Erosion. <i>Frontiers in Earth Science</i> , 9. https://doi.org/10.3389/feart.2021.676059	2021	Methodology
Graf, F., & Frei, M. (2013). Soil aggregate stability related to soil density, root length, and mycorrhiza using site-specific <i>Alnus incana</i> and <i>Melanogaster variegatus</i> s.l. <i>Ecological Engineering</i> , 57, 314–323. https://doi.org/10.1016/j.ecoleng.2013.04.037	2013	Slope stability and root cohesion
Graf, F., te Kamp, L., Auer, M., Acharya, M. S., & Wu, W. (2015). Soil aggregate stability in eco-engineering: Comparison of field and laboratory data with an outlook on a new modelling approach. <i>Springer Series in Geomechanics and Geoengineering</i> , 2015, 29–47. https://doi.org/10.1007/978-3-319-11053-0_4	2015	Slope stability and root cohesion
Gray, D. H., & Sotir, R. B. (1996). <i>Biotechnical and Soil Bioengineering Slope Stabilization: A practical guide for erosion control</i> (J. W. & S. Inc. Wiley Inter-science Publication, Ed.).	1996	Soil and Water Bioengineering
Guastini, E., Preti, F., & Dani, A. (2014). Living part on soil bioengineering structures in Appennino Tosco-emiliano.	2014	Soil and Water Bioengineering
He, Y., Lan, Y., Zhang, H., & Ye, S. (2022). Research characteristics and hotspots of the relationship between soil microorganisms and vegetation: A bibliometric analysis. In <i>Ecological Indicators</i> (Vol. 141). Elsevier B.V. https://doi.org/10.1016/j.ecolind.2022.109145	2022	Plant/Soil interaction
Herrick, J. E., Schuman, G. E., & Rango, A. (2006). Monitoring ecological processes for restoration projects. <i>Journal for Nature Conservation</i> , 14(3–4), 161–171. https://doi.org/10.1016/j.jnc.2006.05.001	2006	Ecology
Hofmann, A., Guastini, E., Bresci, E., & Preti, F. (2015). Learning from the roots of mountain watersheds management. In <i>Idronomia Montana</i> (Vol. 34). EdiBios.	2015	Slope stability and root cohesion
Hojat, A., Arosio, D., Ivanov, V. I., Loke, M. H., Longoni, L., Papini, M., Tresoldi, G., & Zanzi, L. (2020). Quantifying seasonal 3D effects for a permanent electrical resistivity tomography monitoring system along the embankment of an irrigation canal. <i>Near Surface Geophysics</i> , 18(4), 427–443. https://doi.org/10.1002/nsg.12110	2020	Methodology
Hruška, J., Kuda, F., Holík, L., & Vranová, V. (2023). Assessment of slope stability on logged forest-hill slopes using ground-penetrating radar and electrical resistivity tomography. <i>Geological Journal</i> , 58(1), 247–263. https://doi.org/10.1002/gj.4589	2023	Geotechnics

Igwe, O., & Una, C. O. (2019). Landslide impacts and management in Nanka area, Southeast Nigeria. <i>Geoenvironmental Disasters</i> , 6(1). https://doi.org/10.1186/s40677-019-0122-z	2019	Natural hazard
Innocenti, A., Pazzi, V., Borselli, L., Nocentini, M., Lombardi, L., Gigli, G., & Fanti, R. (2023). Reconstruction of the evolution phases of a landslide by using multi-layer back-analysis methods. <i>Landslides</i> , 20(1), 189–207. https://doi.org/10.1007/s10346-022-01971-y	2023	Methodology
IUCN. (2016). Nature-based solutions to address global societal challenges (E. Cohen-Shacham, G. Walters, C. Janzen, & S. Maginnis, Eds.). IUCN International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2016.13.en	2016	Manuals and Guidelines
IUSS. (2022). World Reference Base for Soil Resources.	2022	Manuals and Guidelines
Izquierdo, I., Caravaca, F., Alguacil, M. M., Hernández, G., & Roldán, A. (2005). Use of microbiological indicators for evaluating success in soil restoration after revegetation of a mining area under subtropical conditions. <i>Applied Soil Ecology</i> , 30(1), 3–10. https://doi.org/10.1016/j.apsoil.2005.02.004	2005	Plant/Soil interaction
Janssen, P., Cavaillé, P., Bray, F., & Evette, A. (2019). Soil bioengineering techniques enhance riparian habitat quality and multi-taxonomic diversity in the foothills of the Alps and Jura Mountains. <i>Ecological Engineering</i> , 133, 1–9. https://doi.org/10.1016/j.ecoleng.2019.04.017	2019	Soil and Water Bioengineering
