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Transferability analysis as a supporting tool for the uptake of soil and water bioengineering measures in fire prone areas.

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Whoever feels overlooked reading this page – don´t be, I love you!

Abstract

The present thesis describes the theoretical transfer of soil and water bioengineering (SWBE) as a measure for erosion mitigation to a fire-prone Take-Up Site in the temperate Andes in southern Ecuador. A fire-prone area in the Pisan Mountains/Italy, where SWBE measures are frequently used, served as Leading Site. The Transferability Analysis aims to estimate key barriers or key support factors appearing with the transfer. Various analyses were carried out to support the findings: Autonomous vegetation recovery capacity at the Take-Up Site in post-fire conditions was analyzed using multitemporal vegetation indices from Sentinel 2 images. A soil data base at the Take-Up Site elaborated from field study and laboratory gave information regarding soil properties. To estimate soil loss at both sites the Revised Universal Soil Loss Equation (RUSLE) was used to simulate pre- and post-fire conditions. Further, the fire induced change of the runoff coefficient was estimated for one unburned and one burned basin at the Leading Site. The results showed a high vegetation recovery of grasslands at the Take-Up Site to the level of pre-fire conditions within one year. One key result from the soil analysis was the high infiltration rate in post-fire conditions, probably influencing the subsurface flow. The comparison of erosion behavior showed a moderate mean annual erosion at the Leading Site in pre-fire conditions (33.89 $t/ha^{-1}/yr^{-1}$), with an increase of 285% in post-fire conditions. The mean annual erosion at the Take-Up Site was already high in pre-fire conditions (116.14 $t/ha^{-1}/yr^{-1}$) and showed an increase of 7.16 % in post fire conditions. The runoff coefficient at the Leading Site changed with the fire event from 0.2 to 0.5. Regarding the take-up of SWBE measures to the fire prone area in the temperate Andes probable constraints resulted to be qualified *labor* and *equipment/mechanical instruments*. Key support factors for the transfer were *Botany* and *Materials* as a variety of plants shows important characteristics for SWBE measures, able to compensate constraints in certain cases.

Keywords:

transferability analysis, wildfires, soil and water bioengineering, remote sensing, RUSLE, runoff coefficient

Table of content

1 Introduction

According to the fourth-generation global fire emission database (GFED4), the amount of burned areas due to forest or wildfires increased globally from 2000 to 2012, whereby the most affected ecosystems resulted to be savannahs, open shrubland and subtropical grasslands [1]. Resulting effects on the landscape with probable impacts on adjacent residents vary from a higher surface runoff and therefore altered hydrological behavior of watersheds due to missing or damaged vegetation [2], to gully or surface erosion, as well as concomitant long-term effects on vegetation recovery and its reciprocal effect on soil loss. Further, the intensity of a fire event influences the vegetation´s capacity to recover and therefore also the erosion behavior of the area. Soil and water bioengineering (SWBE) as a sustainable tool to mitigate or stop erosion processes on constructed slopes, in mountainous regions, along river courses, or coasts [3,4], besides can help to significantly improve the process of vegetation recovery after wildfires. In alpine forest fire areas in Central Europe Wasem et al. [5] showed, that reforestation measures can support the development of vegetation by regaining up to 10 years compared to the vegetation development and recovery without anthropogenic support. Depending on region and/or climate conditions, erosive postfire processes can increase partially over the years if they are not stopped with adequate measures when pioneer vegetation is not capable to revegetate the bare soil. Generally, SWBE uses living materials, such as plants or part of plants, as well as inert materials, e.g. wooden logs, and cribs as construction material, therefore covering various scientific fields, such as pedology, botany, hydraulics, and hydrology. The overall aim of SWBE solutions is to improve and provide good conditions for native vegetation and pioneer species, as well as to develop a protective layer in form of biomass at the surface (branches and leaves) and within the upper soil layer (roots, up to 2 m in depth), to prevent erosion by increasing cohesion within soil particles [6,7].

Globally, the use as well as the development of SWBE techniques vary greatly depending on continent, country, and region. In order to integrate SWBE methods to unknown regions, a transferability analysis [TA] can help to identify key barriers, as well as key support factors at the area in question [8].

With the present thesis the transfer of SWBE measures to a fire prone area in the temperate Andes was analyzed to provide a base for pre- and post-fire erosion protection and vegetation recovery measures. As Leading Site, a fire prone area in the Pisan Mountains (Mediterranean region/Italy) was chosen to represent an area where SWBE measures were established after various fire events in order to diminish post-fire soil erosion. As Take-Up Site the basin El Saco in a wildfire area from 2019 at the Temperate Andes in Ecuador was selected, where no anthropogenic post-fire measures for erosion mitigation were undertaken, and SWBE techniques are not frequently used yet for various reasons, such as missing knowledge regarding the techniques to be employed or financial capacity.

The methodology of this thesis is based to a great extent on three scientific articles elaborated in recent years in the context of various, international research projects, which are described in chapter 2. With the first article a TA for SWBE measures was developed to support their uptake in unknown areas. The second article describes the selection of Sentinel 2 derived vegetation indices for the monitoring of post-fire vegetation recovery in the temperate Andes, as well as the analysis of the vegetations´ development within different fire severity areas in the first two post-fire years at the basin El Saco (Ecuador) and therefore the Take-Up Site. The third article investigates basin scaled erosion behavior after the first heavy rainfall events in post-fire conditions at the Leading Site in Calci (Italy).

In addition, further analyses were carried out, aiming to support the decision-making process regarding the implementation of SWBE to the fire prone area and therefore understand key support factors or constraints for the transfer.

The following research aims were defined:

- To understand the autonomous vegetation recovery capacity of the Take-Up Site using the vegetation indices selected in article 2.
- To define soil type, post-fire infiltration capacity and correlations of soil properties at the Take-Up Site.
- To estimate soil erosion in pre- and post-fire conditions to show differences regarding erosion behavior between the Leading and the Take-Up Site.
- To show the change of the runoff coefficient in unburned and burned conditions at the Leading Site.
- To discover key support factors or key barriers accompanying the implementation of SWBE measures to the unknown, fire-prone Take-Up Site.

2 Presentation of the articles

The following scientific articles were authored within interdisciplinary, as well as international research projects, providing the basis for the framework of the thesis. This chapter briefly describes the background and aims, the methods, as well as the results, achieved.

Article 1: ***Maxwald, M.; Crocetti, C.; Ferrari, R.; Petrone, A.; Rauch, H.P.; Preti, F. Soil and Water Bioengineering Applications in Central and South America: A Transferability Analysis. Sustainability 2020, 12, 10505. https://doi.org/10.3390/su122410505***

Background and aims:

Globally, a severe lack of established protocols exists to support SWBE, and in areas where these measures are not used, local authorities have little to no knowledge concerning the existence or applicability of the techniques. Nevertheless, during the last years the scientific interest in SWBE increased in Central and South America which provided the possibility to investigate the question whether a successful application of these techniques is possible on the continent. The aim in this paper is to provide standardized categories for the requirements of SWBE techniques when transferring them to regions with unknown conditions. Standardized categories can close the gap between stakeholders, planning parties and SW bioengineers to support the implementation of SWBE. Further, a method to detect key support factors, as well as key barriers was developed for application when transferring SWBE techniques to new locations.

Methods:

With this article a TA for SWBE measures to unknown areas was developed based on the approach of Gyergyay and Boehler-Baedeker [9]. An empirical database, derived from undertaken SWBE constructions in Central and South America, served to acquire information from Leading Sites in the area in order to assess the ability of transfer to the whole continent and therefore the Take-Up Site.

Results:

The TA undertaken supports the assumption that SWBE techniques can be transferred to Central and South America on a large scale. Key barriers appeared to be the components qualified labor, equipment/mechanical instruments, hydraulics, know-how in soil and water bioengineering, as well as pedology. The components local climate conditions, economic resources and efficiency proved to be neither barriers, nor supporting key factors. Further, materials, monitoring, sustainability, maintenance, and replicability were key factors for a successful transfer to Central and South America. The most important key factor of success was assessed to be botany. At the continent in question various plant species with important characteristics for SWBE are available. Probable constraints through existing key barriers can be compensated by these plants in some cases.

<u>Relevance to the thesis:</u>

The developed TA for SWBE provides the basis by which to assess the transfer of SWBE measures to unknown fire-prone areas by detecting key support factors, as well as key barriers.

<u>Contribution of Melanie Maxwald:</u>

- conceptualization
- methodology
- formal analysis
- writing — original draft preparation
- writing — review and editing
- visualization

***<u>Article 2:</u>* Maxwald, M.; Immitzer, M.; Rauch, H.P.; Preti, F. Analyzing fire severity and post-fire vegetation recovery in the temperate Andes using earth observation data. Fire 2022, 5, 211. https://doi.org/10.3390/fire5060211**

<u>Background and aims:</u>

Post-fire vegetation recovery in wildfire areas strongly depends on fire severity as it influences soil properties, soil seed banks, roots, or rhizomes. The vitality of vegetation and its ability to resprout and regrow in post-fire conditions can be monitored using vegetation indices, derived from Sentinel 2 images. The best vegetation index for post-fire monitoring depends on the vegetation type and climate zone and varies therefore with changing region. This paper aims to select the best vegetation indices for post-fire vegetation monitoring of a wildfire area in the temperate Andes in southern Ecuador, as well as to understand the vegetation´s development in different fire severity classes based on these selected vegetation indices.

<u>Methods:</u>

In a first step, the Relativized Burn Ratio (RBR) was calculated and classified according to the USGS classification of fire severity, as applicable to the fire event in September 2019 using one pre- and one post-fire Sentinel 2 scene from the basin El Saco at the canton Quilanga/Loja in Ecuador. For the second step, 23 vegetation indices were calculated from multitemporal, atmospherically corrected pre- and post-fire Sentinel 2 scenes. Further, various random forest (RF) models classifying the fire severity classes at the basin El Saco were set up with feature selection (dependent-variable: fire severity class, descriptive variables: vegetation indices from different Sentinel 2 scenes). These models served to define the most important and most influencing vegetation indices within the classification process and therefore to find the adequate vegetation indices for post fire monitoring in the temperate Andes. Based on these two selected vegetation indices in a third step the vegetation recovery was statistically analyzed at the basin El Saco within the first two post-fire years per fire severity class (low severity, moderate low severity, moderate high severity).

Results:

The selected vegetation indices for the monitoring of the vegetation recovery in the temperate Andes resulted to be the Leaf Chlorophyll Content Index (LCCI), as well as Normalized Difference Red-Edge and SWIR2 (NDRESWIR). In the first post-fire year the vegetation recovered to a great extent due to vegetation types with a short life cycle such as grass and herb species or shrubs. The delta of the vegetation indices showed that in the first post-fire year increasing vegetation index values correlated positively with increasing fire severity. One year after the fire event, the vitality in low severity and moderate high severity seemed to be at or above the pre-fire level.

Relevance to the thesis:

This paper delivers the vegetation indices to assess the autonomous vegetation recovery capacity in post-fire conditions of the temperate Andes (Take-Up Site).

Contribution of Melanie Maxwald:

- investigation
- conceptualization
- methodology
- formal analysis
- writing — original draft preparation
- writing — review and editing
- visualization

<u>Article 3:</u> Mastrolonardo, G.; Castelli, G.; Certini, G.; Maxwald, M.; Trucchi, P.; Foderi, C.; Errico, A.; Marra, E.; Preti, F. Post-fire erosion and sediment yield in a Mediterranean forest catchment in Italy. Authorea, 2022, 12.

https://doi.org/10.22541/au.166256297.71210800/v1

<u>Background and aims:</u>

Post-wildfire erosion due to damaged vegetation and changing soil properties affects forest and agro-ecosystems. Data-based evidence on post-fire erosion and sediment yield at watershed scale contributes to a better understanding when implementing pre- and post-fire measures, especially in areas with frequent wildfire occurrence, such as the Mediterranean region. The aim of this paper was to deliver further knowledge of post-fire, rainfall-induced runoff processes at basin scale in Mediterranean areas. As study site, the basin of Rio Santo Pietro (SP) in the Pisan Mountains in central Italy was selected. The basin, which is characterized by stony and shallow soils, was affected from a severe forest fire where 1,000 ha of olive groves, maquis, maritime pine, and chestnut forests burned in September 2018.

<u>Methods:</u>

In a first step, the fire severity of the wildfire area was mapped by calculating the RBR, using pre- and post-fire Sentinel 2 images, and checked by a field survey. The next step contained the sediment yield sampling upstream a check dam at the outlet of the basin SP to understand the sediment composition in context with the post-fire rainfalls. Finally, a hydrological model was set up in HEC-HMS to check the relation between the observed erosion and deposition events and the rainfall induced hydrological processes.

<u>Results:</u>

A high amount of mostly non-organic sediment was deposited at the basin´s outlet with the first and the second rainfall events. The subsequent four rain events accumulated material with a high amount of pyrogenic organic matter. Soil erosion estimation of these mentioned first six post-fire rain events resulted to be 7.85 t ha^{-1}, corresponding to 42% of the minimum annual potential erosion rate of the basin in vegetated conditions. Compared to other Mediterranean case studies, this value is moderate and can be explained by the shallow and stony soil, as well as high rainfall erosivity and steep topography at the area in question. The minimum annual potential erosion rate, estimated with the USLE method in normal conditions resulted to be 18.8 t ha^{-1} y^{-1}.

Relevance to the thesis:

Article 3 provides an insight into post-fire analyses carried out at the basin SP, which is part of the fire prone Leading Site in the Pisan Mountains.

Contribution of Melanie Maxwald:

- field and laboratory work
- investigation
- visualization
- writing – original draft preparation

3 Workflow

In a first step the situation of SWBE in general, as well as in Central and South America is explained, and frequently used SWBE measures for fire prevention and post-fire erosion mitigation were described. Based on the three mentioned research articles, within the following synthesis of the analyses the Leading Site (Pisan Mountains/Italy), as well as the Take-Up Site (Basin El Saco/Ecuador) for the TA were defined, and various analyses to support the estimation process regarding an implementation of SWBE measures were undertaken. The first analysis aimed to understand the autonomous vegetation recovery capacity of the Take-Up Site in post-fire conditions using pre-selected vegetation indices from Sentinel 2 images. Further, a soil data base at the Take-Up Site, derived from field study and laboratory data, provided information regarding soil properties. The estimation of pre- and post-fire soil erosion for the Leading and the Take-Up Site delivered information regarding the erosion behavior and its changes with a fire event. In a next step the change of the runoff coefficient in pre- and post-fire conditions was analyzed. The most important step was the TA for the implementation of SWBE measures to the Take-Up Site, as possible key barriers, and key support factors at the area in question were determined.

4 Soil and water bioengineering

SWBE is defined as a nature-based solution for civil and hydraulic engineering [10], as it employs biological components, such as plants or wooden logs aiming to protect (artificial or natural) slopes, riverbanks, or coasts [3,11,12]. The used living materials, such as seeds and (parts of) plants require certain properties, e.g. fast rooting, high bending ability or vegetative reproduction [7]. When planning erosion mitigation measures using SWBE, the development time of the plants to reach the preferred ability of stabilization must be considered [13]. For this reason, living materials are frequently combined with inert materials, such as stones or wooden logs etc. [7,14] at sites which need an immediate erosion mitigation effect.

The discipline SWBE can be separated in two sections:

- Soil bioengineering, which handles shallow landslide and gully stabilization, superficial erosion, and other earth constructions, as well as

- Water bioengineering, which stabilizes riverbanks or coasts and is frequently used in river restoration [4].

Sources document the origin of some SWBE techniques in Europe during the Roman Imperial period [15], as well as in China 2000 BC [11]. Since the mid-1980s, SWBE has taken hold in the scientific community in the Alps, the Mediterranean region, as well as in North America [6,16]. Further, various approaches have been carried out to implement SWBE in regions where these methods are not or sparsely used [8,12,17–20]. In many of these regions, plants were or are still used as construction material by e.g., indigenous people, however, this valuable knowledge has fallen into oblivion in so called civilized areas. Various experiences and projects have shown that the implementation of SWBE measures in low- and middle-income countries is feasible. Since the beginning of the 2000s, various research groups have carried out studies, aiming to understand the applicability of SWBE in countries beyond Europe and Northern America. As a result, significant and seminal studies from Asia (China [11], Nepal [12,21]), Africa (Ethiopia [22]), as well as Central and South America (Caribbean [23,24], El Salvador [25], Nicaragua [18,19], Colombia [26], Ecuador [20,27,28], Brazil [17,29–31]) were published.

4.1 Situation of SWBE in Central and South America

Generally, the use of SWBE techniques is not common in most regions of Central and South America, even if the mitigation of erosion in mountainous, as well as agricultural areas is of utmost importance to protect inhabitants and infrastructure or halt the loss of fertile soil. SWBE, as a nature-based solution, implies social and ecological benefits for inhabitants, flora, and fauna. However, the implementation of SWBE to unknown areas requires various experiments or scientific studies investigating pedologic, botanic and hydraulic issues, depending on the implemented techniques. The interaction between soil, plants (including their development in different circumstances), as well as water (precipitation, groundwater, floods, or waves), must be investigated and measures adapted and/or extended regarding the conditions at the area in question. Over the last two decades, the scientific SWBE community in Central and South America increased and various studies were published. In the Caribbean (Guadeloupe) the suitability of various neotropical tree and shrub species were investigated for usage in SWBE constructions [23,24]. In Central America, studies from El Salvador and Nicaragua were carried out, investigating SWBE prototypes [25], as well as riverine plant species for water bioengineering and economic efficiency [18,19]. In South America Rivera

Posada and Sinisterra Reyes (2006) [26] (Colombia) published a manual book for SWBE techniques. Some studies from international research groups were found in Ecuador, investigating gully erosion mitigation measures for badland restoration [28], as well as wooden check dams and afforestation for sediment reduction [27]. Further, a short-term species suitability test for watershed management and disaster mitigation [20] was carried out. In Brazil, seminal dissertations discuss SWBE applications in the country [32–34]. In addition, various scientific publications resulted, assessing e.g. live cuttings [31], specific plant species [17], the performance of SWBE works [29], as well as environmental conditions and potential demands for SWBE techniques [30]. Despite these important studies, the application of SWBE is not common in Central and South America yet. To implement SWBE techniques widely and sustainably at continent scale, one very important and actual topic is to close the gap between the scientific community and planning, as well as construction parties. The collaboration between municipalities, local authorities and/or universities, as well as the provision of information regarding the advantages, necessities of implementation, and probable limitations will be a critical point to successfully develop SWBE measures adapted to Central and South America.

4.2 Frequently used SWBE measures in fire prone areas

The following chapter provides an excerpt of frequently used (SWBE) measures in fire prone regions. When planning and implementing measures for fire prevention, erosion mitigation and reforestation, the priority basically lies on areas which suffered the greatest damage and therefore present the greatest risk from a hydrogeological point of view and public safety [35]. Generally, securing, and restoration measures should be planned and carried out shortly after the fire event, as erosion damage appears mainly with the first post-fire rainfall events.

While in pre-fire conditions interventions are undertaken to prevent fire from spreading, post-fire measures provide the protection of settlements and infrastructure, as well as the mitigation of instabilities and erosion on slopes. Further, the implementation or improvement of forest roads allows e.g. fire fighters to access the fire area, or workers to execute post-fire measures.

- Pre-fire measures in fire prone areas to prevent fire from spreading

In most cases, a wild or forest fire starts from the ground, what makes it inevitable to target silvicultural measures when aiming to mitigate effects of fire. A change or adaption of tree, shrub, or grass species and improved maintenance leads long-term to a changed litter composition in fire prone areas. The mitigation of easily flammable fuel on forest ground can therefore diminish the spread of fire. When adapting forests to climate change the modification of tree species, should therefore also be discussed as a long-term spatial intervention, and implemented in planning strategies [36]. Other, linear, or zonal preventive measures include e.g. the formation of forest aisles with the complete removal of vegetation. However, with this method problems regarding water, or wind induced soil erosion may appear in these areas. Therefore, the arrangement of green fire barriers in from of species difficult to ignite or shaded fuel breaks aiming to hinder the spread of fires may be a more adequate measure in fire prone areas [36].

- Post-fire SWBE measures in fire prone areas to mitigate erosion

The primary aim after wildfires is to mitigate the increased hydrological and erosive response [37], as well as to prevent long-term soil erosion and land degradation. Less resistance through vegetation means higher velocity and drag force of precipitation compared to pre-fire conditions.

SWBE constructions on slopes or riverbanks basically use a combination of inert materials, such as wooden logs to provide immediate stabilization (e.g. wooden crib wall), as well as living construction material, such as plants to increase cohesion within soil particles by retaining precipitation, minimizing surface runoff by draining water into the ground over the root system, and therefore prevent soil erosion. As often reported, surface runoff increases in post-wildfire areas, as a hydrophobic layer prevents water from draining into the ground [38]. Fast revegetation measures after wildfires can help to break this layer and therefore diminish erosion.

