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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.

Keywords: vegetation evolution; landslide; root area ratio; soil erosion; nature-based solutions

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1. Introduction

Land degradation and soil erosion, due to increasingly frequent extreme hydro-meteorological 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 km^2. 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 m^2 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.pl; *Cornus* sp.pl, *Euonymus europaeus*, *Crataegus monogyna*, and *Prunus spinosa*.

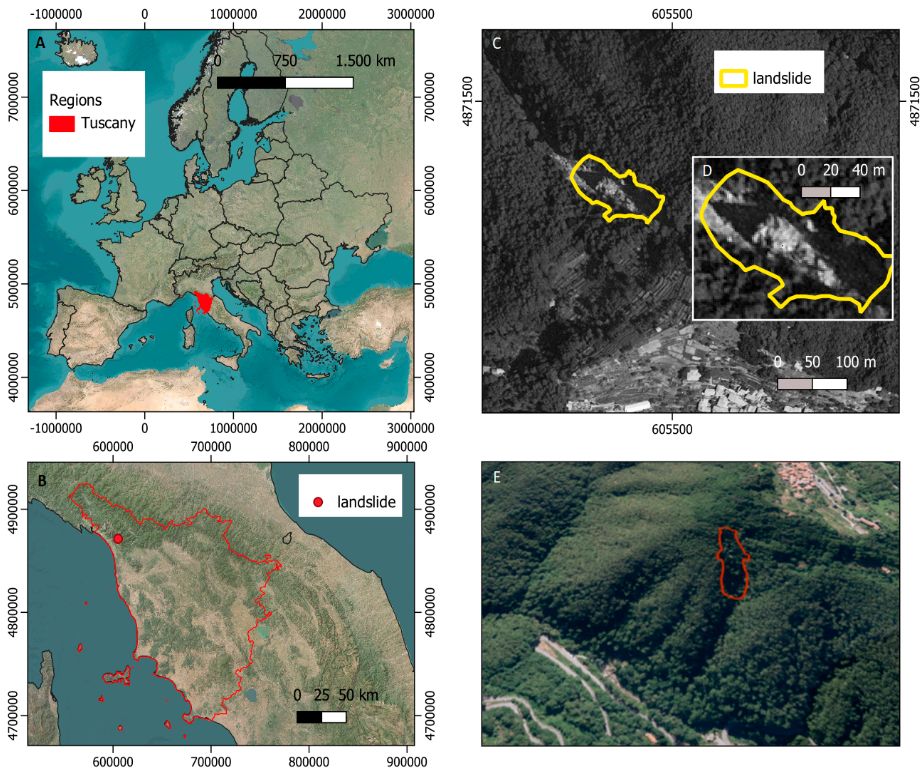

Figure 1. Panel (**A**) displays the location of the Tuscany Region within Europe. Panel (**B**) indicates the specific locations of landslides within the Tuscany Region. Panel (**C**) presents the landslide locations overlaid on the regional orthophoto acquired by the Tuscany Administration in 2016. 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.