Janssen, P., Dommanget, F., Cavaillé, P., & Evette, A. (2021). Does soil bioengineering benefits aquatic biodiversity? An empirical study of the relative influence of local and regional drivers on benthic macroinvertebrate assemblages. <i>Ecological Engineering</i> , 168. https://doi.org/10.1016/j.ecoleng.2021.106287	2021	Soil and Water Bioengineering
Johnson, R. K., Hering, D., Furse, M. T., & Clarke, R. T. (2006). Detection of ecological change using multiple organism groups: Metrics and uncertainty. <i>Hydrobiologia</i> , 566(1), 115–137. https://doi.org/10.1007/s10750-006-0101-8	2006	Ecology
Kakinuma, H., Tsou, C. Y., Higaki, D., Kawakami, R., & Gautum, C. S. (2025). Assessing the long-term effectiveness and socioeconomic benefits associated with ecosystem-based disaster risk reduction measures aimed at mitigating the impact of sediment-related events in Nepal. <i>Progress in Disaster Science</i> , 28. https://doi.org/10.1016/j.pdisas.2025.100464	2025	Natural hazard
Kent, M. . (2012). Vegetation description and data analysis : a practical approach (Second). Wiley-Blackwell.	2012	Ecology
Kettenhuber, P. L. W., dos Santos Sousa, R., Dewes, J. J., Rauch, H. P., Sutili, F. J., & Hörbinger, S. (2023). Performance assessment of a soil and water bioengineering work on the basis of the flora development and its associated ecosystem processes. <i>Ecological Engineering</i> , 186. https://doi.org/10.1016/j.ecoleng.2022.106840	2023	Soil and Water Bioengineering
Kumar, R., Devrani, R., Dangwal, A., Deshmukh, B., & Dutt, S. (2022). Extreme Hydrological Event-Induced Temporal Variation in Soil Erosion of the Assiganga River Basin, NW Himalaya . In <i>Advances in Remote Sensing Technology and the Three Poles</i> (pp. 230–246). Wiley. https://doi.org/10.1002/9781119787754.ch15	2022	Methodology
Laio, F., D’Odorico, P., & Ridolfi, L. (2006). An analytical model to relate the vertical root distribution to climate and soil properties. <i>Geophysical Research Letters</i> , 33(18). https://doi.org/10.1029/2006GL027331	2006	Methodology
Lann, T., Bao, H., Lan, H., Zheng, H., Yan, C., & Peng, J. (2024). Hydro-mechanical effects of vegetation on slope stability: A review. <i>Science of The Total Environment</i> , 926, 171691. https://doi.org/10.1016/j.scitotenv.2024.171691	2024	Slope stability and root cohesion
Lee, Hoesung., & Romero, Jose. (2023). Climate Change 2023 : synthesis report. Intergovernmental Panel on Climate Change.	2023	Manuals and Guidelines

Li, S., Wang, Z., & Stutz, H. H. (2023). State-of-the-art review on plant-based solutions for soil improvement. In <i>Biogeotechnics</i> (Vol. 1, Issue 3). KeAi Communications Co. https://doi.org/10.1016/j.bgtech.2023.100035	2023	Plant/Soil interaction
Löbmann, M. T., Geitner, C., Wellstein, C., & Zerbe, S. (2020). The influence of herbaceous vegetation on slope stability – A review. In <i>Earth-Science Reviews</i> (Vol. 209). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2020.103328	2020	Slope stability and root cohesion
Lu, P.-L. (2014). Using multiple vegetation layers to reduce the risk of rainfall-induced landslides and facilitate post-landslide slope rehabilitation. <i>2</i> (2), 13–17. http://www.accessinternationaljournals.org/arbs	2014	Landslide ecology
Mao, Z. (2022). Root reinforcement models: classification, criticism and perspectives. <i>Plant and Soil</i> , 472(1–2), 17–28. https://doi.org/10.1007/s11104-021-05231-1	2022	Slope stability and root cohesion
Mao, Z., Jourdan, C., Bonis, M. L., Pailler, F., Rey, H., Saint-André, L., & Stokes, A. (2013). Modelling root demography in heterogeneous mountain forests and applications for slope stability analysis. <i>Plant and Soil</i> , 363(1–2), 357–382. https://doi.org/10.1007/s11104-012-1324-2	2013	Slope stability and root cohesion