The implementation of SWBE measures for post-fire erosion mitigation provides various advantages, as most of the material used may come from the site or its surroundings, depending on the location´s conditions [8]. The entry of construction waste or nonbiodegradable materials into the ecosystem of the fire prone area is low and SWBE measures contribute therefore to a healthy environment.

Basically, two categories of post-fire measures can be defined: (a) increase of ground or vegetative cover, and (b) decrease of the runoff´s erosive energy using erosion barriers, designed to decelerate runoff and store eroded sediment on the slopes or similar measures [39].

The following list is an excerpt of most frequently used SWBE measures to implement in post-fire areas and does not portray every possibility of erosion control. Further SWBE measures can be found e.g. in Florineth [7] or Schiechtl [6].

(a) Increase of ground or vegetative cover: [6,7]

Fast measures to recuperate the vegetation layer are important to secure the remaining topsoil and minimize the erosion process. On relevant areas greening can be carried out with various methods whereby the water retaining function of the plants develops with their growth.

- Dry seeding

On stable, roughened raw soil the easiest way to recover vegetative ground cover is to dry seed with a mixture of pioneer grass, herb, and legume species of autochthonous origin, adapted to fire-affected nutrient conditions. A high percentage of herbs and legume species can also contribute to a more fire safe area, as their roots are tendentially deeper, which prevents the plant from drying out and therefore diminishes the fire risk. The sowing process can be undertaken manually or with machines and starter fertilizer may be used if necessary. In mountainous areas with no or difficult access, also a helicopter can be employed to sow the seeds.

- Hydroseeding

Seeds of grass, herbs, or woody plants can be sown with a carrier medium (water) using pumps, hydro seeders, helicopters, or airplanes. The water-seed mixture can be enriched with fertilizers, organic glue (starch), or growth enhancers.

- Mulch seeding

Mulch seeding in post-fire areas is a frequently used method [37], as it tolerates extreme climate conditions, such as cold weather, as well as heat and dryness. The layer of hay or straw is implemented to about 3-4 cm of height on slopes. Additionally, the application of organic glue or jute/coco nets can prevent the mulch from being blown away on steep slopes.

- Seeding mats

This method uses mats of paper, cellulose, straw, etc. containing seeds which are put on slopes and secured with pins, nails, or stakes. To ensure that the mats are in contact with the soil, the slope should be levelled beforehand. Overlapping the mats prevents the soil from being washed out.

- Sod slabs

Sod slabs from the surroundings are placed seamlessly onto the prepared, levelled slope and secured with pegs. The usage of construction machinery provides the possibility to employ larges sod slabs.

- Topsoil application

Topsoil containing seed material can be used to be applied on raw soil by spreading a thin layer, which is left in rough state for a fast vegetation development.

- Afforestation

Woody species, suited to the site in question, are planted on barren areas to accelerate reforestation. The planting method varies with site, accessibility, and available material. When planting along riverbanks, probable changing water levels must be considered.

- Cuttings

Cuttings serve for the fixation of various constructions and are driven into the ground with a few centimeters to emerge above the surface for stabilization or drainage function. Due to the capability to propagate vegetatively, living cuttings are the base for a stable vegetation layer, taking over the stabilizing function in case the wooden structure decays.

(b) Decrease of the runoff´s erosive energy:

Erosion barriers aim to decrease the runoff´s erosive energy, to increase infiltration, as well as to reduce downstream sedimentation [39]. The focus in wildfire areas lies on quickly instigated measures.

- Contour-felled logs [39]

The establishment of contour-felled logs in wildfire areas has several advantages. As the wildfire area is cleared of burned trunks, the felled logs are placed along the contour of the terrain to build a barrier against soil erosion (Figure 1a + b) which further saves transport costs for removal.

- Straw wattles

Tubes of compressed straw are mounted on the contour line of the slope and secured with wooden stakes to increase surface roughness and prevent superficial soil erosion.

- Gully control works [40]

These works consist of various methods, such as e.g. tree spurs, branch layering, or vegetated chase.

Trees spurs: Cut trees (log and crown) are used to secure riverbanks or gullies by securing them with steel cables or wooden stakes (tops point downstream). Coniferous and deciduous trees can be used and, in some cases, further species which are able to propagate vegetatively, or cuttings are implemented additionally to support greening.

Branch layering: Inert trunks are placed along a gully and secured with wooden stakes to prevent it from deepening and further erosion, as well as to support sedimentation.

Vegetated chase: Trapezoidal profiles are constructed with wooden poles, stakes, or square timber. Cuttings and other living material can be implemented into the lateral walls to form branches.

- Walls, sills, and weirs [40]

As post-fire measures transversal erosion barriers can be implemented at watershed scale to retain the sediment. The choice of the measure employed depends on available material, labor, accessibility, and time.

Pile walls: Like the contour felled log method, horizontally arranged pile walls can be constructed to mitigate erosion on slopes or in riverbeds. A pile wall can be implemented in form of a fence, as well as a weir (Figure 1c + d) and aims to retain loose layers of topsoil or sediment.

Sills and weirs, such as wooden crib walls, may be implemented in in different forms along river courses (Figure 1e + f). If SWBE measures are not efficient enough, rock filled gabion cages, or walls with big rocks are further options.

Further measures on riverbanks, as well as slopes can be ground ramps, pilot walls, or palisades.

- Drainage systems [7]

To mitigate the erosive potential of runoff at the subsurface, as well as the surface, channels filled with rocks or inert fascines can be constructed. The channelization of runoff aims to increase the angle of friction, as well as cohesion, and decreases pore water pressure.

After the implementation of a measure a continuous monitoring may help in the following years to adapt and improve methods and results in fire prone areas with similar characteristics.

Figure 1: Post-fire erosion mitigation measures at the wildfire area in the mountains of Pisa/Italy (Take-Up Site): (a + b) Contour felled log erosion barriers; (c + d) Pile walls as sediment traps with deposited sediment after the first post-fire rainfall events; (e) Wooden crib wall at the outlet of a basin; (f) Wooden ground sill combined with rip rap

5 Synthesis of the analyses

The following chapter provides the synthesis of the analyses from the research articles. Various methods are presented to analyze characteristics of the Leading Site, as well as the Take-Up Site. The results provide the foundation regarding the choice if a transfer of SWBE measures to fire prone areas in unknown regions is reasonable and which key barriers or key support factors appear.

5.1 Materials and Methods

5.1.1 Definition of the Sites

- Leading Site: Wildfire area in the Pisan Mountains

The Leading Site is represented by a fire prone area in the Pisan Mountains (Mediterranean Region/Central Italy) where in recent years various fire events destroyed olive groves, maquis and forests of maritime pine or chestnut. The Mediterranean climate (Csa, Köppen-Geiger Classification) is characterized by hot and dry summers with cold, rainy winters. The mean annual precipitation is about 883 mm, the mean annual temperature at 14.4 °C [41] and the slope ranges from 30 – 60%. Since the 1970s more than 75 wildfires appeared in the region during summertime due to the high anthropization [42].

The analyses undertaken in this thesis address a fire event from September 2018, with an extent of 1200 ha. Several ground fires started from spot events, were favored by topography and wind and fire control involved 580 firefighters and 12 aircrafts. For post-fire soil erosion prevention various SWBE measures were implemented at the Leading Site. The most important ones were contour felled logs, pile walls and wooden crib walls as weirs and erosion barriers, as well as reforestation and greening methods.

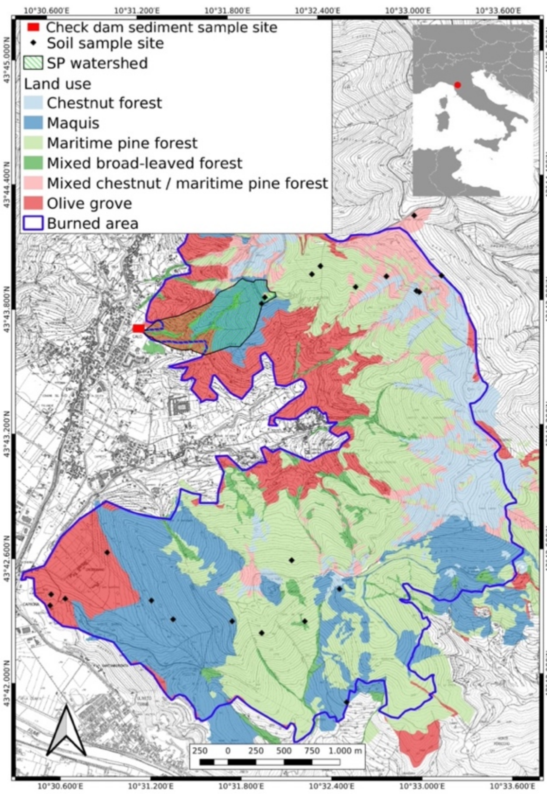

Figure 2: Location and extent of the wildfire area, as well as vegetation types (credit: Cristiano Foderi, Unifi)

- Take-up Site: Wildfire area in Quilanga

The investigated fire prone area lies in the temperate zone (Cfb, Köppen-Geiger Classification) of the southern Andes in Ecuador (canton Quilanga/Loja). Grass- and shrubland with some forest patches characterize the landscape, whereby non-native tree species, such as eucalyptus or pine tend to dry the soil, which also influences the spread of wildfires. Further, coffee production, farming, and pastureland are part of the cultivated landscape. The precipitation value is about 1100 mm per year and the months from December to May are characterized by intense rain events [43]. The wildfire risk increases from June to November. In recent years three major wildfires have been reported, which occurred in 2012, 2016 and 2019 (Figure 4) and were caused by farmers intending to prepare farmland. The investigated fire event lasted for two weeks in September 2019 and affected more than 8000 ha. For the present TA, the basin El Saco with an area of 984 ha, and an altitude of 1520 m a.s.l. at the outlet to 2680 m a.s.l. at the highest point was chosen to be representative and accessible for field work (Figure 3). At the basin El Saco no post-fire measures were carried out which provided the basis to use it as an "unknown" area and therefore analyze the uptake of SWBE measures, as well as the autonomous post-fire vegetation recovery capacity.

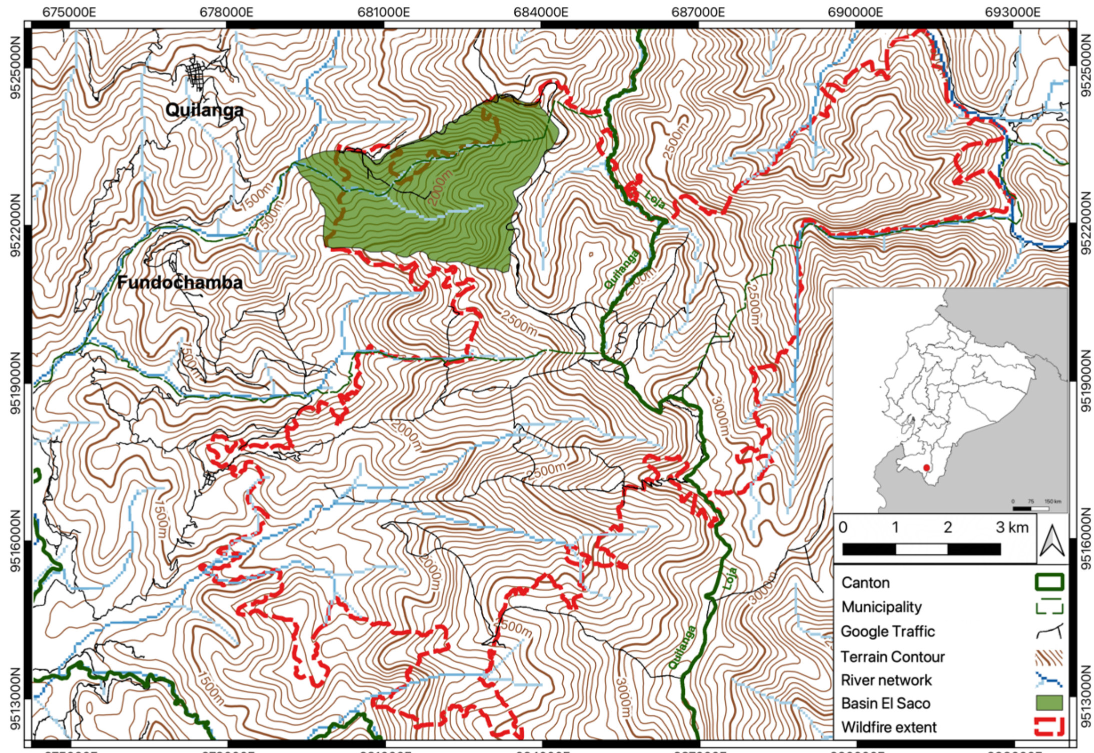

Figure 3: Location and extent of the wildfire area (red), as well as the river basin El Saco (green) in Quilanga, Ecuador; Background: contour map of elevation derived from DEMs (credit: Marc Souris, IRD)

Figure 4: (left) Basin El Saco one month afte the wildfire; (right) Basin El Saco two years after the wildfire

The elaboration of the RBR (Figure 5) showed that about 79.37% of the basin were affected by the fire, whereby the biggest parts were classified as “moderate low severity” (54.74%), “moderate high severity” (21.38%), and “low severity” (18.82%).

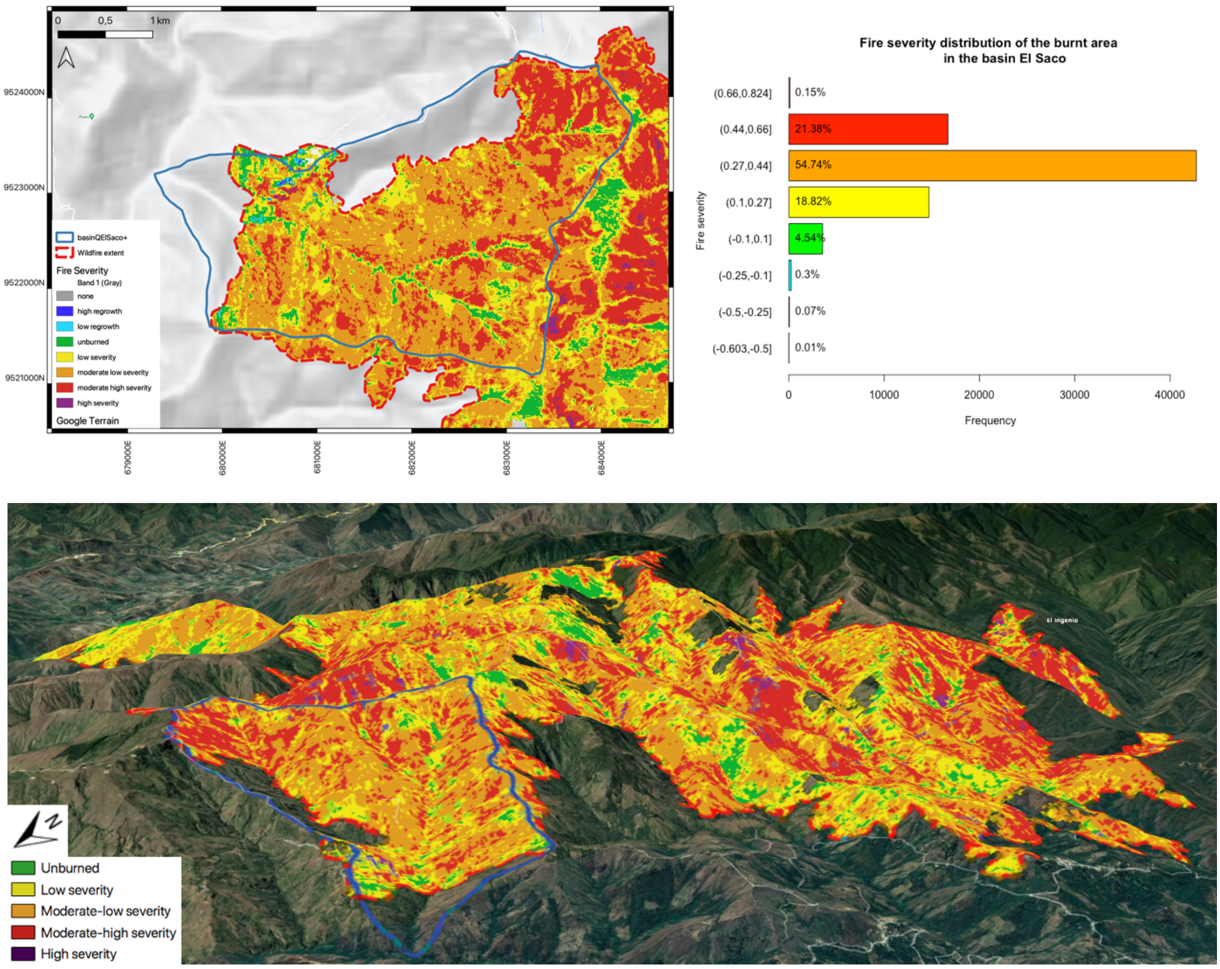

Figure 5: Above: Fire severity after the wildfire in September 2019 at the basin El Saco, canton Quilanga/Ecuador. (Base map: Google Terrain) and distribution of the fire severity within the burnt area of El Saco;

Below: Overview of the wildfire area 2019 from the viewpoint Quilanga in Google Earth Pro.

5.1.2 Post-fire vegetation development at the Take-Up Site

For the monitoring of wildfires or fire prone areas remote sensing methods are used frequently for various purposes such as simple information acquisition regarding vegetation recovery [44–47] or the efficiency of forest restoration treatments [48,49].

Earth observation (EO) data from satellites, such as Sentinel 2 from the Copernicus program of the European Space Agency (ESA) is gained by two identical satellites in the same orbit (Sentinel 2A and 2B), which are equipped with a multispectral imager (MSI) [50]. They deliver high resolution optical imagery inter alia of agriculture, forests, land-use, and land cover change. The wavelengths of the 13 bands range from 443nm to 2190nm, the temporal resolution is 5 days and the spatial resolution 10, 20 or 60m, depending on the band. Especially in wildfire areas fire severity mapping based on satellite data is a tool to estimate the fire´s impact on the area.

To understand the vegetation´s capability of self-recovering in post-fire conditions at the Take-Up Site, a time series analysis was carried out using vegetation indices from Sentinel 2 data. At the area in question, no recovery measures were implemented which provided the possibility to monitor the self-recovering process of the vegetation without anthropogenic influence.

Within article 2 (page 98) two vegetation indices were selected, suited best for analyzing vegetation recovery according to fire severity at the temperate Andes (Leaf Chlorophyll Content Index = LCCI, and Normalized Difference Red-Edge and SWIR2 = NDRESWIR). A time series monitoring was carried out for the basin El Saco over three years (one pre-fire, two post-fire years) using the median of each vegetation index per fire severity class. Further, the delta of the vegetation indices was calculated the first, the second, and the first two post-fire years, to understand the postfire increase of the biomass, which is represented in boxplot diagrams.

The results influence the present TA for SWBE measures to the Take-Up Site, as e.g. a fast, autonomous recovery would influence the decision if post-fire greening measures are necessary.

5.1.3 Soil analyses at the Take-Up Site

The characteristics of soil properties are crucial for the erosion behavior of a basin. To acquire an overview of the soil properties at the Take-Up Site, the following chapter describes the data acquisition process of a field and laboratory study undertaken in November 2019, one month after the fire event. Soil samples from 18 points at the basin El Saco were analyzed.

- Data base of soil properties:

Field monitoring: Infiltration velocity

The field survey was carried out from October 29 to November 4, 2019, one month after the fire event. During this time the infiltration velocity, was determined in each test point using a metal cylinder with a diameter of 29 cm (Figure 6, left). For the determination of the infiltration time, the cylinder was hammered into the soil and filled with a water layer of 4 cm. After measuring the time, the water needed to infiltrate, this step was repeated until the soil was saturated and the infiltration time was stable.

Figure 6: Measurement of infiltration velocity (left) and water drop penetration time (right)

Laboratory tests:

In a next step, the soil samples from the test points were studied in laboratory. To prepare the samples for the analyses, they were air dried and sieved to the fine earth part of 2 mm.

Hydrophobicity

To test the soil samples against hydrophobicity, the soil water repellency (SWR) was measured with the water drop penetration time (WDPR) [51] under controlled atmospheric conditions (temperature and humidity). After putting the dried soil into Petri dishes (three for each sample), five distilled water drops (ca. 100 µl each) were released from 1 cm of height and placed individually on the dish (Figure 6, right). The requested time for the complete infiltration was measured for each drop and the interval classes defined by Doerr [51] (from <5 s “very hydrophilic” to > 5 h “extremely hydrophobic”). The average penetration time of the five drops was calculated per Petri dish and the average of the three dishes was used as the representative value for the sample point.