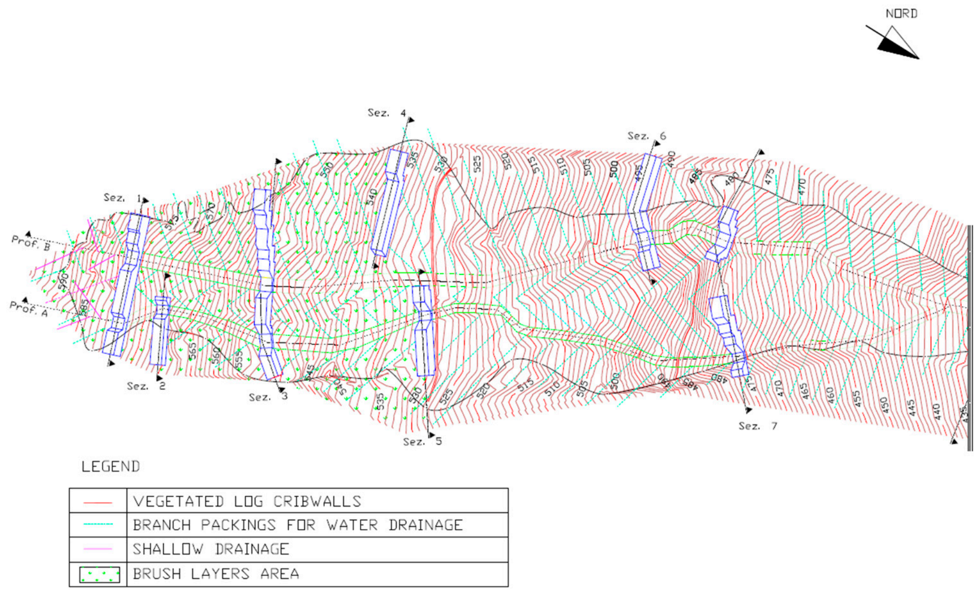

Figure 2. Final project plan of the forest hydraulic technique landslide restoration with different techniques of SWBE.

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 multi-approach 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 samplings. 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 m^2). 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 × 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),

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

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:

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

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].

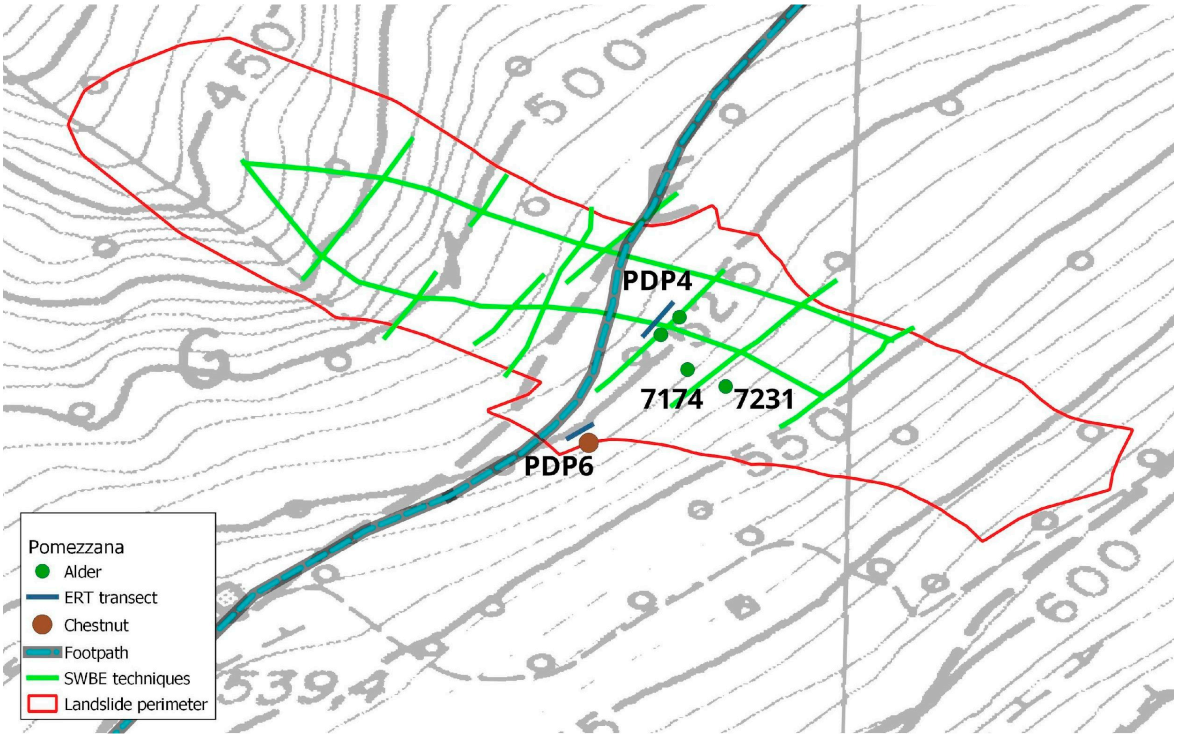

Figure 4. Outline of the 2013 surveys: location of survey points of RAR values and ERT geoelectric analysis.