Mao, Z., Saint-André, L., Genet, M., Mine, F. X., Jourdan, C., Rey, H., Courbaud, B., & Stokes, A. (2012). Engineering ecological protection against landslides in diverse mountain forests: Choosing cohesion models. <i>Ecological Engineering</i> , 45, 55–69. https://doi.org/10.1016/j.ecoleng.2011.03.026	2012	Slope stability and root cohesion
Martin, F. M., Janssen, P., Bergès, L., Dupont, B., & Evette, A. (2021). Higher structural connectivity and resistance against invasions of soil bioengineering over hard-engineering for riverbank stabilisation. <i>Wetlands Ecology and Management</i> , 29(1), 27–39. https://doi.org/10.1007/s11273-020-09765-6	2021	Soil and Water Bioengineering
Marzini, L., D'Addario, E., Papasidero, M. P., Chianucci, F., & Disperati, L. (2023). Influence of Root Reinforcement on Shallow Landslide Distribution: A Case Study in Garfagnana (Northern Tuscany, Italy). <i>Geosciences (Switzerland)</i> , 13(11). https://doi.org/10.3390/geosciences13110326	2023	Slope stability and root cohesion
Maselli, F., Amparo Gilabert, M., & Conese, C. (1998). Integration of High and Low Resolution NDVI Data for Monitoring Vegetation in Mediterranean Environments Even though several studies have shown the enor- $\frac{3}{4}$ CeSIA-Accademia dei Georgofili, Firenze, Italy mous potential of these indices for monitoring vegetation (Vol. 63).	1998	Methodology
Mattia, C., Bischetti, G. B., & Gentile, F. (2005). Biotechnical characteristics of root systems of typical Mediterranean species. <i>Plant and Soil</i> , 278(1–2), 23–32. https://doi.org/10.1007/s11104-005-7930-5	2005	Slope stability and root cohesion
Mickovski, S. B. (2021). Re-thinking soil bioengineering to address climate change challenges. <i>Sustainability (Switzerland)</i> , 13(6). https://doi.org/10.3390/su13063338	2021	Soil and Water Bioengineering
Mickovski, S. B., & Thomson, C. S. (2017). Developing a framework for the sustainability assessment of eco-engineering measures. https://doi.org/10.1016/j.ecoleng.2017.10.004	2017	Methodology
Mickovski, S. B., Gonzalez-Ollauri, A., Thomson, C., Gallagher, C., & Tardio, G. (2022). Assessment of the Sustainability Performance of Eco-Engineering Measures in the Mediterranean Region. <i>Land</i> , 11(4). https://doi.org/10.3390/land11040533	2022	Soil and Water Bioengineering
Mickovski, S. B., Wallace, M., Papic, J. B., & Simeonovski, I. (2023). Modelling and monitoring behavior of vegetated slopes in variable weather conditions. In <i>Smart Geotechnics for Smart Societies</i> (pp. 1876–1880). CRC Press. https://doi.org/10.1201/9781003299127-286	2023	Geotechnics
Miele, P., Di Martire, D., Di Napoli, M., Guerriero, L., & Calcaterra, D. (2021). Temporal efficiencies of soil bioengineering techniques to mitigate geo-hydrological risks. <i>Ecological Engineering</i> , 170. https://doi.org/10.1016/j.ecoleng.2021.106338	2021	Soil and Water Bioengineering

Moos, C., Bebi, P., Schwarz, M., Stoffel, M., Sudmeier-Rieux, K., & Dorren, L. (2018). Ecosystem-based disaster risk reduction in mountains. In <i>Earth-Science Reviews</i> (Vol. 177, pp. 497–513). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2017.12.011	2018	Natural hazard
Moreau, C., Cottet, M., Rivière-Honegger, A., François, A., & Evette, A. (2022). Nature-based solutions (NbS): A management paradigm shift in practitioners' perspectives on riverbank soil bioengineering. <i>Journal of Environmental Management</i> , 308. https://doi.org/10.1016/j.jenvman.2022.114638	2022	Nature based Solutions
Murgia, I., Giadrossich, F., Mao, Z., Cohen, D., Capra, G. F., & Schwarz, M. (2022). Modeling shallow landslides and root reinforcement: A review. <i>Ecological Engineering</i> , 181. https://doi.org/10.1016/j.ecoleng.2022.106671	2022	Slope stability and root cohesion