<u>Organic Matter Content</u>

The content of the organic matter was determined by the Loss on Ignition (LOI) method [52]. Therefore, in a first step the samples were dried at 105°C and then put into the muffle furnace at 480°C for eight hours. With the burnt organic matter and the concomitant loss of weight, the organic matter content could be determined.

<u>Hydrometer method</u>

The particle size analysis was performed according to the hydrometer method [53] to calculate the physical proportions of soil particles (Figure 7).

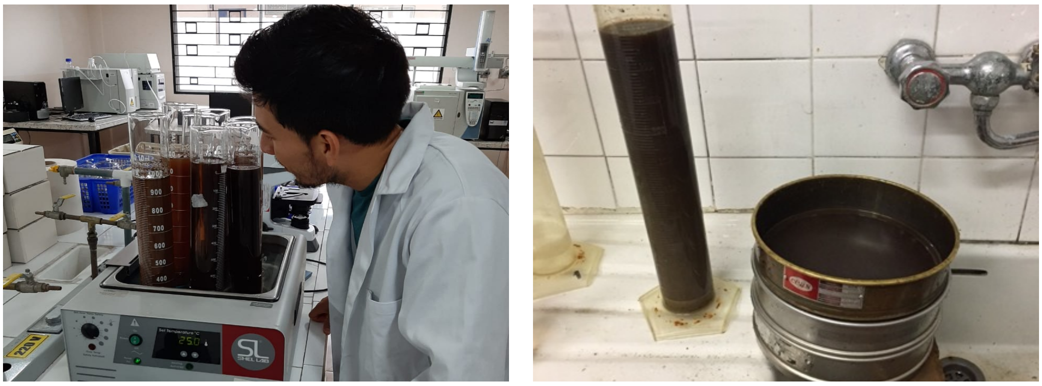

Figure 7: Elaboration of soil texture with the hydrometer method

To understand connections between the variables the Pearson correlation coefficient [54] was calculated for each possible combination.

5.1.4 Estimation of pre- and post-fire erosion using RUSLE

To acquire estimated erosion values of the wildfire areas from the Leading and the Take-Up Sites in pre- and post-fire conditions, the Revised Universal Soil Loss Equation (RUSLE) was used, adapting input parameters. The RUSLE is an empirically based equation utilized by soil conservationists worldwide to estimate erosion induced by water [55–57]. It is derived from a large mass of field data multiplying different spatially distributed input layers influencing erosion and estimates therefore long-term average annual soil loss based on sheet and rill erosion in tons per hectare per year (t/ha^{-1}/yr^{-1}) [55]. The initial Universal Soil Loss Equation (USLE) was developed in the 1950s by Wischmeier and Smith, in cooperation with the U.S. Department of Agriculture (USDA), the Soil Conservation Service (SCS), the Agricultural Research Service (ARS), and the Purdue University to calculate sheet and rill erosion. In 1987, the ARS and the SCS revised the USLE with some cooperators to the RUSLE [55]. The input parameters of the RUSLE depict rainfall erosivity, soil erodibility, topography, cover management and support practices of the area. Generally, from literature many methods are available for the calculation of these mentioned input parameters including mostly open access data products, what is an advantage to assess erosion risk in data scarce areas.

When using a prediction model such as the RUSLE, awareness regarding its limitations by the user is important. As there are numerous calculation methods of the input factors from different proposals of various authors, a certain variability of the estimated erosion values result. Further, the RUSLE does neither estimate deposition e.g. at toes of concave slopes, sediment yields, or ephemeral gully erosion, nor does it provide information regarding characteristics of sediment as needed in certain water quality studies. Also, interactions between fundamental erosion processes are not represented explicitly by the RUSLE and specific data sets can show significant differences between the estimated erosion value and observed data. [58]

Nevertheless, these mentioned limitations are not an indication of the overall performance of the RUSLE as it adequately represents first-order effects of the factors which affect sheet and rill erosion [55,59]. Further, the model is used globally to estimate soil erosion resulting in a high number of values to compare in literature.

The RUSLE equation (Equation 1) is written as follows:

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

Equation 1

R

- Rainfall erosivity [$MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$]

K

- Soil erodibility [$t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$]

LS

- Slope length and steepness [*dimensionless factor*]

C

- Cover management factor [*dimensionless factor*]

P

- Support practices [*dimensionless factor*]

To calculate the spatial input variables for the wildfire areas, different sources derived from open access supply, field or laboratory work were used, depending on data availability (Table 1 and Table 2).

RUSLE input parameters for soil erosion estimation at the Leading Site		
Input factor	**Pre-fire**	**Post-fire**
R	Global rainfall erosivity data base [60]	Global rainfall erosivity data base [60]
K	Base: Soil texture and organic carbon content from a database of the "Regione Toscana" CalcM: Williams [61]	Base: Soil texture and organic carbon content from a database of the "Regione Toscana" CalcM: Williams [61]
LS	Base: DEM 30x30m CalcM: Desmet [62]	Base: DEM 30x30m CalcM: Desmet [62]
C	Base: Mean NDVI values, 1st pre-fire year CalcM: v.d.Knijff [63]	Base: Mean NDVI values, 1st post-fire year CalcM: v.d.Knijff [63] + Setting of thresholds for moderate low, moderate high and high severity areas after Terranova [64]
P	1	1

CalcM = Calculation Method

Table 1: Input data for the pre- and post-fire erosion estimation at the wildfire area in the Pisan Mountains

RUSLE input parameters for soil erosion estimation at the Take-Up Site		
Input factor	**Pre-fire**	**Post-fire**
R	Base: Bustamante [65] CalcM: IDW – Interpolation	Base: Bustamante [65] CalcM: IDW – Interpolation
K	Base: Soil texture: post-fire soil monitoring, Organic Carbon: ISRIC World Soil Information [66] CalcM: Williams [61]	Base: Soil texture: post-fire soil monitoring, Organic Carbon: ISRIC World Soil Information [66] CalcM: Williams [61]
LS	Base: DEM 30x30m [67] CalcM: Desmet [62]	Base: DEM 30x30m [67] CalcM: Desmet [62]
C	Base: Mean NDVI values, 1st pre-fire year CalcM: v.d.Knijff [63]	Base: Mean NDVI values, 1st post-fire year CalcM: v.d.Knijff [63]
P	1	1
CalcM = Calculation Method		

Table 2: Input data for the pre- and post-fire erosion estimation at the wildfire area in Quilanga

- Rainfall erosivity R

The rainfall erosivity factor (in $MJ{\cdot}mm{\cdot}ha^{-1}{\cdot}h^{-1}{\cdot}yr^{-1}$) is calculated on the basis of average monthly cumulated rainfall. For the Leading Site in the Pisan Mountains the open access data base for global rainfall erosivity was used as the input parameter [60]. The rainfall erosivity at the Take-Up Site in Quilanga was spatially elaborated based on interpolated data from the Catamayo watershed located near the basin El Saco [65].

- Soil erodibility K

To calculate the soil erodibility K (in $t{\cdot}ha{\cdot}h{\cdot}ha^{-1}{\cdot}MJ^{-1}{\cdot}mm^{-1}$), the soil texture in percentage (sand, silt, and clay), as well as the percentage of organic carbon content is needed. For the Leading Site a database from the Regione Toscana was used, containing the needed information. The calculation of K for the basin El Saco was carried out using the soil texture from the elaborated data base (chapter 5.1.2) based on the field monitoring undertaken one month after the fire event. The organic carbon content was acquired from ISRIC World Soil Information [66]. The calculation method was carried out as suggested by Williams [61] at both sites.

- Slope length and steepness factor LS

For the elaboration of the slope length and steepness factor LS (unitless) a Digital Elevation Model (DEM) with a resolution of 30x30 m was used at both sites. The calculation of the LS factor was carried out according to the method of Desmet [62].

- Cover management factor C

The cover management factor C (unitless) is the most influencing variable when calculating the amount of erosion using the RUSLE [57,68]. It relates soil loss from land with a specific vegetation cover to soil loss that would result from clean-tilled, continuous fallow land. For estimating changes between pre- and post-fire conditions in an area this factor is the most important one, as with the fire event the vegetation is influenced significantly leading to a higher C-value. Different approaches how to adapt C-factor to burnt areas are found in literature [69–71]. In this case, the method of van der Knijff et al. [63] was applied, using the mean of NDVI time series for the pre-fire, as well as the post-fire year. Basically, it infers the C-factor from vegetation indices available from satellite based remote sensing data, using the NDVI. In literature several mathematical relationships can be found between the NDVI and the C factor. In recent literature only the method of van der Knijff et al. [63] was implemented though (Equation 2, Figure 8)

Equation 2

$$C = \exp\left[-\alpha \cdot \frac{NDVI}{(\beta - NDVI)}\right]$$

whereby α and β are the parameters that determine the shape of the NDVI-C curve.

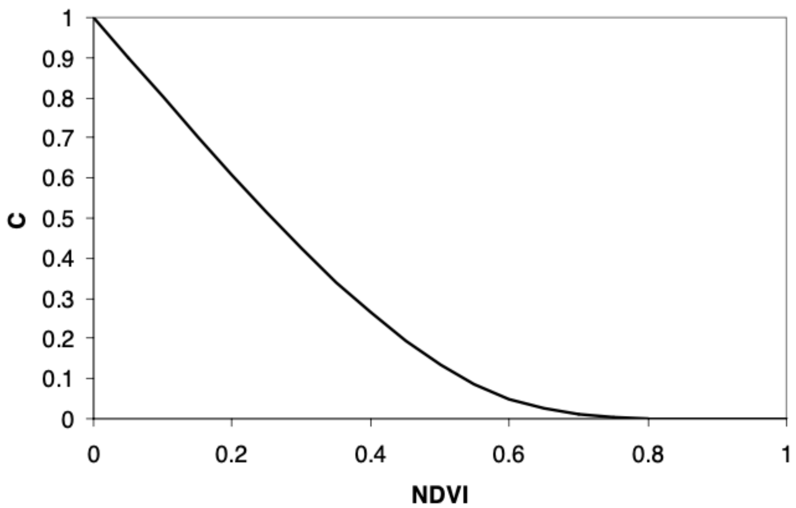

Figure 8: Relationship between NDVI and C using exponential scaling formula (v.d.Knijff et al., 2000)

As with this method an overprediction for the post-fire C factor can appear, in certain cases thresholds for moderate high severity and high severity can be useful [63].

At the Leading, as well as at the Take-Up Site, the mean NDVI was calculated from multitemporal Sentinel 2 data for the first pre-fire and the first post-fire year. After controlling the calculated C values from the NDVI data, it was decided to set thresholds for the post-fire raster at the Leading Site as suggested by Terranova [64]. Areas with moderate low and moderate high severity were set to 0.05 and high severity areas to 0.2. Figure 9 shows the workflow for the erosion estimation in pre- and post-fire conditions.

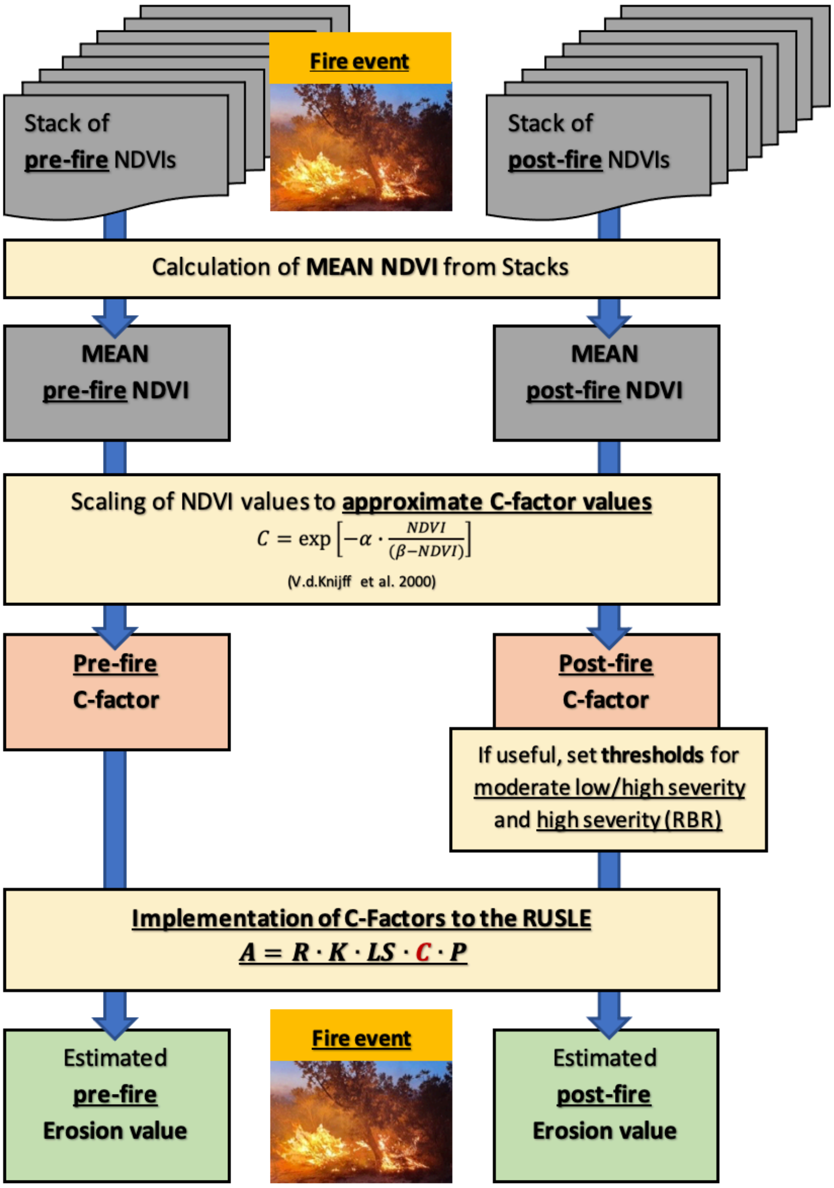

Figure 9: Workflow of pre- and post-fire erosion estimation using NDVI time series for C factor calculation

- Support practice factor P

The support practice factor P (unitless) was taken to be 1 for both areas in pre- and post-fire conditions.

- Validation of the estimated erosion values

To validate the estimated erosion values from the model at the Leading Site the database from Regione Toscana (2020) served as reference for pre-fire conditions. At the Take-Up Site the GloSEM data base [72] provided the necessary information. The comparison of the estimated erosion values in pre- and post-fire conditions at both Sites provide an indication of whether the transfer and/or implementation of SWBE measures is useful.

5.1.5 Estimation of the runoff coefficient in burned and unburned conditions[1]

To demonstrate the effect of (fire induced) missing or diminished vegetation on the runoff behavior of a basin, two basins with similar characteristics at the Leading Site were investigated. One was affected by a fire in September 2021, the other was in vegetated condition. To understand the change of the runoff´s erosive energy with changing vegetation the runoff coefficient C was calculated for various rain events between September 2021 and April 2022 at the two basins (9 rain events in unburned, and 10 rain events in burned conditions). In order to estimate the runoff coefficients, it is necessary to analyze the outflow and inflow at a basin. At the two basins in question, previously installed rain gauges, as well as water level loggers delivered the data for the investigation. From the rainfall data (mm), the intensity (mm/h) was obtained, and consequently, through the rational formula (Equation 3) it was possible to derive the flow rate of the inflows.

Equation 3

$$Q_{\frac{m^3}{s}} = \frac{1}{3.6} * A_b * I_p * C$$

[1] Credits to Andrea Signorile and Federico Preti

Knowing the volume of water transited through the water course (Qm^3/s) and the other parameters, including the inflow (I_p) it is possible to inversely calculate the runoff coefficient C.

5.1.6 Transferability analysis (TA) for SWBE interventions to fire prone areas:

5.1.6.1 Definition: Transferability analysis

A TA aims to analyze the transfer of e.g. a policy, strategy, or measure from one environment (Leading Site) to another (Take-Up Site) and determines the external validity of the concept independently from situation or time. It is a tool for planning entities, stakeholders, etc., in order to estimate key support factors or key barriers present at an unknown Take-Up Site. TAs are frequently used when transferring urban transport policies [9], renewable energy [73], or medical interventions [74,75] from a primary to a target context. For nature-based solutions, such as SWBE, a TA can support the spread and the uptake of sustainable solutions for erosion prevention in unknown areas by sharing knowledge and experience from the Leading Site(s). Further, it supports the planning and executing parties to avoid mistakes from the beginning of the planning process until a measure´s end of life. When performing a TA a positive outcome regarding the implementation of a measure at the Take-Up Site is not always guaranteed though [76], if the potential barriers for the transfer cannot be overcome by factors of success or other planned interventions. The best solution for one site, therefore, may not be the best for another. According to Dolowitz and Marsh [76] the transfer of a policy can be carried out in different stages, such as a complete transfer (copying), a transfer of the ideas behind (emulation), a fusion of various policies (combinations), as well as taking inspiration from a policy with a different jurisdiction (the outcome does not draw on the original idea). There are various sources one can use to locate information for a TA, which are found in literature, workshops, experience, interviews, or field visits for monitoring of the site [9].

5.1.6.2 Transferability analysis for SWBE measures in wildfire areas

Globally, there is a severe lack of established protocols supporting the uptake of SWBE in unknown areas, which also involves wildfire areas. Depending on the region, local authorities have little to no knowledge regarding the applicability of SWBE techniques and their capacity to mitigate (post-fire) erosion with locally available materials and techniques which are also easy to implement. The development of SWBE depends inter alia on policies, frameworks, or tools (such as a specific TA) aimed at encouraging "soft" solutions, including environmental concerns into standard technical practices. As there is a trend towards climate friendly building solutions worldwide, SWBE is gaining importance due to the utilization of living plants as construction material [4]. Fire prone areas can benefit from this spread of knowledge regarding the applicability of SWBE methods in pre-fire conditions by implementing preventive measures, as well as in post-fire conditions by applying e.g. revegetation or erosion mitigation measures. To estimate a measure´s transferability to an unknown area, the TA can be carried out during the planning process, as outlined in the schematic decision path after v.d.Thannen [4], adapted and extended for the implementation of SWBE measures in unknown areas (Figure 10). Basically, a TA gathers sufficient information for the planner to understand if the measures in question are useful for the Take-Up Site. By defining possible appearing constraints the planning process may be adapted accordingly, and key barriers can be overcome. In a "worst-case" scenario, the chosen SWBE techniques are not adequate for the area in question and alternatives should be found.

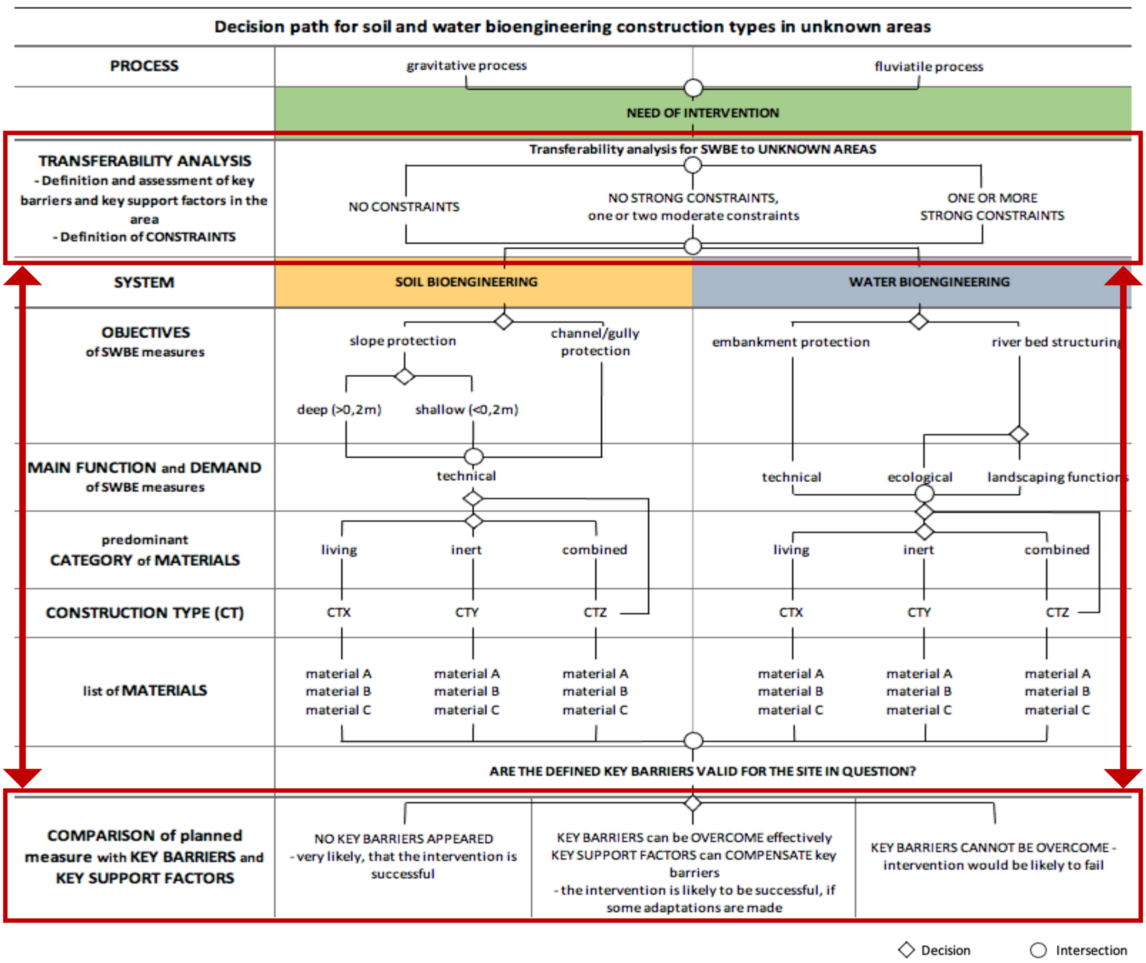

Figure 10: Schematic decision path [4] extended for the implementation of SWBE techniques in unknown areas

5.1.6.3 Working steps of a Transferability Analysis

The structure of the TA undertaken is based on a recommendation from Gyergyay and Boehler-Baedeker [9] and includes the following steps or determinations:

1. Objective of the procedure
2. Impacts of the measure
3. Identification of up-scaling/down-scaling needs
4. Identification of the main phases and its components
5. Identification of the level of importance of the components
6. Assessment of the components in the context of the Take-Up Site
7. Conclusions

- Step 1: Objectives of the procedure

To avoid misinterpretations during the transferability and implementation process clear objectives must be defined for the execution of the TA.