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 ©, 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.

Figure 5. Images of the two explored root systems: plant 7174 on the (**left**) and 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.

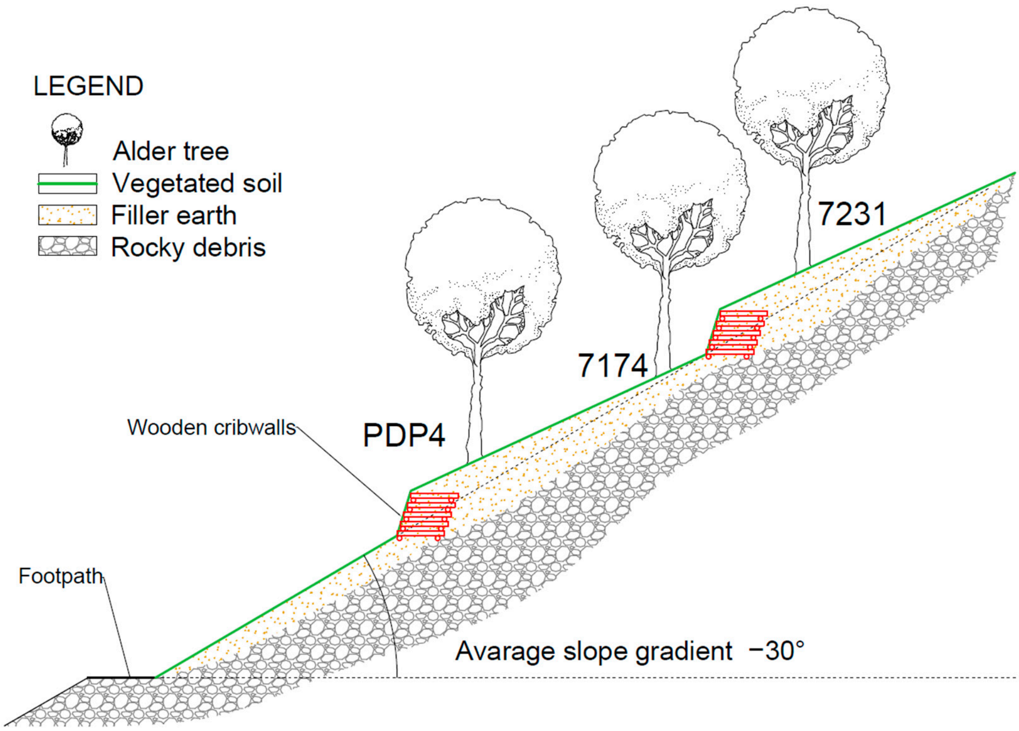

Figure 6. Longitudinal section scheme of the ERT and RAR trees distribution.

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).

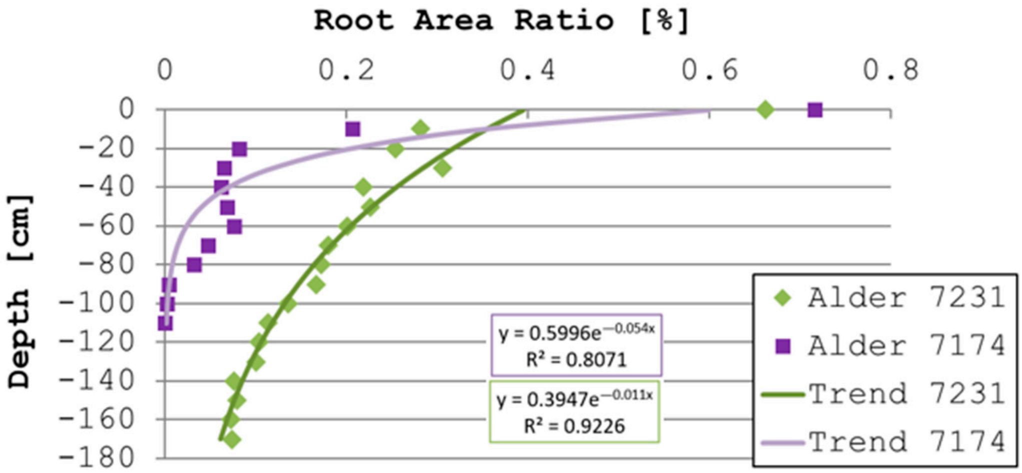

Figure 7. Percentage root area ratio for the two Alders explored.