Nehren, U., Arce-Mojica, T., Barrett, A. C., Cueto, J., Doswald, N., Janzen, S., Lange, W., Vargas, A. O., Pirazan-Palomar, L., Renaud, F. G., Sandholz, S., Sebesvari, Z., Sudmeier-Rieux, K., & Walz, Y. (2023). Towards a typology of nature-based solutions for disaster risk reduction. <i>Nature-Based Solutions</i> , 3, 100057. https://doi.org/10.1016/j.nbsj.2023.100057	2023	Nature based Solutions
Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Külvik, M., Rey, F., van Dijk, J., Vistad, O. I., Wilkinson, M. E., & Wittmer, H. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. In <i>Science of the Total Environment</i> (Vol. 579, pp. 1215–1227). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2016.11.106	2017	Nature based Solutions
Neto, C., Cardigos, P., Oliveira, S. C., & Zêzere, J. L. (2017). Floristic and vegetation successional processes within landslides in a Mediterranean environment. <i>Science of the Total Environment</i> , 574, 969–981. https://doi.org/10.1016/j.scitotenv.2016.09.119	2017	Landslide ecology
Ni, J., Liu, S., Huang, Y., & Gao, Y. (2024). Temperature and plant root effects on soil hydrological response and slope stability. <i>Computers and Geotechnics</i> , 174. https://doi.org/10.1016/j.compgeo.2024.106663	2024	Slope stability and root cohesion
Ormerod, S., Schiechl, H. M., & Stern, R. (1997). Water Bioengineering Techniques for Watercourse, Bank and Shoreline Protection. <i>The Journal of Applied Ecology</i> , 34(4), 1110. https://doi.org/10.2307/2405301	1997	Soil and Water Bioengineering
Pérez-Valera, E., Verdú, M., Navarro-Cano, J. A., & Goberna, M. (2020). Soil microbiome drives the recovery of ecosystem functions after fire. <i>Soil Biology and Biochemistry</i> , 149. https://doi.org/10.1016/j.soilbio.2020.107948	2020	Plant/Soil interaction
Philippot, L., Griffiths, B. S., & Langenheder, S. (2021). Microbial Community Resilience across Ecosystems and Multiple Disturbances. <i>Microbiology and Molecular Biology Reviews</i> , 85(2). https://doi.org/10.1128/mmbr.00026-20	2021	Plant/Soil interaction
Philippot, L., Raaijmakers, J. M., Lemanceau, P., & Van Der Putten, W. H. (2013). Going back to the roots: The microbial ecology of the rhizosphere. In <i>Nature Reviews Microbiology</i> (Vol. 11, Issue 11, pp. 789–799). https://doi.org/10.1038/nrmicro3109	2013	Plant/Soil interaction
Pollen-Bankhead, N., & Simon, A. (2010). Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? <i>Geomorphology</i> , 116(3–4), 353–362. https://doi.org/10.1016/j.geomorph.2009.11.013	2010	Slope stability and root cohesion
Preti, F. (2013). Forest protection and protection forest: Tree root degradation over hydrological shallow landslides triggering. <i>Ecological Engineering</i> , 61(1 PARTC), 633–645. https://doi.org/10.1016/j.ecoleng.2012.11.009	2013	Slope stability and root cohesion
Preti, F., & Giadrossich, F. (2009). Hydrology and Earth System Sciences Root reinforcement and slope bioengineering stabilization by	2009	Slope stability and root cohesion

Spanish Broom (<i>Spartium junceum</i> L.). In Hydrol. Earth Syst. Sci (Vol. 13). www.hydrol-earth-syst-sci.net/13/1713/2009/		
Preti, F., Capobianco, V., & Sangalli, P. (2022). Soil and Water Bioengineering (SWB) is and has always been a nature-based solution (NBS): a reasoned comparison of terms and definitions. <i>Ecological Engineering</i> , 181. https://doi.org/10.1016/j.ecoleng.2022.106687	2022	Soil and Water Bioengineering
Preti, F., Dani, A., & Laio, F. (2010). Root profile assessment by means of hydrological, pedological and above-ground vegetation information for bio-engineering purposes. <i>Ecological Engineering</i> , 36(3), 305–316. https://doi.org/10.1016/j.ecoleng.2009.07.010	2010	Slope stability and root cohesion