- Step 2: Impacts of the measure

In the second step the impacts of the measures should be clarified. Changes or advantages for *Safety, Environment, Ecology, Biodiversity of flora and fauna, Awareness enhancement and Humans* should be estimated when transferring SWBE measures to new, fire prone areas. A description of these issues gives an overview of probable impacts and advantages.

- Step 3: Identification of up-scaling/down-scaling need

The need to up- or down-scale the measures depends on the context conditions and therefore on the implementation size of the Take-Up Site compared to the Leading Site. With the identification of the need for scaling, the planning party can estimate the scope of planification and implementation.

- Step 4: Identification of the main components and the sub-components

In this step the main phases as well as those components contributing to possible success or failure of SWBE measures in post-fire areas were identified, which provides the basis for the following assessment. The list of a measure´s components and its assessment depend on the experience of the Leading Site [9], on the planned measure in the context of the Take-Up Site, as well as on information from existing literature. Basically, the main phases and its components elaborated within Article 1 were also found to be valid for the estimation of the transfer of SWBE measures to fire prone areas.

- Step 5: Identification of the level of importance of the components

This working step includes the importance-rating of the individual components from the viewpoint of the Take-Up Site by “high”, “medium”, or “low”. Experiences from the Leading Site or advice from experts may help to determine importance and this choice can be reinforced by additional comments [9].

- Step 6: Assessment of the components in the context of the Take-Up Site

Based on experience concerning difficulties or positive results encountered at the Leading Site, a subjective assessment scheme evaluates the components descriptively and numerically. The assessment scale ranges from +2 to -2.

- +2 strong support for transferability
- +1 moderate support for transferability
- 0 no support or no constraints
- -1 moderate constraint for transferability
- -2 strong constraint for transferability

Within the present TA step 5 and 6 are merged, to provide a better overview regarding probable relations between the individual components.

- Step 7: Conclusions of the TA

The last step of the TA serves to draw conclusions regarding the possible transferability of SWBE to the Take-Up Site. Key factors of success, key barriers, and mitigating actions to overcome barriers should be adequately discussed. Based upon this discussion, the probability of a successful transfer of SWBE to the Take-Up Site appears.

Three rules of thumb can be stated for the concluding assessment [9]:

1. With one or more strong constraints, it is likely that the measure will not be transferable without overcoming this condition in the Take-Up Site
2. If no strong, but one or two moderate constraints appear, a transfer of the measure is likely to be challenging. The constraining conditions must be addressed effectively.
3. In the case, that no constraints appear, the transfer of the measure is likely to perform successfully at the Take-Up Site.

5.2 Results

5.2.1 Post-fire vegetation development at the Take-Up Site

When planning SWBE measures in an unknown, fire prone area, the vegetation´s capability of self-recovery plays a major role. The following analyses show information extracted from multitemporal Sentinel 2 data regarding the development of the vegetation at the Take-Up Site.

- Short-term time series of vegetation recovery at fire severity classes

The short-term time series monitoring with the two selected vegetation indices LCCI and NDRESWIR (Figure 11 and Figure 12) clearly shows the effect of the wildfire on the biomass with the lowest median values right after the event in September 2019. The rapid recuperation time of the vegetation in the first post-fire rainy season can be observed. According to the median values the regrowth after one year appeared therefore to be at about the same level as before the fire event. As the basin of El Saco is mainly covered by open grassland, which was primarily affected by moderate low severity and moderate high severity, this vegetation type seemed to also recover due to its short life cycle.

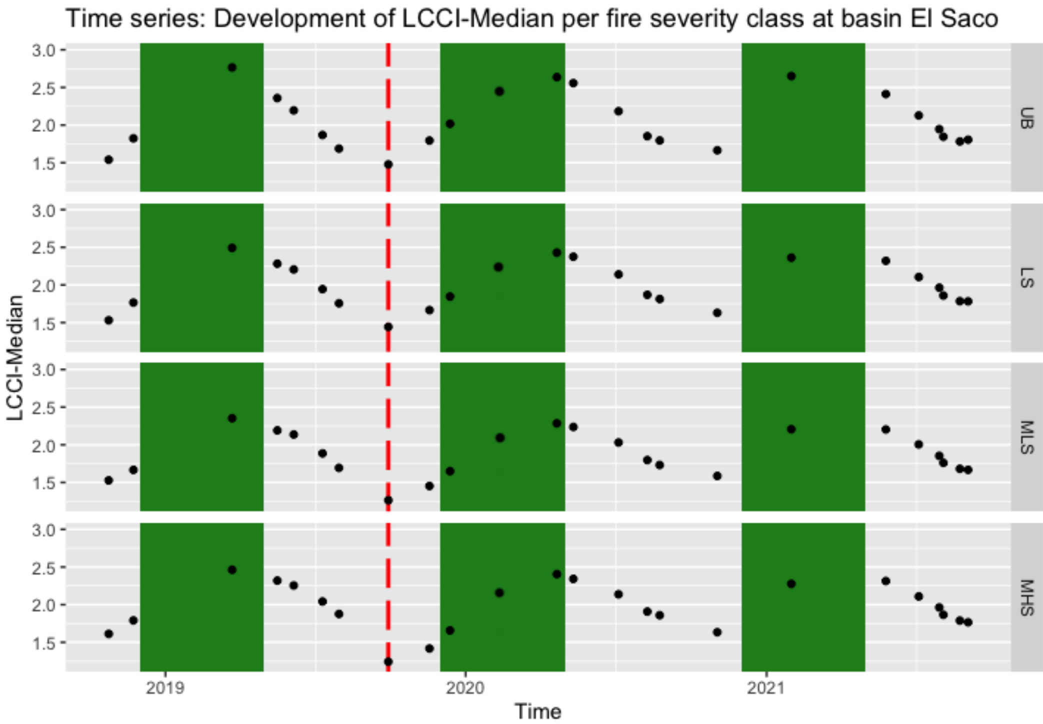

Figure 11: Pre- and post-fire time series monitoring of the vegetation at basin El Saco using the median LCCI values per fire severity class

Figure 12: Pre- and post-fire time series monitoring of the vegetation at basin El Saco using the median NDRESWIR values per fire severity class

- Delta-LCCI and Delta-NDRESWIR of the first two post-fire years

When calculating the delta of the vegetation indices for the first post-fire year it is shown, that with increasing fire severity an increase in vegetation recovery resulted (Figure 13 and Figure 14). Areas with the highest severity (moderate high severity) showed therefore the highest recuperation of vegetation. In the second post-fire year an equilibrated, slightly decreasing median can be observed with increasing fire severity. This result is consistent with the time series analysis and implies that within the first post-fire year the vegetation recovers strongly due to plant species with a short life cycle.

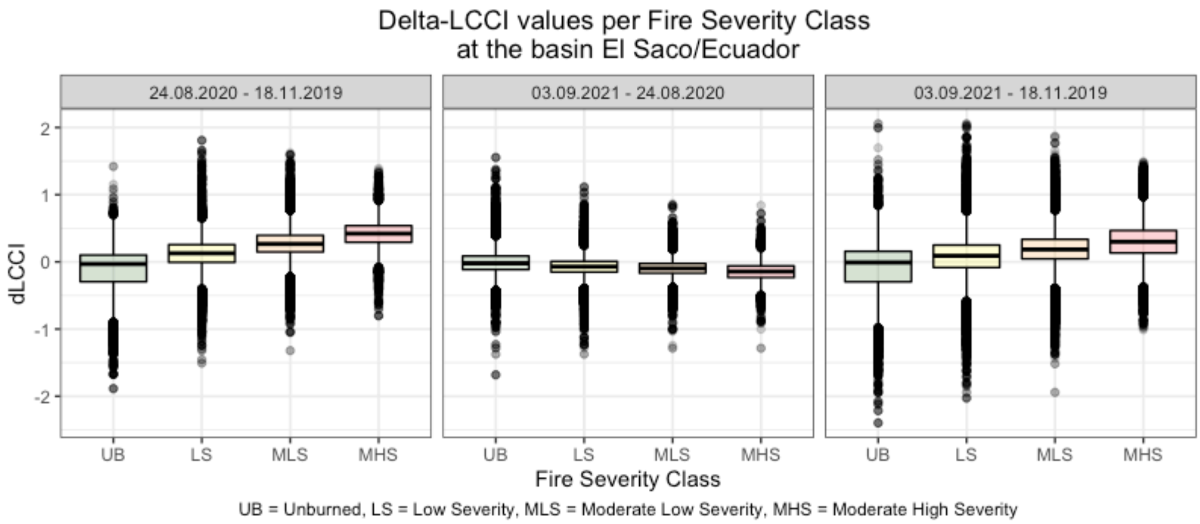

Figure 13: Boxplots of dLCCI values per Fire Severity Classes from the first two post-fire years at the basin El Saco

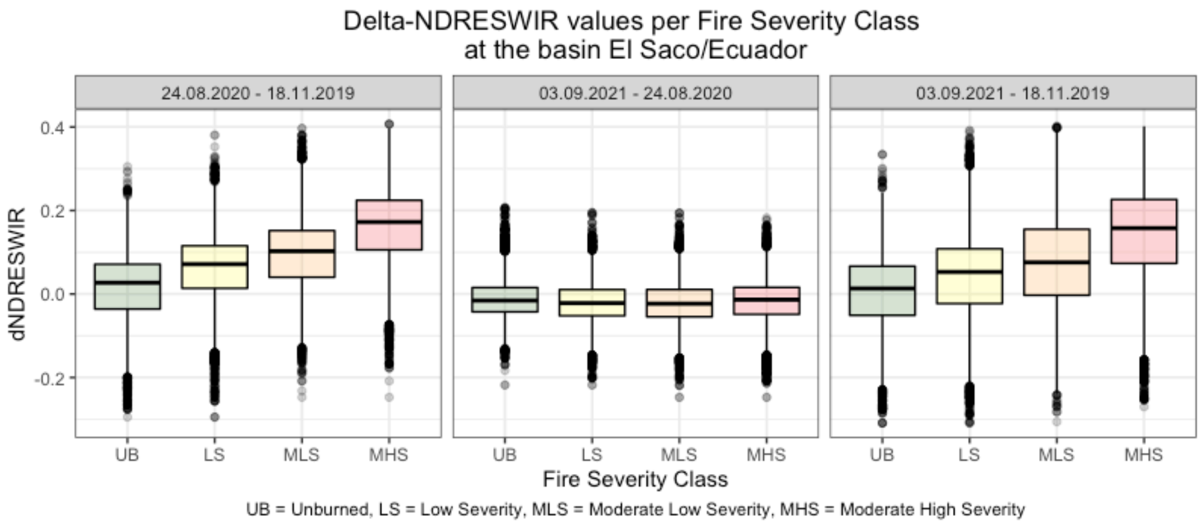

Figure 14: Boxplots of dNDRESWIR values per Fire Severity Classes from the first two post-fire years at the basin El Saco

5.2.2 Soil analyses at the Take-Up Site

Table 3 shows the descriptive statistics of the variables from the elaborated soil data base at the basin El Saco. The mean infiltration time from the field study with the cylinder was 254.19 mm/h. Laboratory results of the water drop penetration time showed a mean of 5.81 sec for the soil samples and therefore slightly to moderately repellent result (on the edge to wettable). The mean soil organic matter content was 8.40% and due to the proportion of sand, silt and clay all soil sample points were defined to be clay (Figure 15).

N = 18 Variables	**Min**	**Median**	**Mean**	**Max**	**St. Dev.**	**Skewness**	**Kurtosis**
Infiltration velocity [mm/h] (Cylinder)	24.04	155.57	254.19	1046.17	300.15	1.76	4.72
Water Drop Penetration Time [sec]	0.13	1.02	5.81	39.31	11.95	2.25	6.38
Soil Organic Matter [%]	3.72	8.18	8.40	14.98	2.79	0.62	3.11
Sand [%]	9.00	17.50	19.44	41.00	9.16	1.12	3.37
Silt [%]	6.00	11.00	11.83	22.00	4.01	1.20	4.12
Clay [%]	44.00	70.50	68.56	83.00	10.67	-0.78	2.91

Table 3: Descriptive statistics of the variables from the data base used for the statistical analysis at the basin El Saco

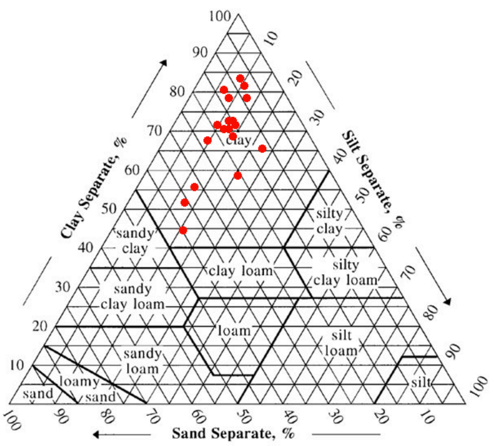

Figure 15: Soil types (red dots) of the sample points in the basin el Saco

- Correlation of soil properties

Statistically significant correlations were found between variables from the database: Soil organic matter, type of vegetation, WDPT, clay, and sand. These combinations, as well as the slope of the belonging linear correlation (positive, negative) led to the following conclusion for the basin El Saco:

- The soil organic matter content in the post fire soil samples was tendentially higher in grassland (1), followed by cultivated areas (2) and *Baccharis latifolia* (3). The lowest soil organic matter content was found in the sample points of the *Pinus sp.* (4) area.
- The lower the clay content, the higher the result of the WDPT.
- The higher the sand content, the higher the result of the WDPT.

Variable 1	**Variable 2**	**Pearson correlation coefficient**	**p-value**
Soil organic matter	Vegetation type	-0.641	0.006*
Clay	WDPT	-0.622	0.008*
Sand	WDPT	0.742	0.001*

*Statistically significant correlations

Table 4: Correlations between variables of the elaborated soil dataset at the basin El Saco in postfire conditions

5.2.3 Estimation of pre- and post-fire erosion using RUSLE

The following analysis aims to clarify the differences in erosion behavior between the Leading Site in the Pisan Mountains and the Take-Up Site in the canton Quilanga with pre- and post-fire conditions. Based on the results, the transfer of SWBE measures to the Take-Up Site can be better estimated.

- Leading Site Wildfire Pisan Mountains

At the Leading Site in the Pisan Mountains the mean annual erosion value at the affected area in pre-fire conditions and therefore with intact vegetation, was estimated to be 33.89 t/ha^{-1}/yr^{-1} which is confirmed by the mean annual erosion value of the database from the Regione Toscana (32.05 t/ha^{-1}/yr^{-1}). The difference to the median value (12.80 t/ha^{-1}/yr^{-1}) resulted to be significant though, which indicates a heterogenous erosion behavior within the area in question with high outliers and therefore areas with higher erosion due to variance of various factors, such as topography or slope. Further, an overestimation due to the C-factor calculation method derived from the mean NDVI could also be an explanation [63].

The estimated mean annual post-fire erosion was 96.68 t/ha^{-1}/yr^{-1}, and therefore about 2.85 times higher than in pre-fire conditions. This coincides with a study at a Mediterranean basin [57] which indicated an increase of mean soil loss in post-fire conditions of 260%. Also, the post-fire erosion estimation resulted in a high difference between the mean and the median value from the area in question.

Table 5 provides the most important statistical values from the erosion simulation.

Estimated soil erosion values at the Leading Site Calci

	Min	1st Quartile	Median	Mean	3rd Quartile	Max	Standard Deviation
Pre-fire	0.00	4.05	12.80	***33.89***	35.60	999.12	64.93
Post-fire	0.00	17.40	45.65	***96.68***	109.54	999.94	139.59
DB Regione Toscana	18.52		-	***32.05***		45.57	-

Values in t/ha^{-1}/yr^{-1}

Table 5: Comparison of the estimated mean annual erosion values from RUSLE with the database from Regione Toscana in the Pisan Mountains

Figure 16 shows the calculated mean NDVI derived from Sentinel 2 time series in pre- and post-fire conditions. Figure 17 and Figure 18 provide the distribution of the cover management factor C, as well as the estimated annual erosion values at the Pisan Mountains.