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 coefficient 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) × 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.

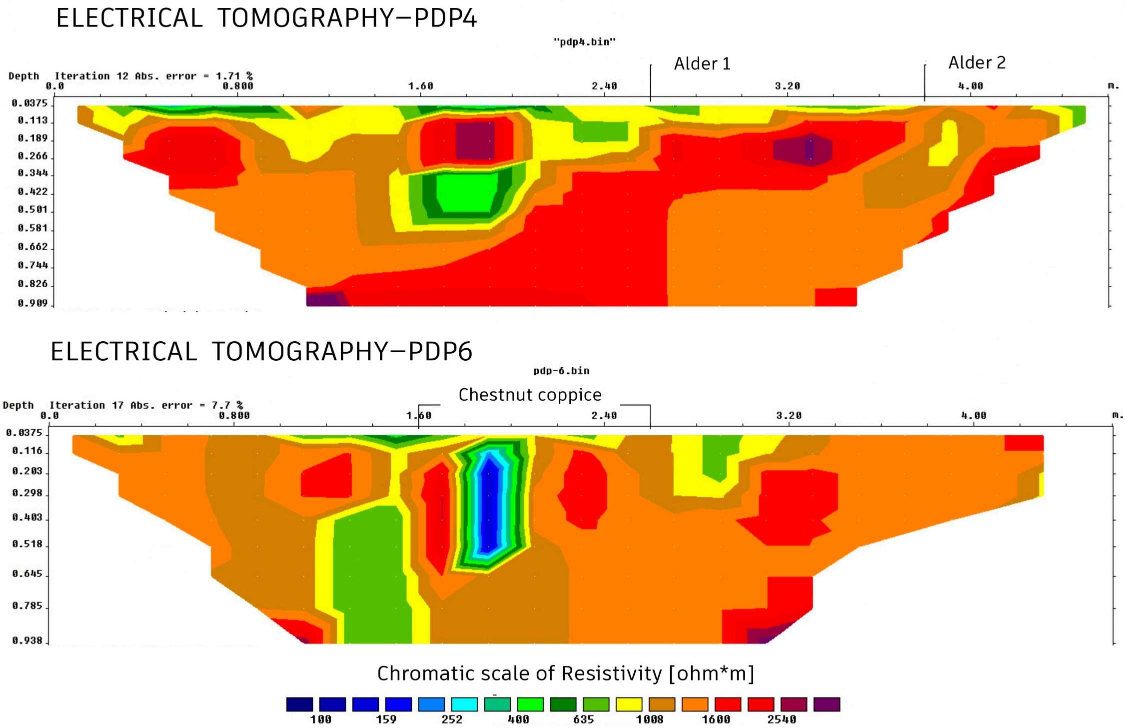

Figure 8. ERT: Electrical tomography graphical results for transect PDP-4 and transect PDP-6.