Preti, F., Dani, A., Giambastiani, Y., & Giachi, E. (2025). Slope stability time evolution of a shallow landslide restored by Soil and Water Bioengineering (SWBE) techniques: A case study in Northwest Tuscany (Italy). <i>Ecological Engineering</i> , 214, 107570. https://doi.org/10.1016/j.ecoleng.2025.107570	2025	Soil and Water Bioengineering
Preti, F., Dani, A., Noto, L. V., & Arnone, E. (2022). On the Leonardo's rule for the assessment of root profile. <i>Ecological Engineering</i> , 179. https://doi.org/10.1016/j.ecoleng.2022.106620	2022	Methodology
Preti, F., Guastini, E., & Chirico, G. (2016). Learning from the roots of mountain watersheds management.	2016	Slope stability and root cohesion
Punetha, P., Samanta, M., & Sarkar, S. (2019). Bioengineering as an effective and ecofriendly soil slope stabilization method: A review. In <i>Advances in Natural and Technological Hazards Research</i> (Vol. 50, pp. 201–224). Springer Netherlands. https://doi.org/10.1007/978-3-319-77377-3_10	2019	Soil and Water Bioengineering
Qin, M., Cui, P., Jiang, Y., Guo, J., Zhang, G., & Ramzan, M. (2022). Occurrence of shallow landslides triggered by increased hydraulic conductivity due to tree roots. <i>Landslides</i> , 19(11), 2593–2604. https://doi.org/10.1007/s10346-022-01921-8	2022	Slope stability and root cohesion
R Core Team. (2024). “R: a language and environment for statistical computing” R Foundation for Statistical Computing.	2024	Manuals and Guidelines
Rauch, H. P., Sutli, F., & Hörbinger, S. (2014). Installation of a Riparian Forest by Means of Soil Bio Engineering Techniques—Monitoring Results from a River Restoration Work in Southern Brazil. <i>Open Journal of Forestry</i> , 04(02), 161–169. https://doi.org/10.4236/ojf.2014.42022	2014	Soil and Water Bioengineering
Rauch, H. P., von der Thannen, M., Raymond, P., Mira, E., & Evette, A. (2022). Ecological challenges* for the use of soil and water bioengineering techniques in river and coastal engineering projects. <i>Ecological Engineering</i> , 176. https://doi.org/10.1016/j.ecoleng.2021.106539	2022	Soil and Water Bioengineering
Regione Lazio. (2006). <i>Manuale di Ingegneria Naturalistica: Sistemazione dei Versanti</i> . Assessorato all'Ambiente e Cooperazione tra i popoli Direzione Regionale Ambiente e Cooperazione tra i popoli.	2006	Manuals and Guidelines
Restrepo, C., Walker, L. R., Shiels, A. B., Busmann, R., Claessens, L., Fisch, S., Lozano, P., Negi, G., Paolini, L., Poveda, G., Ramos-Scharrón, C., Richter, M., & Velázquez, E. (2009). Landsliding and Its Multiscale Influence on Mountainscapes. <i>BioScience</i> , 59(8), 685–698. https://doi.org/10.1525/bio.2009.59.8.10	2009	Natural hazard
Rey, F., Bifulco, C., Bischetti, G. B., Bourrier, F., De Cesare, G., Florineth, F., Graf, F., Marden, M., Mickovski, S. B., Phillips, C., Peklo, K., Poesen, J., Polster, D., Preti, F., Rauch, H. P., Raymond, P., Sangalli, P., Tardio, G., & Stokes, A. (2019). Soil and water bioengineering: Practice and research needs for reconciling natural hazard control and ecological restoration. In <i>Science of the Total Environment</i> (Vol. 648, pp. 1210–1218). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2018.08.217	2019	Soil and Water Bioengineering
Rey, F., Dupire, S., & Berger, F. (2024). Forest-based solutions for reconciling natural hazard reduction with biodiversity benefits. <i>Nature-Based Solutions</i> , 5, 100114. https://doi.org/10.1016/j.nbsj.2024.100114	2024	Nature based Solutions

Rousset, J., Piton, G., François, A., Didier, M., & Evette, A. (2025). Biogeomorphic assessment of natural streambank structures in the Alps: A step to improve soil and water bioengineering techniques. <i>Earth Surface Processes and Landforms</i> , 50(9). https://doi.org/10.1002/esp.70126	2025	Soil and Water Bioengineering
Ruangpan, L., Vojinovic, Z., Sabatino, S. Di, Leo, L. S., Capobianco, V., Oen, A. M. P., McClain, M., & Lopez-Gunn, E. (2019). Nature-Based Solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area. https://doi.org/10.5194/nhess-2019-128	2019	Nature based Solutions