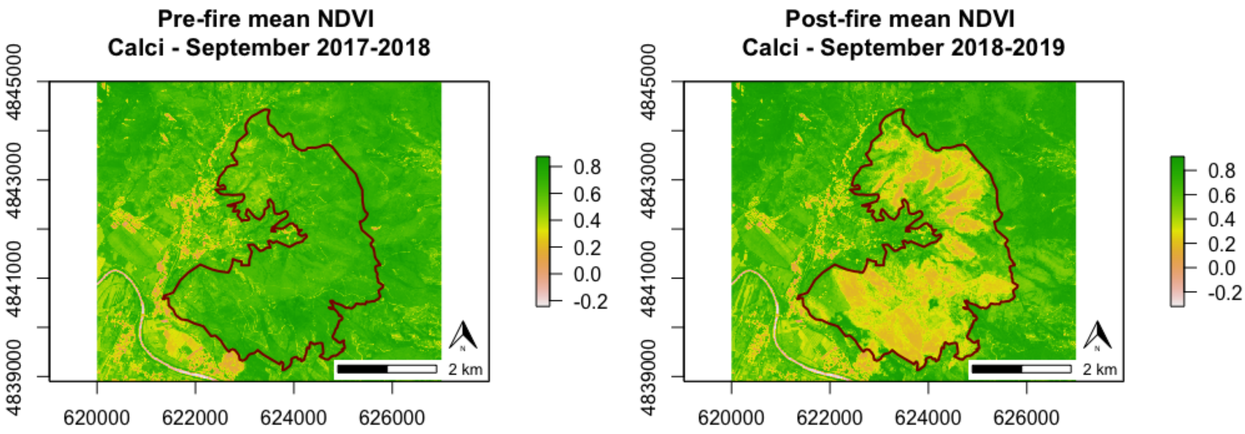

Figure 16: Mean NDVIs used for the C-factor calculation simulating pre- and post-fire conditions at the Pisan Mountains

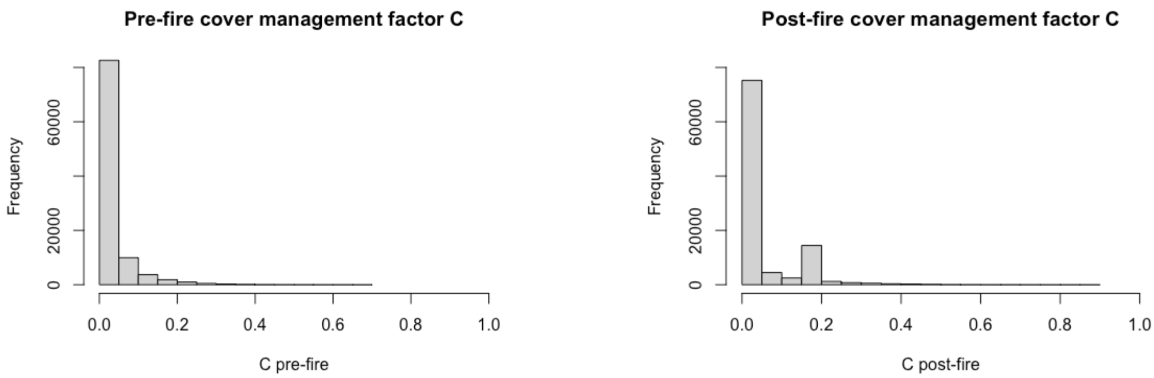

Figure 17: Distribution of the cover management factor C in pre- and post-fire conditions at the Pisan Mountains

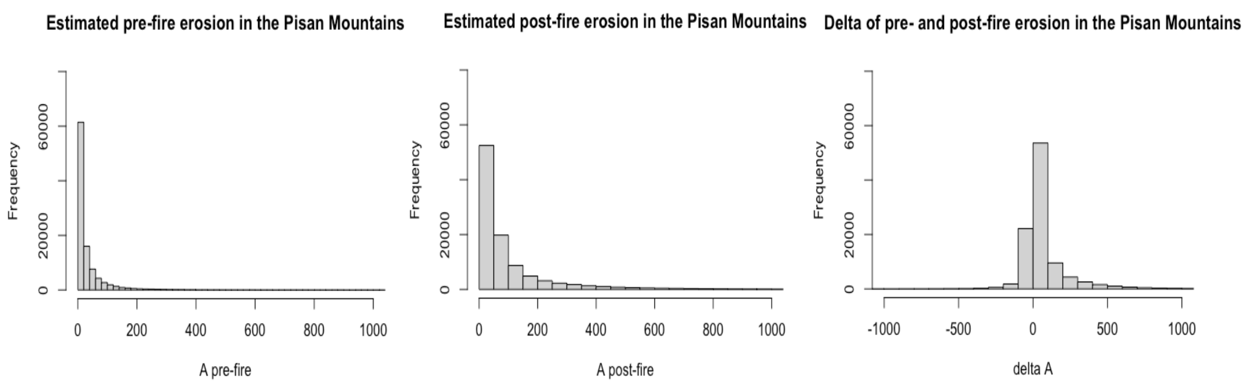

Figure 18: Distribution of the estimated annual erosion values (A) in pre- and post-fire conditions at the Pisan Mountains

- Take-Up Site Wildfire Quilanga

Table 6 shows the statistical description of the estimated annual erosion values at the Take-Up Site in Quilanga for pre- and post-fire conditions. Already in pre-fire conditions the basin El Saco is affected by intense soil erosion with a mean of 116.14 $t/ha^{-1}/yr^{-1}$. The GloSEM data base [72] shows an even higher mean erosion value of the basin El Saco under normal conditions. The effect of the fire event on soil erosion in the first post-fire year is moderate with a plus of 8.32 $t/ha^{-1}/yr^{-1}$ and therefore a mean increase of 7.16%. The difference between the mean and the median erosion values within the basin is relatively small, which indicates a homogenous erosion behavior of the area over the year.

Estimated soil erosion values at the Take-Up Site Basin El Saco

	Min	1st Quartile	Median	Mean	3rd Quartile	Max	Standard Deviation
Pre-fire	0.03	53.69	104.548	***116.14***	159.19	1643.89	85.82
Post-fire	0.05	59.35	112.72	***124.46***	173.45	1551.51	86.27
GloSEM [72]	18.00	-	-	***153.84***	-	>200	-

Values in $t/ha^{-1}/yr^{-1}$

Table 6: Comparison of the estimated mean annual erosion values from RUSLE with the GloSEM database at the basin El Saco

Figure 19 shows the pre-fire, as well as the post-fire mean NDVI elaborated from a Sentinel 2 time series and used for the C-factor calculation.

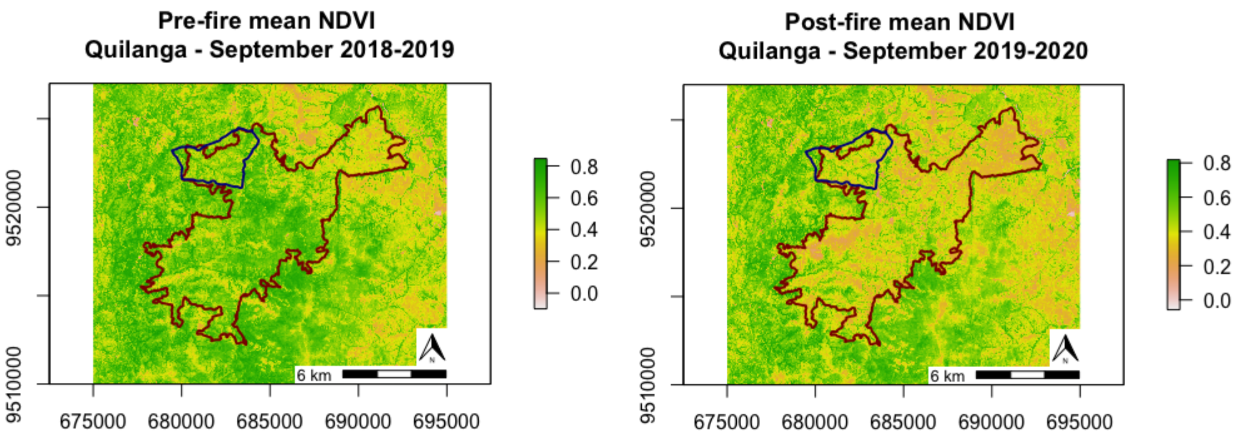

Figure 19: Mean NDVIs used for the C-factor calculation simulating pre- and post-fire conditions at the basin El Saco

Figure 20 and Figure 21 illustrate the distribution of the calculated, mNDVI derived C factor, as well as the annual erosion values in pre-fire and post-fire conditions, and their delta.

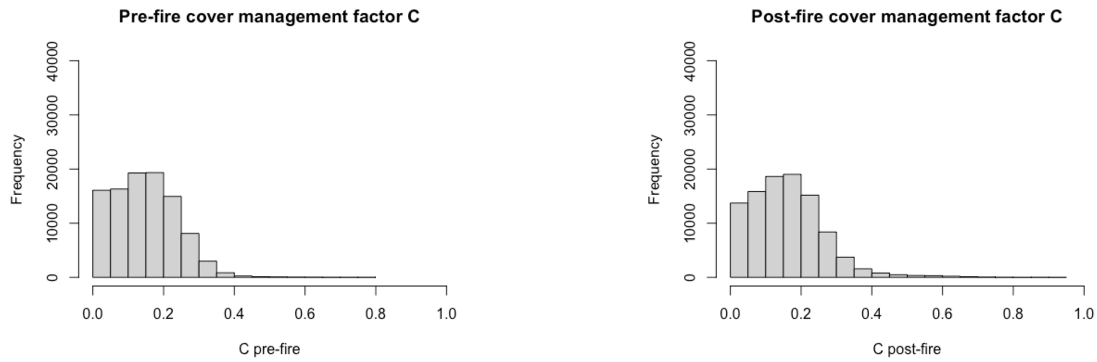

Figure 20: Distribution of the cover management factor C in pre- and post-fire conditions at the basin El Saco

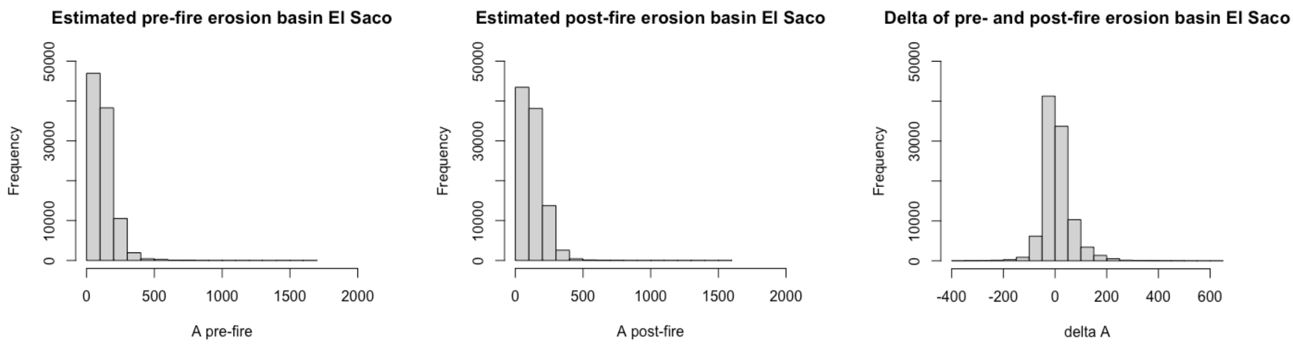

Figure 21: Distribution of the estimated annual erosion values (A) in pre- and post-fire conditions at the basin El Saco

5.2.4 Estimation of the runoff coefficient in burned and unburned conditions[2]

5.2.4.1 Burned basin

The analyses show an average runoff coefficient of 0.5 for the investigated rain events. This value expresses a moderate degree of surface runoff due to the fire event, which occurred during the previous summer. It is an indication of a sparse and unevenly distributed tree and shrub cover on the ground. Further, it represents the post-fire soil conditions which are influenced especially in the first weeks following the fire event.

[2] Credits to Andrea Signorile and Federico Preti

UNBURNED						Rational formula			$Q=a*h^b$
Date rain event	I max mm/h	A basin km²	C	tc h	h max m	Q m³/s	a	b	$Q=a*h^b$ m³/s
17/09/2021	27.6	0.107	0.3	0.229	0.18	0.28	5.0871	1.699	0.28
04/10/2021	27.7	0.107	0.2	0.229	0.15	0.20	5.0871	1.699	0.20
01/11/2021	8.5	0.107	0.2	0.229	0.06	0.04	5.0871	1.699	0.04
03/11/2021	11.2	0.107	0.1	0.229	0.06	0.04	5.0871	1.699	0.04
14/11/2021	9.3	0.107	0.1	0.229	0.06	0.04	5.0871	1.699	0.04
14/11/2021	7.7	0.107	0.2	0.229	0.06	0.04	5.0871	1.699	0.04
04/12/2021	6.7	0.107	0.2	0.229	0.06	0.04	5.0871	1.699	0.04
08/12/2021	5.9	0.107	0.2	0.229	0.06	0.04	5.0871	1.699	0.04
31/03/2022	12.0	0.107	0.3	0.229	0.09	0.09	5.0871	1.699	0.09

Table 7 shows the parameters used for the runoff coefficient calculation.

Table 7: Parameters for the runoff coefficient calculation at the burned basin

5.2.4.2 Unburned basin

The average runoff coefficient of the unburned basin resulted to be 0.2 which indicates a reduced surface runoff. A large amount of precipitation was intercepted by the present vegetation during the event and/or infiltrated into the soil. This hydrographic basin was also arranged with terraces that have increased its draining qualities and therefore decreased runoff (and the runoff coefficient). Table 8 shows the parameters used for the runoff coefficient calculation.

BURNED						Rational formula			$Q=a*h^b$
Date rain event	I max mm/h	A basin km²	C	tc h	h max m	Q m³/s	a	b	$Q=a*h^b$ m³/s
17/09/2021	27.6	0.172	0.8	0.32	0.42	1.01	9.2345	2.5492	1.01
04/10/2021	27.7	0.172	0.6	0.32	0.37	0.73	9.2345	2.5492	0.73
01/11/2021	8.5	0.172	0.5	0.32	0.22	0.19	9.2345	2.5492	0.19
03/11/2021	11.2	0.172	0.4	0.32	0.22	0.19	9.2345	2.5492	0.19
14/11/2021	9.3	0.172	0.6	0.32	0.25	0.27	9.2345	2.5492	0.27
14/11/2021	7.7	0.172	0.4	0.32	0.19	0.13	9.2345	2.5492	0.13
04/12/2021	15.2	0.172	0.4	0.32	0.26	0.30	9.2345	2.5492	0.30
08/12/2021	5.9	0.172	0.4	0.32	0.17	0.10	9.2345	2.5492	0.10
31/03/2022	15.2	0.172	0.4	0.32	0.26	0.30	9.2345	2.5492	0.30
23/04/2022	20.1	0.172	0.4	0.32	0.30	0.43	9.2345	2.5492	0.43

Table 8: Parameters for the runoff coefficient calculation at the unburned basin

5.2.5 Transferability analysis of SWBE interventions to fire-prone areas of the temperate Andes

5.2.5.1 Step 1: Objectives of the procedure

The objective of this TA is to estimate whether the implementation of SWBE methods and techniques to unknown fire-prone areas can be useful for fire-prevention, as well as post-fire soil erosion mitigation in the temperate Andes (Take-Up Site). At the area in question wildfires occur frequently with intervals of few years (<5), yet SWBE is not a common instrument to mitigate soil erosion, basically due to missing knowledge and awareness by locals, as well as lack of research.

5.2.5.2 Step 2: Impacts of the measure

When implementing SWBE measures at the Take-Up Site probable impacts range from increasing safety, environmental advantages, and ecosystem services. Further, ecological benefits may also result, and biodiversity can be strengthened. Awareness with regard to environmental protection can result in a change of farming practices and people´s consciousness in other aspects of life may also increase. Table 9 highlights possible impacts on fire-prone areas in the Temperate Andes when implementing SWBE measures.

Impacts on	Description
Safety	SWBE constructions can prevent or mitigate erosion on slopes and banks in fire prone areas [37,77]. Local settlements, agricultural land, and infrastructure are therefore protected.
Environment and ecosystem services	SWBE as part nature-based solutions provides various benefits for the environment at the Take-Up Site. By supporting a fast regrowth of the fire affected vegetation, the microclimate at the area is improved and nesting sites or hiding places for animals are provided.
Ecology	The materials used for SWBE constructions are to a great extent biodegradable materials (wooden logs, nets, seeds, or plants etc.) [7]. This fact conserves resources in comparison with other civil engineering techniques of slope stabilization [78]. Resource intensive materials (concrete) or construction waste are omitted [4].
Biodiversity of flora and fauna	The recuperation of animal species (mammals) after a fire event can be supported by the provision of key habitat elements (logs, rocks, large trees), enhancing the living conditions [79]. SWBE constructions can support the resettlement of flora and fauna when impacted by a fire event, as habitats are strengthened (pre-fire) or recreated (post-fire) with the implementation of proper measures.
Awareness Enhancement	The inclusion of local inhabitants in planning and/or construction processes of SWBE measures can lead to awareness enhancement regarding the protection of the environment, as well as a change of land preparation practices for farming. At the Take-Up Site clearing and deforestation using fire is still a present and cheap method to prepare land for agriculture what leads frequently to uncontrollable wildfires in dryer periods [80].

Humans	The implementation of SWBE measures in fire-prone areas can create employment in the planning and construction phase, as well as during the use phase when maintenance of the interventions is needed [8]. With increasing interest of inhabitants for sustainable methods, consciousness in further aspects of life may be risen (e.g. plastic reduction, waste management, renewable energy, …)

Table 9: Impacts of SWBE constructions on the environment at the Take-Up Site.

5.2.5.3 Step 3: Identification of up-scaling/down-scaling need

In the present case no upscaling or downscaling need arises, as the individual SWBE measures described in chapter 4.2 could be taken as it regarding their dimension (as single or combined measures), to be theoretically implemented in the Take-Up Site. Carrying out measures on a small scale (e.g. one specific wildfire area) makes it easier to establish contact with local engineers or technicians and thereby to acquire information regarding the conditions respectively to customize constructions individually to the local needs.

5.2.5.4 Step 4: Identification of the main phases and the components

The main phases within this process of the TA for SWBE measures to fire prone areas were defined as:

1. Planning Phase
2. Construction Phase
3. Use Phase
4. End of Life Phase

These phases consist of various components on which the mitigation of erosion problems appearing in fire prone areas depends (Figure 22). During the initial Planning Phase of SWBE measures for erosion mitigation in fire prone areas, *knowledge* concerning the applicable techniques, *local climate conditions*, *botany*, *hydraulics* or *pedology* are important. During the Construction Phase the availability of adequate *material*, *qualified labor*, *equipment and mechanical instruments*, as well as *economic resources* must be addressed. Further, the Use Phase includes the components *monitoring*, *efficiency*, *sustainability*, and *maintenance*. The End-of-Life Phase depends on the measure´s *replicability* by locals.

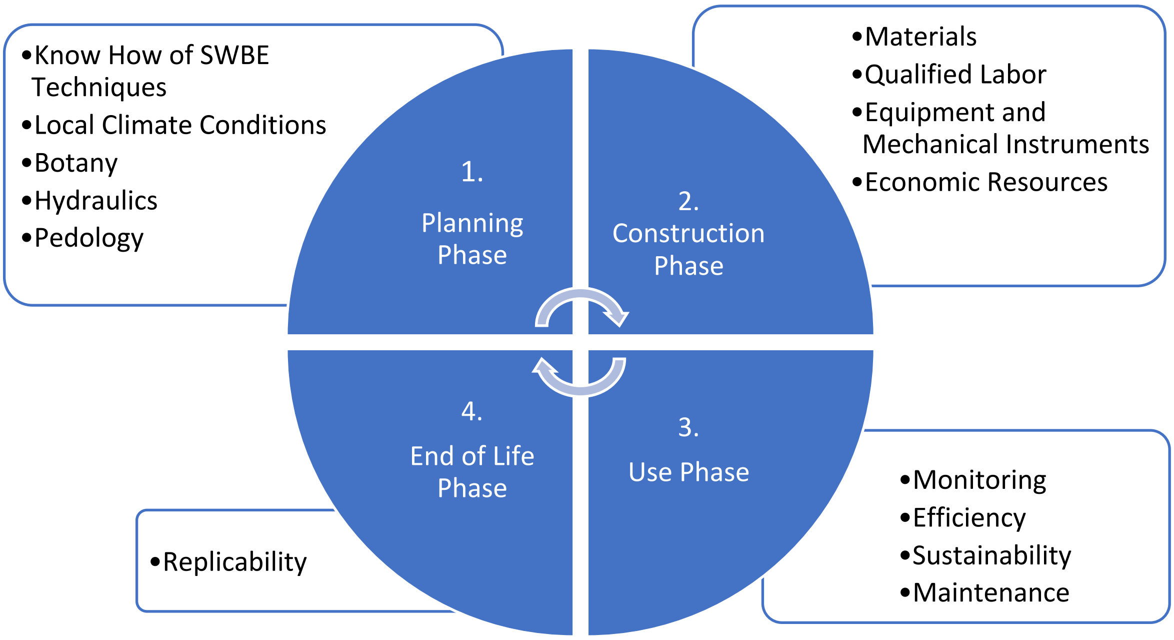

Figure 22: The main phases of a Soil-, Water Bioengineering measure and its components to be assessed within the Transferability Analysis [8]

5.2.5.5 Step 5 and 6: Assessment of the components

In Table 10 the importance of the components is assessed from the viewpoint of the Take-Up Site and their likely support or constraint for transferability is graded. Additional comments provide arguments regarding the grading procedure.

Components	**Level of importance in Quilanga (Take-Up Site)**	**Likely support or constraint for transferability to the Take-Up Site**	**Comments**
Know How of SWBE Techniques	High	0	No expert on SWBE measures is present at the community at the Take-Up Site. Nevertheless, various technicians are working at the municipality what provides the possibility to develop the Know-How needed for the area in question.
Local climate conditions	Medium	0	Due to the dryer period between June and November (time of wildfire events) the implementation of SWBE measures must consider possible water shortage or abundance, depending on the moment of construction. The growth of plants depends on the availability of water. The stability of a construction before de plant´s full development depends on extreme rain conditions.
Botany	High	+2	A key benefit for implementation of SWBE at the Take-Up Site. Fast growing plant species are present with the characteristics needed for SWBE measures, such as fast biomass growth or bending ability.
Hydraulics	Medium	-1	Extreme precipitation at the Take-Up site can influence a plant´s ability of taking roots at the preferred site. In case it is washed out, its stabilizing effect cannot be

			developed what makes it important to use combined measures with wooden structures and living plant parts.
Pedology	Low	-1	Due to frequent tectonic movements and earthquakes at the Take-Up Site movements within slopes must be considered when planning erosion mitigation measures. The combination of wooden structures and developed vegetation can therefore be useful to prevent a slope from sliding.
Materials	High	+2	High availability of plants and wooden logs (Eucalyptus and Pinus species) at the Take-Up Site
Qualified Labor	High	-1	Interest in the topic SWBE is present but formation courses and trainings are needed to undertake measures and maintenance.
Equipment and Mechanical Instruments	High	-1	As the Take-Up Site is in a rural area some difficulties with the procurement of equipment and mechanical instruments can appear. Towns nearby could provide the necessary equipment. Access to construction sites with heavy machinery could be problematic.
Economic resources	Medium	0	The building-costs of SWBE constructions are economically competitive. Awareness enhancing at the municipality regarding the benefits of the SWBE measures can help to enable funding.
Monitoring	High	+1	Monitoring ensures the development of SWBE measures at the area in question. It is important to document and share experiences with regions of similar characteristics.
Efficiency	High	+1	Good technical results can be expected if proper measures are selected and implemented. Experimental sites at the Take-Up Site can help to further understand the efficiency of SWBE measures.
Sustainability	Medium	+1	SWBE measures are sustainable if a few factors are respected. The public interest is a key aspect to a successful and sustainable implementation. Promotion of SWBE and workshops can help to maintain the efficiency over time. Maintenance can be realized autonomously from the residents (technically and economically)
Maintenance	Medium	+1	Especially the living parts of the constructions should be maintained in the first years. Maintenance depends mostly on the availability of financial resources and public interest.
Replicability	High	+1	Participation and inclusion of inhabitants from the beginning of the planning process simplifies a possible replication of the measures in future.