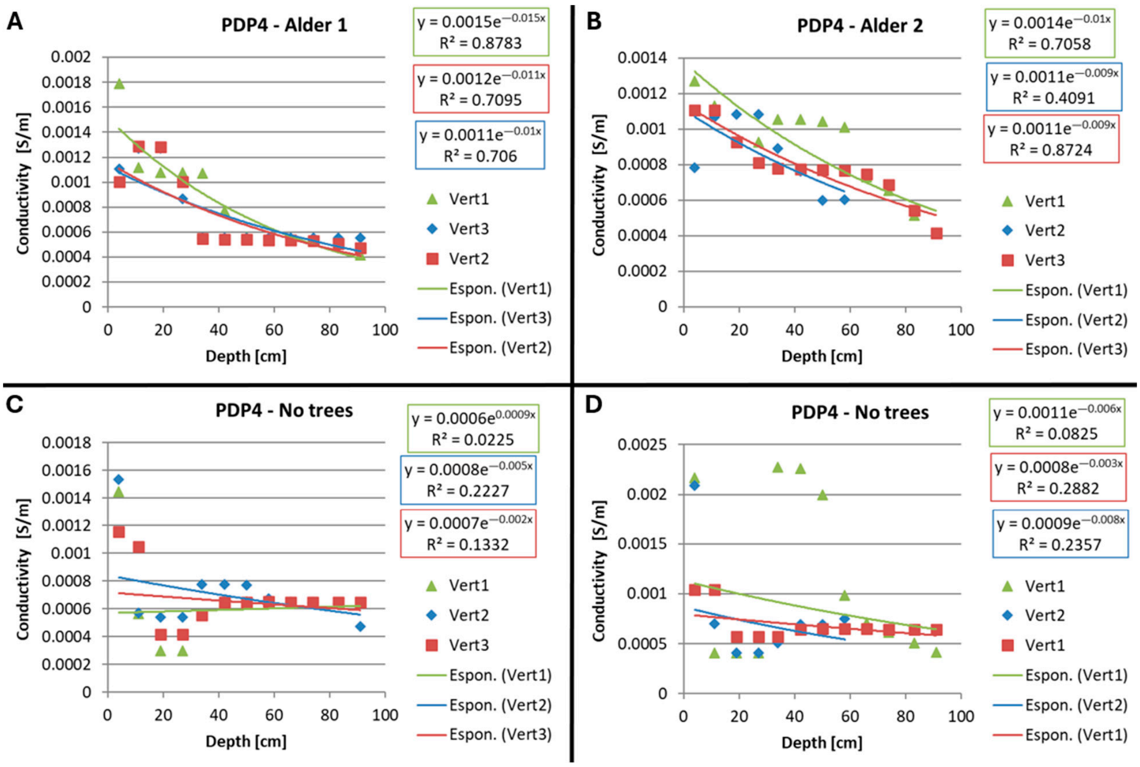

Figure 9. ERT graphical results in PDP-4: Correlation between conductivity and depth for Alder 1 (**A**) and Alder 2 (**B**). (**C**,**D**) The trend of conductivity values in depth in portions of the transect where there are no trees.