Ruault, J. F., Dupré la Tour, A., Evette, A., Allain, S., & Callois, J. M. (2022). A biodiversity-employment framework to protect biodiversity. <i>Ecological Economics</i> , 191, 107238. https://doi.org/10.1016/J.ECOLECON.2021.107238	2022	Ecology
Schiechl, H. M. ., & Horstmann, N. K. . (1980). <i>Bioengineering for land reclamation and conservation</i> . University of Alberta Press.	1980	Manuals and Guidelines
Schmidt, K. M., Roering, J. J., Stock, J. D., Dietrich, W. E., Montgomery, D. R., & Schaub, T. (2001). The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. <i>Canadian Geotechnical Journal</i> , 38(5), 995–1024. https://doi.org/10.1139/cgj-38-5-995	2001	Slope stability and root cohesion
Schmitt, K., Schäffer, M., Koop, J., & Symmank, L. (2018). River bank stabilisation by bioengineering: potentials for ecological diversity. <i>Journal of Applied Water Engineering and Research</i> , 6(4), 262–273. https://doi.org/10.1080/23249676.2018.1466735	2018	Nature based Solutions
Schwarz, M., Lehmann, P., & Or, D. (2010). Quantifying lateral root reinforcement in steep slopes - from a bundle of roots to tree stands. <i>Earth Surface Processes and Landforms</i> , 35(3), 354–367. https://doi.org/10.1002/esp.1927	2010	Slope stability and root cohesion
Schwarz, M., Preti, F., Giadrossich, F., Lehmann, P., & Or, D. (2010). Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy). <i>Ecological Engineering</i> , 36(3), 285–291. https://doi.org/10.1016/j.ecoleng.2009.06.014	2010	Slope stability and root cohesion
Sidle, R. C., & Bogaard, T. A. (2016). Dynamic earth system and ecological controls of rainfall-initiated landslides. In <i>Earth-Science Reviews</i> (Vol. 159, pp. 275–291). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2016.05.013	2016	Landslide ecology
Singh, A. K. (2010). Bioengineering techniques of slope stabilization and landslide mitigation. <i>Disaster Prevention and Management: An International Journal</i> , 19(3), 384–397. https://doi.org/10.1108/09653561011052547	2010	Natural hazard
Smith, D. J., Wynn-Thompson, T. M., Stremmer, M. A., Williams, M. A., Seiler, J. R., & Hession, W. C. (2023). Root reinforcement and extracellular products reduce streambank fluvial erosion. <i>Science of the Total Environment</i> , 896. https://doi.org/10.1016/j.scitotenv.2023.165125	2023	Slope stability and root cohesion
Sorolla, A., Piera, E., Mota-freixas, B., Salvans, G. S., Rueda, I., Prats, A. L., & Unzeta, C. (2021). Improvement of the plantation success in a crib wall in a mediterranean hydro-meteorological risks scenario—practical results. <i>Sustainability (Switzerland)</i> , 13(21). https://doi.org/10.3390/su132111785	2021	Soil and Water Bioengineering
Stokes, A., Atger, C., Bengough, A. G., Fourcaud, T., & Sidle, R. C. (2009). Desirable Plant root traits for protecting natural and engineered slopes against landslides. In <i>Plant and Soil</i> (Vol. 324, Issue 1, pp. 1–30). https://doi.org/10.1007/s11104-009-0159-y	2009	Slope stability and root cohesion
Stokes, A., Douglas, G. B., Fourcaud, T., Giadrossich, F., Gillies, C., Hubble, T., Kim, J. H., Loades, K. W., Mao, Z., McIvor, I. R., Mickovski, S. B., Mitchell, S., Osman, N., Phillips, C., Poesen, J., Polster, D., Preti, F., Raymond, P., Rey, F., ... Walker, L. R. (2014). Ecological mitigation of hillslope instability: Ten key issues facing	2014	Soil and Water Bioengineering

researchers and practitioners. In <i>Plant and Soil</i> (Vol. 377, Issues 1–2, pp. 1–23). Kluwer Academic Publishers. https://doi.org/10.1007/s11104-014-2044-6		
Su, X., Jia, J., Zhang, J., Li, X., & Zhang, M. (2024). Spatiotemporal evolutionary characteristics of vegetation restoration after historical earthquake landslides from 1985 to 2020: A case study of Tianshui City, China. <i>Ecological Indicators</i> , 169. https://doi.org/10.1016/j.ecolind.2024.112798	2024	Landslide ecology