Table 10: Assessment of the components from the viewpoint of the Take-Up site

5.2.5.6 Step 7: Conclusions of the Transferability Analysis

Based on the assessment of the components two key supporting factors appear: *Botany*, as well as *Materials*. Biodiversity is very high at the Take-Up Site and fast-growing autochthonous plant species are present. Moderate support regarding the implementation of SWBE measures provide the components *Monitoring, Efficiency, Sustainability, Maintenance,* and *Replicability*.

Neither support, nor constraint provide the components *Know-How, Local Climate Conditions, and Economic Resources*. Four components were assessed as moderate constraints: *Hydraulics, Pedology*, *Qualified Labor* and *Equipment*.

When comparing the assessment values with the components´ level of importance at the Take-Up Site in Quilanga, *Qualified Labor*, as well as *Equipment and Mechanical Instruments* are probable barriers for the implementation of SWBE measures (high importance, but moderate constraint). *Know-How of SWBE Techniques* also showed high importance for the site in question but possessed neither support nor constraint regarding the transferability.

The lack of qualified labor can be compensated by holding theoretical seminars and/or practical workshops. Generally, the interest in the topic is high (if SWBE is known) and the will to learn could be reinforced easily. The barrier of missing equipment or mechanical instruments can be overcome by renting these from neighboring towns. If the access to the site is not possible with heavy machinery, workers can be sent by foot to excavate manually, however with increasing construction time. Also, the use of horses for material transportation is an option. Anyhow, the security of workers and animals involved must be ensured though. Further, the seasonal time of implementation during the year plays a major role regarding accessibility of the sites. Heavy rainfalls and thunderstorms in the mountainous region can occur during the rainy season within minutes, which makes it difficult to construct from December to May. Also, knowhow regarding SWBE measure can be supported by implementing the topic in additional university curricula and therefore increase the public interest.

Based on these points it can be stated that no strong constraints appeared for the Take-Up Site. However, the mentioned possible barriers must be addressed adequately when planning SWBE measures in the fire prone Take-Up Site.

5.3 Discussion

- Development of vegetation at the Take-Up Site in post-fire conditions

The analysis of the vegetation´s self-recovering potential within the first post-fire years is very important in order to estimate the necessity of SWBE measures. In fire-prone areas with a return period of less than five years multitemporal vegetation indices derived from satellite images can help substantially to understand the development of vegetation in post-fire conditions. The differentiation between vegetation type and its life cycle is a key aspect to know what type of SWBE measure should be implemented when and where. The analysis at the Take-Up Site showed, that within one post-fire year the plant species from the grassland recovered to a great extent, which coincides with the results of a study of a North American mixed prairie area [47]. Further, Asrar, et al. [81] stated, that a higher leaf production was achieved in burned prairie grassland areas. Other studies indicated, that more severely damaged vegetation recovers more rapidly than areas with lower severity [44,82]. The rapid recovery can be attributed to various reasons, such as the release of nutrients that comes with fire [83], as well as the short life cycle of species. SWBE greening measures in grassland areas would therefore be important if e.g. a change of the plant composition were targeted to introduce more drought resistant (autochthonous) plants into the ecosystem. However, with vegetation indices only no information on plant species is provided. Reference data from field surveys or orthophotos can help to acquire information concerning species distribution [84]. This can be helpful when planning SWBE measures with the aim to revegetate or mitigate erosion.

- Soil properties and fire severity

The relations found to exist between the soil properties at the Take-Up Site, indicated that the organic matter at the sample points correlated with the different types of vegetation. This concurs with the findings of Doerr et al. (2000) who stated that the vegetation cover influences the organic matter in the soil, which is another driving factor for hydrophobicity [85]. Further, some sources state, that a sandy texture and a high organic fraction in soil correlate positively with the hydrophobicity [86,87], which underlines the results of the correlations in the present study. The infiltration analysis at the basin El Saco showed a fast water uptake from the soil in post-fire conditions, which could lead to accumulated subsurface flow (in pre- and post-fire conditions), causing erosion. The implementation of SWBE measures, may not only help to mitigate erosion, but also channel water within slopes using drainage systems and therefore prevent landslides on the long-term.

- Estimation of pre- and post-fire erosion using RUSLE

When elaborating estimated erosion values using the RUSLE in pre- and post-fire conditions the adaption of the C-factor appeared to be enough to acquire reasonable results. The calculation of the C-factor derived from the mean NDVI can be challenging for wider areas at the Take-Up Site due to high precipitation during the year resulting in heavy cloud covering in the satellite images. Small catchments can be monitored easily, for bigger areas clouds must be masked to get exact mean NDVI values, which can be time consuming.

An important difference between the Leading Site and the Take-Up Site is the amount of erosion in pre- as well as post-fire conditions. While the Leading Site is characterized by a moderate mean annual erosion value, the Take-Up Site shows very high erosion values in pre-fire conditions. The explication for this can be the different types of vegetation, topography, as well as soil types. While the Leading Site was covered mainly by forest areas, the main vegetation at the Take-Up Site is grassland. Nevertheless, the result of this analysis in the Take-Up Site underlines the general presence of severe soil erosion on a national scale. To date erosion behavior at the Take-Up Site, as well as in the adjacent region has been poorly investigated. Apart from global data products, estimating erosion it is difficult to acquire valid and open access erosion estimation values. Soil erosion and landslides are a problem affecting people, infrastructure, and the economy. The presence of wildfires in the region exacerbates the situation. Erosion estimation studies in pre- and post-fire conditions may help to increase the awareness of the problem. For the transfer of SWBE measures it seems that it is more important to promote the topic within the country Ecuador, but not necessarily in combination with wildfires even if the benefits can also be obtained by fire prone areas. For the estimation regarding an implementation of SWBE measures the RUSLE can be a useful extension in the planning process.

- Estimation of the runoff coefficient in burned and unburned conditions

The aim of this analysis was to demonstrate the change of the runoff coefficient C coming with a fire event. At the location of the burned basin in the Pisan Mountains the vegetation and edaphic conditions were temporarily altered whereby approximately 50% of the precipitation flowed superficially towards the outlet, leading to an increase of hydraulic risk. The unburned basin with vegetation showed about 20% surface runoff coming from precipitation.

At the Take-Up Site neither precipitation nor discharge data was available in temporal high resolution for burned conditions. The vegetation between the Leading Site and the Take-Up Site is very different. However, as the main vegetation type at the basin El Saco is grassland, the influence of the fire on the runoff coefficient should not be that high compared to the Leading Site.

- Transferability analysis

The results of the present TA are similar to the analysis carried out in article 1 for SWBE measures to Central and South America at continent scale. Nevertheless, this analysis for a fire prone area changed the perspective from a whole continent to a specific site. Mickovski and Van Beek [88] stated that the local and regional environmental conditions must be considered carefully to create sustainable SWBE systems. For the Take-Up Site these considerations are e.g. increasing hydraulic forces with higher discharge during extreme precipitation events or pedologic aspects influencing the consolidation work. Sufficient preparation and education of workers can ensure the sustainable implementation of SWBE measures to (fire prone) areas. The contact established with the residents and social networking are key issue in these cases, as they result in a large amount of voluntary work through the inhabitants towards maintaining the constructions. If construction sites are invaded by animals, such as cows, the function of the measure cannot develop to its full extent, as desired vegetation growth is impeded. At the area in question the necessity to feed an animal, which is feeding families is often greater than an erosion problem. Ownership rights (legal or illegal) should therefore be clarified before planning the measure.

The analysis of the post-fire vegetation recovery shows, that the necessity to implement SWBE measures in grassland is minimal, as the area is recovered within one post-fire year. Areas with forests and higher fire severity can benefit from the implementation of an adequate measure to mitigate erosion. However, the soil erosion estimation in normal conditions indicated, that the usual soil loss in the area is high, which makes it increasingly important to develop effective measures which are easy to implement and replicable. Badly secured streets of bare soil are often constructed with the help of bulldozers, without water drainage system or revegetation measures. Due to intense rain events, the appearance of cracks and gullies affect the area, as well as the security of people. This problem becomes worse with the occurence of wildfires. It can be stated, that in areas with high erosion risks, the application of (post-fire) erosion mitigation treatments is (almost always) more beneficial than doing nothing. To date studies from the USA and the Mediterranean region concentrate on mulching (straw, wood and hydromulch) and barriers at hillslope scale, while larger scales and/or further SWBE measures are scarcely addressed [37]. To ensure that the most effective post-fire measures and probable combinations are implemented at a site, further field and model testing must be carried out, which is even more true for the Take-Up Site. The high availability of plants bearing supporting characteristics for SWBE measures combined with a high level of precipitation and a warm climate makes it almost impossible that the living part of a SWBE measure does not grow at all. In areas with low-income, investigation in techniques of low environmental impact and high socio-economic sustainability is important to find economically sustainable solutions for local communities and diminish dependence upon national or international institutions. SWBE measures can help to maximize the use of local labor force and local materials. It therefore constitutes an effective approach with socio-economic and environmental advantages. For further information and investigation on local plant species the open access plant species database, developed by Perez et al. [89] could be a tool towards documenting vegetation for SWBE in Central and South America.

5.4 Conclusions and outlook

With this thesis a method for the estimation of a successful transfer of post-fire erosion mitigation to unknown fire prone areas was presented. It was demonstrated that a successful implementation of SWBE measures at the Take-Up Site is possible if adequate actions are taken within the planning and construction process. However, further research must be carried out regarding specific construction techniques or botanical questions. Due to the conditions at the Take-Up Site and the general high erosion value it is recommended to implement more robust measures (erosion barriers). Simple greening actions with grass and herb species may be not enough to adequately halt erosion. Not only fire prone areas, but the whole region would benefit from investigation and implementation of SWBE measures for erosion mitigation. For future investigation it would be interesting to develop a remotely sensed index for the uptake possibility of SWBE measures in an area to facilitate the planning process. Further, not only erosion prevention or post-fire recuperation strategies, but also educational work can have a positive impact on prevention of fire events. As farmers use fire for field preparation [80] the development of e.g. an application such as the Fire Weather

Index (FWI) [90], adapted to the area and showing the daily wildfire risk, could help to prevent the spreading of fire events on days when wildfire risk is high.

6 References

1. Giglio, L.; Randerson, J.T.; van der Werf, G.R. Analysis of Daily, Monthly, and Annual Burned Area Using the Fourth-Generation Global Fire Emissions Database (GFED4). *J Geophys Res Biogeosci* **2013**, *118*, 317–328, doi:10.1002/jgrg.20042.

2. Mastrolonardo, G.; Castelli, G.; Certini, G.; Maxwald, M.; Trucchi, P.; Foderi, C.; Errico, A.; Marra, E.; Preti, F. *Post-Fire Erosion in Stony and Shallow Soils of a Forest Catchment in Italy*; 2022;

3. 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, doi:10.1016/j.ecoleng.2021.106539.

4. von der Thannen, M.; Hoerbinger, S.; Paratscha, R.; Smutny, R.; Lampalzer, T.; Strauss, A.; Rauch, H.P. Development of an Environmental Life Cycle Assessment Model for Soil Bioengineering Constructions. *European Journal of Environmental and Civil Engineering* **2020**, *24*, 141–155, doi:10.1080/19648189.2017.1369460.

5. Wasem, U.; Hester, C.; Wohlgemuth, T. Waldverjüngung Nach Feuer - Konkurrenzstarke Lärche. *Bündnerwald 63/1* **2010**, 28–33.

6. Schiechtl, H.M. FAO watershed management field manual. Vegetative and soil treatment measures. *FAO Conservation Guide (FAO)* 1985.

7. Florineth, F. *Pflanzen Statt Beton Sichern Und Gestalten Mit Pflanzen*; 2. Auflage.; Patzer Verlag, 2012; ISBN 978-3-87617-124-1.

8. Maxwald, M.; Crocetti, C.; Ferrari, R.; Petrone, A.; Rauch, H.P.; Preti, F. Soil and Water Bioengineering Applications in Central and South America: A Transferability Analysis. *Sustainability (Switzerland)* **2020**, *12*, 1–31, doi:10.3390/su122410505.

9. Gyergyay, B.; Boehler-Baedeker, S. Transferability Analysis: Innovative Sustainable Urban Solutions from Europe, Singapore, China and Latin America Available online: https://www.rupprecht-

consult.eu/fileadmin/migratedRupprechtAssets/Documents/SOLUTIONS_D1.3_Transferability_Analysis.pdf (accessed on 12 December 2022).

10. Preti, F.; Capobianco, V.; Sangalli, P. Soil and Water Bioengineering (SWB) Is and Has Always Been a Nature-Based Solution (NBS): A Reasoned Comparison of Terms and Definitions. *Ecol Eng* **2022**, *181*, doi:10.1016/j.ecoleng.2022.106687.

11. Stokes, A.; Sotir, R.; Chen, W.; Ghestem, M. Soil Bio- and Eco-Engineering in China: Past Experience and Future Priorities. *Ecol Eng* **2010**, *36*, 247–257, doi:10.1016/j.ecoleng.2009.07.008.

12. Lammeranner, W.; Rauch, H.P.; Laaha, G. Implementation and Monitoring of Soil Bioengineering Measures at a Landslide in the Middle Mountains of Nepal. *Plant Soil* **2005**, *278*, 159–170, doi:10.1007/s11104-005-7012-8.

13. Weissteiner, C.; Schenkenbach, N.; Lammeranner, W.; Kalny, G.; Rauch, H.P. Cutting Diameter on Early Growth Performance of Purple Willow (*Salix Purpurea* L.). *J Soil Water Conserv* **2019**, *74*, 380–388, doi:10.2489/jswc.74.4.380.

14. Acharya, M.S. Analytical Approach to Design Vegetative Crib Walls. *Geotechnical and Geological Engineering* **2018**, *36*, 483–496, doi:10.1007/s10706-017-0342-5.

15. Schlüter, U. Zur Geschichte Der Ingenieurbiologie. *Landschaft und Stadt* **1984**, *16*, 2–9.

16. Evette, A.; Labonne, S.; Rey, F.; Liebault, F.; Jancke, O.; Girel, J. History of Bioengineering Techniques for Erosion Control in Rivers in Western Europe. *Environ Manage* **2009**, *43*, 972–984, doi:10.1007/s00267-009-9275-y.

17. Sutili, F.J.; Durlo, M.A.; Bressan, D.A. POTENCIAL BIOTÉCNICO DO SARANDI-BRANCO (Phyllanthus Sellowianus Müll. Arg.) E VIME (Salix Viminalis L.) PARA REVEGETAÇÃO DE MARGENS DE CURSOS DE ÁGUA. *Ciência Florestal* **2005**, *14*, 13–20, doi:10.5902/198050981777.

18. Petrone, A.; Preti, F. Suitability of Soil Bioengineering Techniques in Central America: A Case Study in Nicaragua. *Hydrol Earth Syst Sci* **2008**, *12*, 1241–1248, doi:10.5194/hess-12-1241-2008.

19. Petrone, A.; Preti, F. Soil Bioengineering for Risk Mitigation and Environmental Restoration in a Humid Tropical Area. *Hydrol Earth Syst Sci* **2010**, *14*, 239–250, doi:10.5194/hess-14-239-2010.

20. Preti, F.; Petrone, A. Soil Bio-Engineering for Watershed Management and Disaster Mitigation in Ecuador: A Short-Term Species Suitability Test. *IForest* **2013**, *6*, 95–99, doi:10.3832/ifor0636-006.

21. Dhital, Y.P.; Kayastha, R.B.; Shi, J. Soil Bioengineering Application and Practices in Nepal. *Environ Manage* **2013**, *51*, 354–364, doi:10.1007/s00267-012-0003-7.

22. Reubens, B.; Nyssen, J.; Poesen, J.; Woldekidan, H.; Zenebe, A.; Girmay, G.; Deckers, J.; Taha, N.; Tewoldeberhan, S.; Gebrehiwot, K.; et al. Establishment and Management of Woody Vegetation to Control Gully Erosion. *Tigray Livelihood Papers* **2008**, *8*.

23. Mira, E.; Rousteau, A.; Tournebize, R.; Robert, M.; Evette, A. Evaluating the Suitability of Neotropical Trees and Shrubs for Soil and Water Bioengineering: Survival and Growth of Cuttings from Ten Caribbean Species. *Ecol Eng* **2022**, *185*, doi:10.1016/j.ecoleng.2022.106808.

24. Robert, M.; Evette, A.; Gayot, M.; Procopio, L.; Bernus, J.; Rousteau, A.; Imbert, D.; Labbouz, L. Typologie Des Ripisylves Des Rivières de Guadeloupe, Un Premier Pas Vers Le Développement de Techniques de Génie Végétal Avec Des Espèces Locales. *Sciences Eaux & Territoires* **2022**, 7–14, doi:10.20870/revue-set.2022.39.7060.

25. Hoerbinger, S.; Urbina, R.J.C.; Poizat, S.G.; Rauch, H.P. Design of a Soil Bioengineering Prototype in El Salvador. *Design of a Soil Bioengineering Prototype in El Salvador.* 2019.

26. Rivera Posada, J.H.; Sinisterra Reyes, J.A. *Uso Social de La Bioingeniería Para El Control de La Erosión Severa*; Corporación Autónoma Regional del Valle del Cauca, 2006; ISBN 9789589386484.

27. Borja, P.; Molina, A.; Govers, G.; Vanacker, V. Check Dams and Afforestation Reducing Sediment Mobilization in Active Gully Systems in the Andean Mountains. *Catena (Amst)* **2018**, *165*, 42–53, doi:10.1016/j.catena.2018.01.013.

28. Borja, P.; Vanacker, V.; Alvarado, D.; Govers, G. Restoration of Badlands through Applying Bio-Engineering Techniques in Active Gully Systems: Evidence from the Ecuadorian Andes. In Proceedings of the Geophysical Research Abstracts Vol. 14, EGU2012-6581; 2012; Vol. 14.

29. Kettenhuber Wolff, P.L.; dos Santos Sousa, R.; Dewes, J.J.; Rauch, H.P.; Sutili, F.J.; Hörbinger, S. Performance Assessment of a Soil and Water Bioengineering Work on the Basis of the Flora Development and Its Associated Ecosystem Processes. *Ecol Eng* **2023**, *186*, 1–12, doi:https://doi.org/10.1016/j.ecoleng.2022.106840.

30. Prates Bisso, F.; Hörbinger, S.; Rauch, H.P.; Prates Bisso Dambróz, A. Environmental Conditions and Potential Demands for Soil Bioen- Gineering Techniques in the Region of Cruz Alta - RS in Southern Brazil.; November 2016.

31. Maffra, C.R.B.; Sousa, R. dos S.; Sutili, F.J.; Pinheiro, R.J.B. Evaluation of Live Cuttings Effect on Slope Stability. *Floresta e Ambiente* **2019**, *26*, 1–9, doi:10.1590/2179-8087.073817.

32. Sutili, F. Bioengenharia de Solos No Âmbito Fluvial Do Sul Do Brasil : Espécies Aptas, Suas Propriedades Vegetativo-Mecânicas e Emprego Na Prática. Dissertation, University of Natural Resources and Life Sciences (Boku): Vienna, 2007.

33. Sousa, R. dos S. Production Planning and Control Methodology for Soil Bioengineering Works. PhD, Universidade Federal de Santa Maria: Santa Maria, 2019.

34. Kettenhuber, P. Plantas Herbáceas Nativas Do Brasil Para Controle Da Erosão Do Solo. PhD, Universidade Federal de Santa Maria: Santa Maria, 2021.

35. Fernández, C.; Vega, J.A.; Vieira, D.C.S. Assessing Soil Erosion after Fire and Rehabilitation Treatments in NW Spain: Performance of Rusle and Revised Morgan-Morgan-Finney Models. *Land Degrad Dev* **2010**, *21*, 58–67, doi:10.1002/ldr.965.