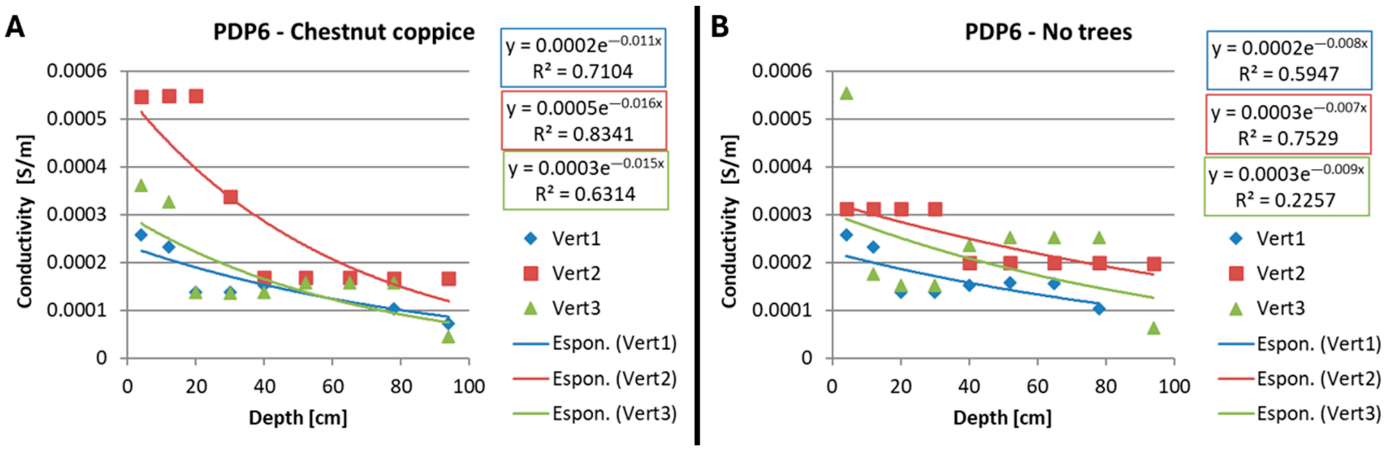

Figure 10. ERT graphical results in PDP-6: Correlation between conductivity and depth in Chestnut coppice (**A**) and no trees portion (**B**).

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.

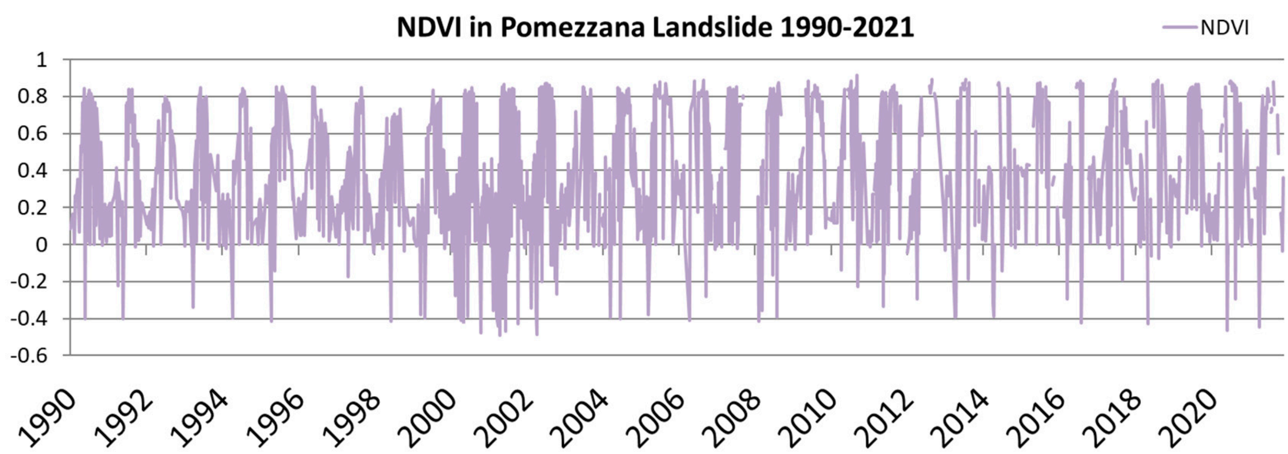

Figure 11. All NDVI data in the period observed.

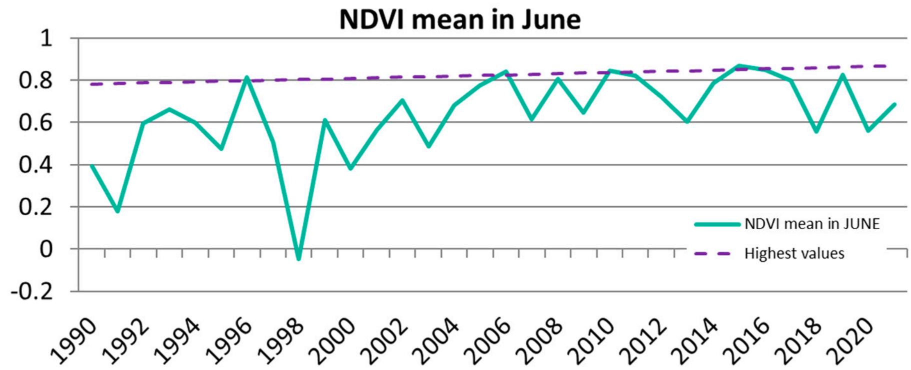

Figure 12. NDVI mean value of June of each year.

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 para-natural 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, CO_2 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 corresponds 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 $Ar(z) = e^{bz}$ => $\ln(z) = bz$). 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 understand better 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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