Takaoka, S. (2024). A landscape-level study on vegetation richness of ancient landslide areas. <i>Progress in Physical Geography</i> , 48(1), 45–59. https://doi.org/10.1177/03091333231206314	2024	Landslide ecology
Tardio, G., & Mickovski, S. B. (2016). Implementation of eco-engineering design into existing slope stability design practices. <i>Ecological Engineering</i> , 92, 138–147. https://doi.org/10.1016/j.ecoleng.2016.03.036	2016	Soil and Water Bioengineering
Tardio, G., & Mickovski, S. B. (2023). A Novel Integrated Design Methodology for Nature-Based Solutions and Soil and Water Bioengineering Interventions: The Tardio & Mickovski Methodology. <i>Sustainability</i> , 15(4), 3044. https://doi.org/10.3390/su15043044	2023	Slope stability and root cohesion
Tardio, G., González-Ollauri, A., & Mickovski, S. B. (2016). A non-invasive preferential root distribution analysis methodology from a slope stability approach. <i>Ecological Engineering</i> , 97, 46–57. https://doi.org/10.1016/j.ecoleng.2016.08.005	2016	Methodology
Tarolli, P., Preti, F., & Romano, N. (2014). Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. In <i>Anthropocene</i> (Vol. 6, pp. 10–25). Elsevier Ltd. https://doi.org/10.1016/j.ancene.2014.03.002	2014	Natural hazard
Tian, G., Vose, J. M., Coleman, D. C., Geron, C. D., & Walker, J. T. (2004). Evaluation of the effectiveness of riparian zone restoration in the southern Appalachians by assessing soil microbial populations. <i>Applied Soil Ecology</i> , 26(1), 63–68. https://doi.org/10.1016/j.apsoil.2003.10.003	2004	Plant/Soil interaction
Tisserant, M., Bourgeois, B., González, E., Evette, A., & Poulin, M. (2021). Controlling erosion while fostering plant biodiversity: A comparison of riverbank stabilization techniques. <i>Ecological Engineering</i> , 172. https://doi.org/10.1016/j.ecoleng.2021.106387	2021	Soil and Water Bioengineering
Tisserant, M., González-Sargas, E., Evette, A., Bourgeois, B., & Poulin, M. (2024). A functional characterization of bioengineered plant communities along riverbanks. <i>Ecological Engineering</i> , 204. https://doi.org/10.1016/j.ecoleng.2024.107279	2024	Soil and Water Bioengineering
Tofani, V., Bicocchi, G., Rossi, G., Segoni, S., D'Ambrosio, M., Casagli, N., & Catani, F. (2017). Soil characterization for shallow landslides modeling: a case study in the Northern Apennines (Central Italy). <i>Landslides</i> , 14(2), 755–770. https://doi.org/10.1007/s10346-017-0809-8	2017	Geotechnics
Tron, S., Dani, A., Laio, F., Preti, F., & Ridolfi, L. (2014). Mean root depth estimation at landslide slopes. <i>Ecological Engineering</i> , 69, 118–125. https://doi.org/10.1016/j.ecoleng.2014.03.019	2014	Slope stability and root cohesion
Uzielli, M., Geppetti, A., Borselli, L., Renzi, S., & Preti, F. (2025). Comparative geotechnical analysis of slope stabilization through conventional, soil and water bioengineering, and combined solutions. <i>Ecological Engineering</i> , 212. https://doi.org/10.1016/j.ecoleng.2024.107487	2025	Geotechnics
Vergani, C., Chiaradia, E. A., & Bischetti, G. B. (2012). Variability in the tensile resistance of roots in Alpine forest tree species. <i>Ecological Engineering</i> , 46, 43–56. https://doi.org/10.1016/j.ecoleng.2012.04.036	2012	Slope stability and root cohesion
Vergani, C., Giadrossich, F., Buckley, P., Conedera, M., Pividori, M., Salbitano, F., Rauch, H. S., Lovreglio, R., & Schwarz, M. (2017). Root reinforcement dynamics of European coppice woodlands and their effect on shallow landslides: A review. In <i>Earth-Science Reviews</i> (Vol.	2017	Slope stability and root cohesion

167, pp. 88–102). Elsevier B.V. https://doi.org/10.1016/j.earsci-rev.2017.02.002		