36. Wang, H.H.; Finney, M.A.; Song, Z.L.; Wang, Z.S.; Li, X.C. Ecological Techniques for Wildfire Mitigation: Two Distinct Fuelbreak Approaches and Their Fusion. *For Ecol Manage* 2021, *495*.

37. Girona-García, A.; Vieira, D.C.S.; Silva, J.; Fernández, C.; Robichaud, P.R.; Keizer, J.J. Effectiveness of Post-Fire Soil Erosion Mitigation Treatments: A Systematic Review and Meta-Analysis. *Earth Sci Rev* 2021, *217*.

38. DeBano, L.F. The Role of Fire and Soil Heating on Water Repellency in Wildland Environments: A Review. *J Hydrol (Amst)* **2000**, *231–232*, 195–206, doi:10.1016/S0022-1694(00)00194-3.

39. Robichaud, P.R.; Pierson, F.B.; Brown, R.E.; Wagenbrenner, J.W. Measuring Effectiveness of Three Postfire Hillslope Erosion Barrier Treatments, Western Montana, USA. *Hydrol Process* **2008**, *22*, 159–170, doi:10.1002/hyp.6558.

40. Zeh, H. *Soil Bioengineering Construction Type Manual*; European Federation for Soil Bioengineering: Zürich, 2007;

41. Merkel, A. Climate-Data Available online: https://en.climate-data.org/ (accessed on 31 July 2022).

42. Pausas, J.G.; Llovet, J.; Rodrigo, A.; Vallejo, R. Are Wildfires a Disaster in the Mediterranean Basin? - A Review. *Int J Wildland Fire* **2008**, *17*, 713, doi:10.1071/WF07151.

43. Gobierno autónomo descentralizado del canton Quilanga Plan de Ordenamiento Territorial Del Cantón Quilanga, Tema: Precipitación 2014.

44. White, J.D.; Ryan, K.C.; Key, C.C.; Running, S.W. *Remote Sensing of Forest Fire Severity and Vegetation Recovery*; 1996; Vol. 6;.

45. Pérez-Cabello, F.; Montorio, R.; Alves, D.B. Remote Sensing Techniques to Assess Post-Fire Vegetation Recovery. *Curr Opin Environ Sci Health* 2021, *21*.

46. Bowd, E.J.; McBurney, L.; Lindenmayer, D.B. Temporal Patterns of Vegetation Recovery after Wildfire in Two Obligate Seeder Ash Forests. *For Ecol Manage* **2021**, *496*, doi:10.1016/j.foreco.2021.119409.

47. Li, M.; Guo, X. Evaluating Post-Fire Vegetation Recovery in North American Mixed Prairie Using Remote Sensing Approaches. *Open J Ecol* **2018**, *08*, 646–680, doi:10.4236/oje.2018.812038.

48. van Leeuwen, W.J.D. Monitoring the Effects of Forest Restoration Treatments on Post-Fire Vegetation Recovery with MODIS Multitemporal Data. *Sensors* **2008**, *8*, 2017–2042.

49. Romo Leon, J.R.; van Leeuwen, W.J.D.; Casady, G.M. Using MODIS-NDVI for the Modeling of Post-Wildfire Vegetation Response as a Function of Environmental Conditions and Pre-Fire Restoration Treatments. *Remote Sens (Basel)* **2012**, *4*, 598–621, doi:10.3390/rs4030598.

50. European Space Agency; European Union Copernicus Open Access Hub Available online: https://scihub.copernicus.eu/twiki/do/view/SciHubWebPortal/TermsConditions (accessed on 30 September 2021).

51. Doerr, S.H. On Standardizing the "water Drop Penetration Time" and the "Molarity of an Ethanol Droplet" Techniques to Classify Soil Hydrophobicity: A Case Study Using Medium Textured Soils. *Earth Surf Process Landf* **1998**, *23*, 663–668, doi:10.1002/(SICI)1096-9837(199807)23:7<663::AID-ESP909>3.0.CO;2-6.

52. Hoogsteen, M.J.J.; Lantinga, E.A.; Bakker, E.J.; Tittonell, P.A. An Evaluation of the Loss-on-Ignition Method for Determining the Soil Organic Matter Content of Calcareous Soils. *Commun Soil Sci Plant Anal* **2018**, *49*, 1541–1552, doi:10.1080/00103624.2018.1474475.

53. Papuga, K.; Kaszubkiewicz, J.; Wilczewski, W.; Stas, M.; Belowski, J.; Kawałko, D. Soil Grain Size Analysis by the Dynamometer Method - A Comparison to the Pipette and Hydrometer Method. *Soil Science Annual* **2018**, *69*, 17–27, doi:10.2478/ssa-2018-0003.

54. Reimann, C.; Filzmoser, P.; Garrett, R.; Dutter, R. *Statistical Data Analysis Explained: Applied Environmental Statistics with R*; John Wiley & Sons, 2008;

55. Renard, K.G.; Foster, G.R.; Weesies, G.A.; Porterr, J.P. RUSLE: Revised Universal Soil Loss Equation. *J Soil Water Conserv* **1991**, *46*, 30–33.

56. Lanorte, A.; Cillis, G.; Calamita, G.; Nolè, G.; Pilogallo, A.; Tucci, B.; de Santis, F. Integrated Approach of RUSLE, GIS and ESA Sentinel-2 Satellite Data for Post-Fire Soil Erosion Assessment in Basilicata Region (Southern Italy). *Geomatics, Natural Hazards and Risk* **2019**, *10*, 1563–1595, doi:10.1080/19475705.2019.1578271.

57. Rulli, M.C.; Offeddu, L.; Santini, M. Modeling Post-Fire Water Erosion Mitigation Strategies. *Hydrol Earth Syst Sci* **2013**, *17*, 2323–2337, doi:10.5194/hess-17-2323-2013.

58. Schuerz, C.; Herrnegger, M. Input Data Generation for the RUSLE. In *Soil Erosion Risk Modelling with R*; Vienna, 2019.

59. Renard, K.G.; Foster, G.R.; Weesies, G.A.; McCool, D.K.; Yoder, D.C. *Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE)*; United States Department of Agriculture (USDA), Ed.; Washington, DC, 1997; Vol. 703; ISBN 0-16-048938-5.

60. Panagos, P.; Borrelli, P.; Meusburger, K.; Yu, B.; Klik, A.; Lim, K.J.; Yang, J.E.; Ni, J.; Miao, C.; Chattopadhyay, N.; et al. Global Rainfall Erosivity Assessment Based on High-Temporal Resolution Rainfall Records. *Sci Rep* **2017**, *7*, doi:10.1038/s41598-017-04282-8.

61. Williams, J.R. The EPIC Model - Soil Erosion. . In *Computer Models of Watershed Hydrology*; Singh, V.P., Ed.; Water Resources Publications: Highlands Ranch, 1995; pp. 909–1000.

62. Desmet, P.J.J.; Govers, G. *A GIS Procedure for Automatically Calculating the USLE LS Factor on Topographically Complex Landscape Units Carbon Cycling in Soils Subject to Sediment Deposition View Project Accurately Simulating Transient Landscape Evolution View Project*; 1996;

63. van der Knijff, J.M.; Jones, R.J.A.; Montanarella, L. *European Soil Bureau Soil Erosion Risk Assessment Italy Soil Erosion Risk Assessment in Europe*;

64. Terranova, O.; Antronico, L.; Coscarelli, R.; Iaquinta, P. Soil Erosion Risk Scenarios in the Mediterranean Environment Using RUSLE and GIS: An Application Model for Calabria

(Southern Italy). *Geomorphology* **2009**, *112*, 228–245, doi:10.1016/j.geomorph.2009.06.009.

65. Alberto, J.; Bustamante, C.; Eitzinger, A. *Assessment of Water Erosion Risk in the Subwatershed Alamor, River Catamayo-Chira, Ecuador*;

66. Batjes, N.H.; Ribeiro, E.; van Oostrum, A. Standardised Soil Profile Data to Support Global Mapping and Modelling (WoSIS Snapshot 2019). *Earth Syst Sci Data* **2020**, *12*, 299–320, doi:10.5194/essd-12-299-2020.

67. Souris, M. Marc Souris Directeur de Recherche, IRD Available online: http://www.savgis.org/ecuador.htm (accessed on 12 December 2022).

68. Ochoa-Cueva, P.; Fries, A.; Montesinos, P.; Rodríguez-Díaz, J.A.; Boll, J. Spatial Estimation of Soil Erosion Risk by Land-Cover Change in the Andes OF Southern Ecuador. *Land Degrad Dev* **2013**, *26*, 565–573, doi:10.1002/ldr.2219.

69. Borrelli, P.; Robinson, D.A.; Fleischer, L.R.; Lugato, E.; Ballabio, C.; Alewell, C.; Meusburger, K.; Modugno, S.; Schütt, B.; Ferro, V.; et al. An Assessment of the Global Impact of 21st Century Land Use Change on Soil Erosion. *Nat Commun* **2017**, *8*, doi:10.1038/s41467-017-02142-7.

70. Monfreda, C.; Ramankutty, N.; Foley, J.A. Farming the Planet: 2. Geographic Distribution of Crop Areas, Yields, Physiological Types, and Net Primary Production in the Year 2000. *Global Biogeochem Cycles* **2008**, *22*, doi:10.1029/2007GB002947.

71. Bontemps, S.; Boettcher, M.; Brockmann, C.; Kirches, G.; Lamarche, C.; Radoux, J.; Santoro, M.; van Bogaert, E.; Wegmüller, U.; Herold, M.; et al. Multi-Year Global Land Cover Mapping at 300 M and Characterization for Climate Modelling: Achievements of the Land Cover Component of the ESA Climate Change Initiative. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives; International Society for Photogrammetry and Remote Sensing, April 28 2015; Vol. 40, pp. 323–328.

72. Borrelli, P.; Ballabio, C.; Yang, J.E.; Robinson, D.A.; Panagos, P. GloSEM: High-Resolution Global Estimates of Present and Future Soil Displacement in Croplands by Water Erosion. *Sci Data* **2022**, *9*, 406, doi:10.1038/s41597-022-01489-x.

73. Bößner, S.; Suljada, T.; Johnson, F.X.; Bruno, A.; Morales, J.R.; Hu, M.; Bhamidipati, P.L.; Haselip, J. Policy Transfer Processes and Renewable Energy Penetration: A Comparative Analysis of Peru, Thailand, and Uganda. *Sustainable Earth* **2020**, *3*, 1–18, doi:10.1186/s42055-019-0019-4.

74. Schloemer, T.; Schröder-Bäck, P. Criteria for Evaluating Transferability of Health Interventions: A Systematic Review and Thematic Synthesis. *Implementation Science* **2018**, *13*, 1–17, doi:10.1186/s13012-018-0751-8.

75. Wang, S.; Moss, J.R.; Hiller, J.E. Applicability and Transferability of Interventions in Evidence-Based Public Health. *Health Promot Int* **2006**, *21*, 76–83, doi:10.1093/heapro/dai025.

76. Dolowitz, D.P.; Marsh, D. Learning from Abroad: The Role of Policy Transfer in Contemporary Policy-Making. *Governance* **2000**, *13*, 5–23, doi:10.1111/0952-1895.00121.

77. Zaimes, G.N.; Kasapidis, I.; Gkiatas, G.; Pagonis, G.; Savvopoulou, A.; Iakovoglou, V. Targeted Placement of Soil Erosion Prevention Works after Wildfires. In Proceedings of the IOP Conference Series: Earth and Environmental Science; IOP Publishing Ltd, December 9 2020; Vol. 612.

78. Paratscha, R.; von der Thannen, M.; Smutny, R.; Lampalzer, T.; Strauss, A.; Rauch, H.P. Screening LCA of Torrent Control Structures in Austria. *International Journal of Life Cycle Assessment* **2019**, *24*, 129–141, doi:10.1007/s11367-018-1501-5.

79. Hale, S.; Mendoza, L.; Yeatman, T.; Cooke, R.; Doherty, T.; Nimmo, D.; White, J.G. Evidence That Post-Fire Recovery of Small Mammals Occurs Primarily via in Situ Survival. *Divers Distrib* **2022**, *28*, 404–416, doi:10.1111/ddi.13283.

80. Armenteras, D.; González, T.M.; Ríos, O.V.; Elizalde, M.C.M.; Oliveras, I. Fire in the Ecosystems of Northern South America: Advances in the Ecology of Tropical Fires in

Colombia, Ecuador and Peru. *Caldasia* **2020**, *42*, 1–16, doi:10.15446/caldasia.v42n1.77353.

81. Asrar, G.; Myneni, R.B.; Li, Y.; Kanemasu, E.T. Measuring and Modeling Spectral Characteristics of a Tallgrass Prairie. *Remote Sens Environ* **1989**, *27*, 143–155, doi:10.1016/0034-4257(89)90014-X.

82. Gordon, C.E.; Price, O.F.; Tasker, E.M. Mapping and Exploring Variation in Post-Fire Vegetation Recovery Following Mixed Severity Wildfire Using Airborne LiDAR: *Ecological Applications* **2017**, *27*, 1618–1632, doi:10.1002/eap.1555.

83. Caon, L.; Vallejo, V.R.; Coen, R.J.; Geissen, V. Effects of Wildfire on Soil Nutrients in Mediterranean Ecosystems. *Earth Sci Rev* 2014, *139*, 47–58.

84. Immitzer, M.; Neuwirth, M.; Böck, S.; Brenner, H.; Vuolo, F.; Atzberger, C. Optimal Input Features for Tree Species Classification in Central Europe Based on Multi-Temporal Sentinel-2 Data. *Remote Sens (Basel)* **2019**, *11*, doi:10.3390/rs11222599.

85. Doerr, S.H.; Shakesby, R.A.; Walsh, R.P.D. Soil Water Repellency: Its Causes, Characteristics and Hydro-Geomorphological Significance. *Earth Sci Rev* **2000**, *51*, 33–65, doi:10.1016/S0012-8252(00)00011-8.

86. Weninger, T.; Filipović, V.; Mešić, M.; Clothier, B.; Filipović, L. Estimating the Extent of Fire Induced Soil Water Repellency in Mediterranean Environment. *Geoderma* **2019**, *338*, 187–196, doi:10.1016/j.geoderma.2018.12.008.

87. Bughici, T.; Wallach, R. Formation of Soil-Water Repellency in Olive Orchards and Its Influence on Infiltration Pattern. *Geoderma* **2016**, *262*, 1–11, doi:10.1016/j.geoderma.2015.08.002.

88. Mickovski, S.B. Re-Thinking Soil Bioengineering to Address Climate Change Challenges. *Sustainability (Switzerland)* **2021**, *13*, doi:10.3390/su13063338.

89. Perez, J.; Condes Salazar, R.; Stokes, A. An Open Access Database of Plant Species Useful for Controlling Soil Erosion and Substrate Mass Movement. *Ecol Eng* **2017**, *99*, 530–534, doi:10.1016/j.ecoleng.2016.11.035.

90. Copernicus Climate Change Service Fire Weather Index Available online: https://climate.copernicus.eu/fire-weather-index (accessed on 21 June 2022).

7 Appendix

Article 1: Maxwald, M.; Crocetti, C.; Ferrari, R.; Petrone, A.; Rauch, H.P.; Preti, F. Soil and Water Bioengineering Applications in Central and South America: A Transferability Analysis. *Sustainability* **2020**, 12, 10505.

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Article 2: Maxwald, M.; Immitzer, M.; Rauch, H.P.; Preti, F. Analyzing fire severity and post-fire vegetation recovery in the temperate Andes using earth observation data. *Fire* **2022**, 5, 211.

https://doi.org/10.3390/fire5060211

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Article 3: Mastrolonardo, G.; Castelli, G.; Certini, G.; Maxwald, M.; Trucchi, P.; Foderi, C.; Errico, A.; Marra, E.; Preti, F. Post-fire erosion and sediment yield in a Mediterranean forest catchment in Italy. *Land Degradation and Development* **2022** (Preprint)

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7.1 Article 1

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Article

Soil and Water Bioengineering Applications in Central and South America: A Transferability Analysis

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Abstract: The present work describes a transferability analysis for soil and water bioengineering techniques as an instrument for sustainable erosion control in Central and South America based on an empirical data base from the last decades. In total, 31 case studies in Mexico, Nicaragua, Guatemala, Colombia, Ecuador and Brazil generated a database from an area where soil and water bioengineering techniques are not commonly used. The Transferability Analysis is structured in seven steps: (1) Objectives of the procedure, (2) Impacts of the measure, (3) Identification of up-scaling/down-scaling needs (4) Identification of the main phases and its components, (5) Identification of the level of importance of the components, (6) Assessment of the components in the context of the Take-Up Site and (7) Conclusions. For the assessment of soil and water bioengineering via the Transferability Analysis, in step 4 the following main phases have been identified from the data base: (a) Planning Phase, (b) Construction Phase, (c) Use Phase, as well as (d) End of Life Phase of a construction. Within these categories, 14 components have been defined: (a) know-how of soil and water bioengineering techniques, local climate conditions, botany, hydraulics, pedology; (b) materials, qualified labor, equipment and mechanical instruments, economic resources; (c) monitoring, efficiency, sustainability, maintenance; (d) replicability. The following assessment of the components allowed to determine key barriers, as well as key support factors for the transfer of soil and water bioengineering. As a result, barriers appeared to be the components qualified labor, equipment/mechanical instruments, hydraulics, know-how in soil and water bioengineering and pedology. Neither barriers, nor supporting key factors resulted to be the components local climate conditions, economic resources and efficiency. Supporting key factors for the transfer were materials, monitoring, sustainability, maintenance and replicability. The most important key factor of success was assessed to be botany, as various plant species with important characteristics for soil and water bioengineering are available in Central and South America, able to compensate the constraints through barriers in certain cases.

Keywords: transferability analysis; soil and water bioengineering; Central America; South America; sustainable erosion control

1. Introduction

Global efforts towards mitigating disaster risks and natural hazards for the protection of resident populations, forests or agricultural land represents a major concern being addressed by communities, governments and NGO's. While poverty is one aspect resulting in a higher exposure to natural hazards, according to the Global Assessment Report on Disaster Risk Reduction 2019, overall vulnerability depends further upon location, age, gender, income group, possible disabilities and access to social protection systems [1]. Investigation and application of efficient instruments for risk mitigation and erosion control are and will be an important issue for continued work. Within this process, certain parameters, such as minimal environmental impact, economical sustainability, as well as maximum use of local labor and materials, must be considered [2] as what leads to a growing public interest in nature-based solutions (NBS). The European Commission defines NBS as solutions, which are inspired and supported by nature, and highlights the cost-effectiveness, the environmental, social and economic benefits. Further, NBS bring more nature and natural features, as well as processes into cities, land or seascapes, through locally adapted, resource efficient and systemic interventions. They support resilience, benefit biodiversity and enhance the delivery of a range of ecosystem services [3].

1.1. Soil and Water Bioengineering

Soil and water bioengineering (SWBE) as an NBS for civil and hydraulic engineering corresponds to these mentioned demands, by employment of biological components, such as plants or wooden logs, for the protection of slopes or riverbanks [4–7]. The selection of the living materials, such as seeds, plants or parts of plants depends strongly on their properties, such as rooting capacity, bending ability or vegetative reproduction [8]. Further, plants need development time to reach the preferred ability to stabilize slopes or riverbanks [9]. Therefore, living materials are frequently used in combination with inert materials, such as stones, wooden logs or other auxiliary materials to achieve immediate effect [8]. Generally, the discipline SWBE can be separated in two sections:

- Soil bioengineering (SBE), which handles shallow landslide and gully stabilization, protection against superficial erosion and other earth constructions, as well as
- Water bioengineering (WBE), which protects and stabilizes riverbanks and is frequently used in river restoration [10].

SWBE is an old method, used during the Roman Imperial period in Europe [11] Further sources show the use of fascines to control torrential flood waters in Asian countries 2000 BC [4] Since the mid-1980s the idea to address and investigate SWBE spread across Europe again [12,13] in particular in the area of the Alps and Mediterranean regions and has increasingly taken hold. Further, various experiences have shown that the application of SWBE constructions in low- and middle-income countries is possible, and a few research groups have carried out studies since the beginnings of the 2000s in countries beyond Europe. Within this process, significant and seminal publications examining regions in Asia such as China [4] and Nepal [6,7,14], Africa (Ethiopia [15]) and Central and South America (Brazil [16], Colombia [17], Nicaragua [18–21], Ecuador [22–24]) resulted.