Vianna, V. F., Fleury, M. P., Menezes, G. B., Coelho, A. T., Bueno, C., da Silva, J. L., & Luz, M. P. (2020). Bioengineering techniques adopted for controlling riverbanks' superficial erosion of the Simplicio Hydroelectric Power Plant, Brazil. <i>Sustainability</i> (Switzerland), 12(19). https://doi.org/10.3390/SU12197886	2020	Nature based Solutions
von der Thannen, M., Hoerbinger, S., Muellebner, C., Biber, H., & Rauch, H. P. (2021). Case study of a water bioengineering construction site in Austria. Ecological aspects and application of an environmental life cycle assessment model. <i>International Journal of Energy and Environmental Engineering</i> , 12(4), 599–609. https://doi.org/10.1007/s40095-021-00419-8	2021	Soil and Water Bioengineering
Walker, L. R. S. A. B. . (2013). <i>Landslide Ecology</i> (1st ed.). Cambridge University Press.	2013	Landslide ecology
Walker, L. R., Velázquez, E., & Shiels, A. B. (2009). Applying lessons from ecological succession to the restoration of landslides. <i>Plant and Soil</i> , 324(1), 157–168. https://doi.org/10.1007/s11104-008-9864-1	2009	Landslide ecology
Wang, X., Hong, M. M., Huang, Z., Zhao, Y. F., Ou, Y. S., Jia, H. X., & Li, J. (2019). Biomechanical properties of plant root systems and their ability to stabilize slopes in geohazard-prone regions. <i>Soil and Tillage Research</i> , 189, 148–157. https://doi.org/10.1016/j.still.2019.02.003	2019	Slope stability and root cohesion
Wickham, H. (2016). <i>Data Analysis</i> (pp. 189–201). https://doi.org/10.1007/978-3-319-24277-4_9	2016	Manuals and Guidelines
Yan, Y., Zhuang, Q., Zan, C., Ren, J., Yang, L., Wen, Y., Zeng, S., Zhang, Q., & Kong, L. (2021). Using the Google Earth Engine to rapidly monitor impacts of geohazards on ecological quality in highly susceptible areas. <i>Ecological Indicators</i> , 132. https://doi.org/10.1016/j.ecolind.2021.108258	2021	Natural hazard
Zaimes, G. N., Tardio, G., Iakovoglou, V., Gimenez, M., Garcia-Rodriguez, J. L., & Sangalli, P. (2019). New tools and approaches to promote soil and water bioengineering in the Mediterranean. <i>Science of the Total Environment</i> , 693. https://doi.org/10.1016/j.scitotenv.2019.133677	2019	Soil and Water Bioengineering
Zayadi, R., Kusuma, Z., Setyo Leksono, A., & Yanuwadi, B. (2020). The Influence of Vegetation Roots on Slope Stability in Landslide Susceptible Areas. <i>International Journal of Civil Engineering and Technology</i> , 11(4), 124–133. http://www.iaeme.com/IJCIET/index.asp?IType=IJCIET&VType=11&IType=4JournalImpactFactor	2020	Slope stability and root cohesion
Zeh, Helgard. (2007). <i>Ingenieurbiologie : Handbuch Bautypen = Génie biologique : manuel de construction = Ingegneria naturalistica : quaderno delle opere tipo = Soil bioengineering : construction type manual = Ingeniería biológica : manual técnico</i> . Vdf Hochschulverlag an der ETH.	2007	Manuals and Guidelines
Zhang, H., Zhao, Z., Ma, G., & Sun, L. (2020). Quantitative evaluation of soil anti-erodibility in riverbank slope remediated with nature-based soil bioengineering in Liaohe River, Northeast China. <i>Ecological Engineering</i> . https://doi.org/10.1016/j.ecoleng.2020.105840	2020	Soil and Water Bioengineering
Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., Ning, D., Hou, Y., & Liu, S. (2017). A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. <i>Journal of Hydrology</i> , 546, 44–59. https://doi.org/10.1016/j.jhydrol.2016.12.040	2017	Natural hazard
Zhu, D. Y., Lee, C. F., Qian, Q. H., & Chen, G. R. (2005). A concise algorithm for computing the factor of safety using the Morgenstern-Price method. <i>Canadian Geotechnical Journal</i> , 42(1), 272–278. https://doi.org/10.1139/t04-072	2005	Slope stability and root cohesion

Zuur, A. F., Ieno, E. N., & Elphick, C. S. (2010). A protocol for data exploration to avoid common statistical problems. <i>Methods in Ecology and Evolution</i> , 1(1), 3–14. https://doi.org/10.1111/j.2041-210x.2009.00001.x	2010	Methodology
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