1.2. Research Gap and Objectives of the Study

When transferring SWBE to unexplored areas, the technical feasibility, meaning the existence of technical conditions and technological necessities to realize the interventions, with focus on the disposability of autochthone plants, which possess the required biotechnical characteristics, have to be estimated [25]. During recent years, scientific interest in SWBE gradually gained popularity in Central and South America where plant species have been tested regarding their ability to fulfill slope stabilizing needs [26] and SWBE constructions e.g., to protect infrastructure have been implemented [27]. It is a cost-effective solution using local material or low-cost labor and allows the involvement of the local population in management and maintenance [6]. Nevertheless, globally a severe lack of established protocols to support the uptake of SWBE exists, and local authorities have little to no knowledge regarding the applicability of these techniques. Rey et al. [28] states, that the development of SWBE is consistent with policies aimed at encouraging "soft" solutions by including environmental concerns into standard technical practices. With regard to the worldwide trend to climate-friendly building solutions, SWBE constructions are gaining importance due to the utilization of living plants as construction material [10]. To build capacity in communities with contractors or authorities is therefore a major concern, whereby one research gap was to define standardized categories for the needs of SWBE when transferring the techniques to regions with unknown conditions. Generally, close interactions and therefore clear communication between stakeholders and SW bioengineers are necessary to support implementation of SWBE [28]. Standardized categories may close the gap between the mentioned parties and improve communication and general interaction. Therefore, during the present study, a Transferability Analysis for SWBE has been developed to be able to detect factors of success or barriers thereto when applying sustainable erosion techniques to new locations. Generally, Transferability Analyses are widely used e.g., for the transfer of urban transport policies from one city to another [29]. Further application areas are renewable energy [30], as well as the transfer of medical interventions from a primary context to a target context [31]. When transferring a policy to another site with different conditions, a positive outcome is not always guaranteed [32]. The best solution for one site is not necessarily the best for another location, country, continent or vice-versa. One advantage of a standardized Transferability Analysis Tool for SWBE is therefore the establishment of defined context conditions from Leading Sites, where SWBE techniques have already been constructed, to share knowledge for the application in other regions with similar or other characteristics. It provides an opportunity to learn from experience and assists towards avoiding mistakes in the future. The result may support the development of SWBE, as it provides an instrument to communities, local authorities or universities providing information regarding the advantages and necessities of implementation, as well as an assessment within different contexts of application.

1.3. Locations of the Leading Sites Used for the Transferability Analysis

As the present study focuses on developing a Transferability Analysis Tool for SWBE, constructions built during the last two decades in Central and South America have been selected as Leading Sites. The selection aimed to cover all the climatic areas where SWBE constructions have been implemented: the Centro American area, the Tropical Andes, the Subtropics with Atlantic influence and the Tropics with Pacific influence. A further criterion was the availability of data from the period of construction as well as active monitoring and therefore continuous scientific accompaniment during and after the implementation process. For the selection of the SWBE constructions which were used for the analysis, the report "Identificación de practicas inovadoras para la mitigación del riesgo a nivel regional latinoamericano con enfoque de Ingeniería Naturalística" [33], written within the project *Vulnerability estimation and Disaster Risk reduction at urban level in Ecuador-ECHO/DIP/BUD/2011/91002*, has been used as a basis to acquire the necessary information regarding the undertaken soil preservation measures and therefore the Leading Sites. In most cases, this source reports upon the used plant species, as well as other natural and artificial materials of the implemented SWBE techniques. The term construction, used in this study, represents a single or a combination of different SWBE techniques, implemented at a site where erosion is causing problems or slope stabilization is needed.

A total of 31 construction sites have been chosen from the mentioned report (Table 1, Figure 1), whereas 24 were coordinated from a research group DAGRI (former GESAAF) within the framework of international projects. In total, 9 of 31 sites are located in Nicaragua (2004–2007, 2010); 9 in Ecuador (2008, 2010, 2012); 6 in Colombia (2011); 4 in Brazil (2003, 2005, 2010); 2 in Mexico (2009, 2012), as well as 1 in Guatemala (2010). These 31 interventions are divided into 19 soil bioengineering (SBE) and 12 water bioengineering (WBE) constructions. In the Centro American area, 12 sites are located (Nicaragua, Mexico and Guatemala); 9 in the Tropical Andes (Ecuador and Colombia), 4 in the subtropics with Atlantic influence (Brazil), and 6 in the tropics with Pacific influence (Ecuador). Within a SWBE construction at one site, several different techniques have been applied, depending on the circumstances, as well as the local needs.

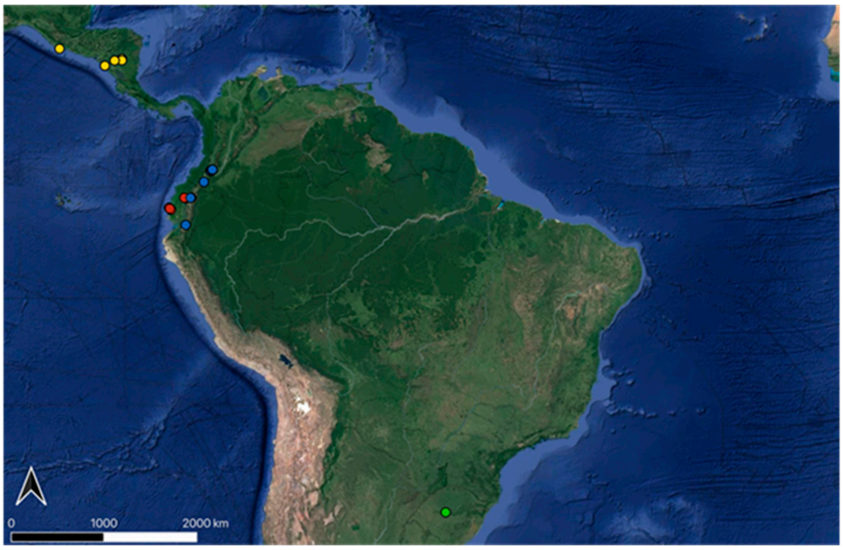


Figure 1. Locations of described soil and water bioengineering constructions.

Table 1. Summary of the analyzed sites divided per geographic area, country and application.

	Central America		Tropical Andes		Subtropics—Atlantic Influence		Tropics—Pacific Influence		TOTAL
Type	**Soil**	**Water**	**Soil**	**Water**	**Soil**	**Water**	**Soil**	**Water**	
Nicaragua	5	4	-	-	-	-	-	-	**9**
Mexico	2	-	-	-	-	-	-	-	**2**
Guatemala	-	1	-	-	-	-	-	-	**1**
Ecuador	-	-	2	1	-	-	4	2	**9**
Colombia	-	-	6	-	-	-	-	-	**6**
Brazil	-	-	-	-	-	4	-	-	**4**
TOTAL	**7**	**5**	**8**	**1**	**-**	**4**	**4**	**2**	**31**

1.4. SWBE Techniques at the Leading Sites

In the 31 Leading Sites, 15 different SWBE techniques have been realized (Table 2): 15 *double crib walls* in Brazil, Colombia, Ecuador and Nicaragua, (7 WBE, 8 SBE constructions); 7 *triangular* (“*latino*”) *crib walls* [34,35] in Colombia and Ecuador (SBE); 1 *single-walled crib wall* in Guatemala (WBE); 7 *slope grids* in Colombia, Ecuador, Mexico and Nicaragua (2 WBE, 5 SBE); 13 *palisades* in Brazil, Colombia, Ecuador and Nicaragua (1 WBE, 12 SBE); 6 *pile walls* in Ecuador and Nicaragua (SBE); 3 *drainage and stabilizing fascines* in Ecuador and Nicaragua (SBE); 2 *brush layers* in Ecuador and Nicaragua (1 WBE, 1 SBE); 5 *living brush mattresses* (WBE) in Brazil, Ecuador, Guatemala and Nicaragua; 1 *palisade with living cuttings and living brush mattress in a gully* (SBE) in Mexico; 2 *revegetated riprap* in Brazil (WBE); 1 *anchoring of living and dead tree spurs at riverbanks* in Brazil (WBE); 2 *seedings of herbaceous species* in Ecuador (1 WBE, 1 SBE); 5 *transplantations of sod slabs* in Colombia and Ecuador (SBE); 6 *fabrics for revegetation* in Colombia, Ecuador and Nicaragua (1 WBE, 5 SBE). In total, 76 relevant techniques were implemented in the 31 Leading Sites: 70% (53) of soil bioengineering and 30% (23) of water bioengineering constructions.

Table 2. Summary of the soil and water bioengineering (SWBE) techniques at the Leading Sites.

Type of Technique	Nicaragua	Mexico	Guatemala	Ecuador	Colombia	Brazil	TOTAL
(1) double crib wall	x	-	-	x	x	x	**15**
(2) single-walled crib wall	-	-	x	-	-	-	**1**
(3) triangular ("latino") crib wall	-	-	-	x	x	-	**7**
(4) slope grids	x	x	-	x	x	-	**7**
(5) palisades	x	-	-	x	x	x	**13**
(6) pile walls	x	-	-	x	-	-	**6**
(7) drainage and stabilizing fascines	x	-	-	x	-	-	**3**
(8) brush layers	x	-	-	x	-	-	**2**
(9) living brush mattresses	x	-	x	x	-	x	**5**
(10) palisade with living cuttings and living brush mattress in a gully	-	x	-	-	-	-	**1**
(11) revegetated riprap	-	-	-	-	-	x	**2**
(12) anchoring of living and dead tree spurs at riverbanks	-	-	-	-	-	x	**1**
(13) seedings of herbaceous species	-	-	-	x	-	-	**2**
(14) transplantations of sod slabs	-	-	-	x	x	-	**5**
(15) fabrics for revegetation	x	-	-	x	x	-	**6**
TOTAL							**76**

The following paragraph describes examples of SWBE constructions at the Leading Sites, containing all the techniques listed in Table 2:

(1) In Las Maravillas (Ecuador) a riverine consolidation technique with a *living wooden double crib wall* and a length of 36 m along the river course was carried out in 2008 (Figure 2). Already during the monitoring undertaken in 2012 the work was found damaged. According to the locals, the work was in good condition until 3rd March 2012 when a flood destroyed a part of the construction. Due to the good condition of the remaining 8 m of the wooden crib wall and the presence of sprouts from the cuttings reaching a height of 4 m and a diameter of 8 cm throughout the site, there are strong doubts that the increasing water level took the construction away.

Figure 2. Water bioengineering (WBE) construction at Las Maravillas after the finalization in 2008 (Petrone, 2008).

(2) In 2009, a 300 m long and 5 m high WBE construction was implemented at the bank of the river Coyolate at the entrance to the community Santa Odilia in the municipality La Nueva Concepción (Guatemala) (Figure 3). The erosion was caused by the changing water level of the river itself. For protection of the inhabitants the riverbank has been secured constructing a single-walled crib wall at the base. At the slope, living branches have been anchored and covered with soil to support vegetative recovery.

(**a**) (**b**)

Figure 3. WBE construction at La Nueva Concepción (**a**) single walled crib wall at the base and living branches at the slope (Petrone, 2009); (**b**) after the finalization in 2009 (Petrone, 2009).

(3) In 2012 (7) a 16 m long and 10 m high soil bioengineering intervention was implemented on a slope at the street Av. Maldonado in Quito (Ecuador) (Figure 4). At the base, a wooden triangular ("latino") crib wall was constructed. Over the upper part of the slope a living wooden grid and a new sward using sod slabs ("chambas de kykuyo") were implemented. Monitoring of the vegetation was undertaken 3 months after the construction. The development of the plants was satisfactory, and the construction was in good condition. In 2018 the crib wall at the base showed signs of decay. The sods developed well, covering the crib wall and the wooden grid. Further, the implemented vegetation grew in a satisfactory way and was able to take over the stabilizing function at the slope.

(**a**) (**b**)

Figure 4. SBE construction at Av. Maldonado in Quito (**a**) after the finalization in 2012 (Petrone, 2012); (**b**) monitoring in 2018 (Maxwald, 2018).

(4) In Jipijapa (Ecuador) an SBE construction with an area of 459.05 m^2 was built in 2008 to protect the street located below the slope (Figure 5). A total of two lines of living palisades and a series of wooden contour structures positioned in rows were erected in the soil. In 2012 the work was found to be in good condition. The functionality of the inert section (wooden logs of the palisades and contour structures) was still present, and the occurrence of superficial laminar erosion was halted completely. Due to a number of failures which occurred during the operation of the irrigation plan, the planted cuttings did not sprout perfectly. In December 2018 what first came to immediate attention was the plants' dryness due to the climate conditions in the area (Subtropics with Atlantic influence) at this

time. Further, in the lower section down by the street, garbage was found along the whole construction site which is presumably influencing the vitality of the plants in this section. As already predicted during the monitoring procedure in 2012 the wooden logs of the construction were decomposed to a large degree and the plants had taken over the stabilizing function. The aim to stop the erosion of the slope was achieved based also on the carefully chosen measurements for the project.

(**a**) (**b**)

Figure 5. Soil bioengineering (SBE) construction at Jipijapa (**a**) after the finalization in 2008; (Petrone, 2008) (**b**) monitoring in 2018 (Google Streetview, 2018).

(5) In the district of La Isla in Santo Domingo (Ecuador) a river consolidation work was constructed in 2010 by implementing a living wooden double crib wall for riparian protection and hedge brush layers on the upper part of the slope (Figure 6). In 2012 the construction was found in perfect condition. The inert material used (crib wall) had maintained its functionality for 2 years, the erosion process was completely halted, and the area had recuperated environmentally. A high percentage of the placed cuttings survived. In 2012, the approximate lifespan of the inert part of the work was estimated at 5 to 10 years. No damage was reported during the course of the monitoring. In 2018 the construction was not found due to incorrectly noted coordinates, therefore no information regarding its development since 2012 or the current condition of the construction are available at this time.

Figure 6. WBE construction at La Isla in Santo Domingo after the finalization in 2010. (Petrone, 2010).

(6) In the community of Jacomulco (province Veracruz, Mexico) in 2009, a palisade with living cuttings and living brush mattress was implemented in gullies (Figure 7), which were caused by heavy rainfalls in the area. The total length of the gullies was 50 m, the depth 0.8 m. With the intervention, soil was recovered, and the nearby house protected from runoff water.

(**a**) (**b**)

Figure 7. SBE construction at Jacomulco (**a**) gully in 2009; (Talamantes P., 2009) (**b**) after the finalization of the work in 2009 (Talamantes P., 2009).

(7) In 2010, an 80 m long and 7 m high WBE construction was implemented at a riverbank in the municipality of Santa Cruz do Sul (Province Río Grande do Sul, Brazil) (Figure 8). The erosion appeared after the construction of a dam what modified the section of the river. The intervention's aim was to restructure the slope through physical and ecological restoration using WBE techniques, such as vegetated riprap, living palisades, anchoring of living and dead tree spurs, as well as the implementation of rooted shrubs and cuttings.

Figure 8. WBE construction at Santa Cruz do Sul after the finalization in 2010 (Sutili F.J., 2010).

(8) The construction in San Luis de Chillogallo in Quito (Ecuador) was built in 2012 and has a length of 10 m and a height of 40 m (Figure 9). At the base of the slope a living wooden double and triangular ("latino") crib wall with a stairway at the right side was constructed. In the above part living palisades as well as a pile wall have been implemented and shrubby vegetation, as well as sod slabs ("chambas de kykuyo") planted to recover the sward. A total of 3 months after the finalization of the construction, the development of the plants was evaluated as being satisfactory. In December 2018 the wooden logs of the crib wall showed signs of decomposition, but all told the construction was stable. Noticeable was the strong development of the sods which were covering the crib wall. The logs of the living palisades as well as the planted shrubs were in good condition. Over the whole construction no signs of erosion were observable apart from some soil movements due to the formation of a footpath by the local inhabitants.

(**a**) (**b**)

Figure 9. SBE construction in San Luis de Chillogallo in Quito (**a**) after the finalization in 2012; (Petrone, 2012) (**b**) monitoring in 2018 (Maxwald, 2018).

(9) The construction in Membrillal (Ecuador) was carried out in 2008 on an area of 1333.85 m^2 next to a High School (Figure 10). The aim was vegetative recovery using soil bioengineering techniques. On the steep slope various wooden contour structures, living palisades and fascines of living branches with a draining and stabilizing function, as well as a net of Cabuya (agave fiber) with a covering function were implemented. In 2012 the construction was found in suboptimal condition. While within the previous 4 years the inert sections (wooden pegs of the palisades and contour structures) retained its functionality and the laminar erosion, as well as the formation of ditches was halted, the living sections (cuttings) did not survive in a satisfactory way. This was primarily due to the drought which affected the region right after the conclusion of the work. As a result, the local inhabitants were not able to irrigate the seedlings. It was estimated that the inert part of the construction would endure from 3 to 5 years. As expected, in 2018 the net of Cabuya was completely decayed and the wooden structures showed signs of advanced decomposition but were still stabilizing the slope. Vegetation recovered the lower part of the slope but was found with no leaves due to climate conditions and the plants' phenological development at the time of the monitoring. A few ditches, due to rill erosion in the area where the net of Cabuya was implemented were formed as only a small number of plants covered the specific area. Further, building site waste from elsewhere was also deposited there and a pig from a neighbor had settled in the area.

(**a**) (**b**)

Figure 10. SBE construction at Membrillal (**a**) after the finalization in 2008 (Petrone, 2008); (**b**) monitoring in 2018 (Maxwald, 2018).

(10) In 2010 in the village of San Miguél in the Province S. Domingo (Ecuador) an SBE construction was carried out on a 86 m long and 26 m high area with the aim to reconstruct the shrubby vegetation there with wooden palisades at the slope toe and various rows of wooden living contour structures (4 m in length, alternating every 3 m) (Figure 11). The monitoring of the vegetation is shown in Table 9c. In 2012 the construction was found to be in good condition. Due to the seeded sward and the good development of the cuttings, the cover of the area was satisfactory. Aside from a few instabilities due to heavy rainfall in December 2010 and April 2011, no immediate risks to the site were reported and the inert materials showed full stability. Between November 2011 and May 2012, a number of instabilities were naturally covered once again by vegetation. According to the local inhabitants, the planted species developed well. One reported problem was the use of the area as meadowland by a neighbor. The duration for the use of the inert material employed in 2012 was estimated at 1 to 3 years. On 16th April 2016 an earthquake (epicenter 27 km southeast from Muisne) with magnitude of 7.8 on Richter scale [36] caused the landslide of the slope which destroyed the construction. A suggestion for improvement could therefore be the implementation of a living wooden double crib wall with a ground resistance layer (wooden logs or stones) as a solid foundation for the slope or a flattening of the latter.

(**a**) (**b**)

Figure 11. SBE construction at San Miguél (**a**) after the finalization in 2010 (Petrone, 2010); (**b**) monitoring in 2018 (Maxwald, 2018).

2. Materials and Methods

A Transferability Analysis aims to show the applicability of e.g., policies from one context (Leading Site) to another (Take-Up Site) and tries, therefore, to demonstrate the external validity of the concept, independently from situation or time. Dolowitz and Marsh [32] state, that a transfer of policy can be carried out in various grades such as (1) a complete transfer (copying), (2) transfer of the ideas behind the policy (emulation), (3) fusions of different policies (combinations) and (4) taking inspiration from a policy with a different jurisdiction, whereby the final outcome does not actually draw on the original idea. Depending on the topic being assessed, sources of information used for the analysis can be found in literature, interviews, workshops, existing experience and field visits for on-site monitoring [29]. A Transferability Analysis identifies factors of success, as well as potential barriers for the transfer of a policy or concept by defining Leading Sites which provide information for the Take-Up Sites.

For the structure of the Transferability Analysis, the approach of Gyergyay and Boehler-Baedeker [29] was modified and adapted to SWBE needs. It contains the following elements:

1. Objectives of the procedure
2. Impacts of the measure
3. Identification of up-scaling/down-scaling needs
4. Identification of the main phases and its components
5. Identification of the level of importance of the components
6. Assessment of the components in the context of the Take-Up Site
7. Conclusions

2.1. *Objectives of the Procedure*

In a first step, the objectives for the execution of the Transferability Analysis must be defined in order to avoid misinterpretations during the subsequent transferability and implementation process.

2.2. *Impacts of the Measure*

The second step includes the clarification of the impacts of the measures. For SWBE the description should include changes or advantages in Safety, Environment, Ecology, Biodiversity of flora and fauna and Awareness enhancement. These issues were chosen partly based on the methodology of Gyergyay and Boehler-Baedeker [29], as well as on the authors' expertise and experience. Each issue is described, and an overview of these impacts provided.

2.3. *Identification of Up-Scaling/Down-Scaling Needs*

Within the third step the need of up- or down-scaling of the measures is identified, depending on the context conditions and therefore mainly the implementation size of the Take-up Site in comparison to the Leading Site.

2.4. *Identification of the Main Phases and Its Components*

In the fourth step of the Transferability Analysis for SWBE various main phases, which could contribute to success or failure of a measure, have been identified and a cycle of the sequential arrangement in time has been established (Figure 12).

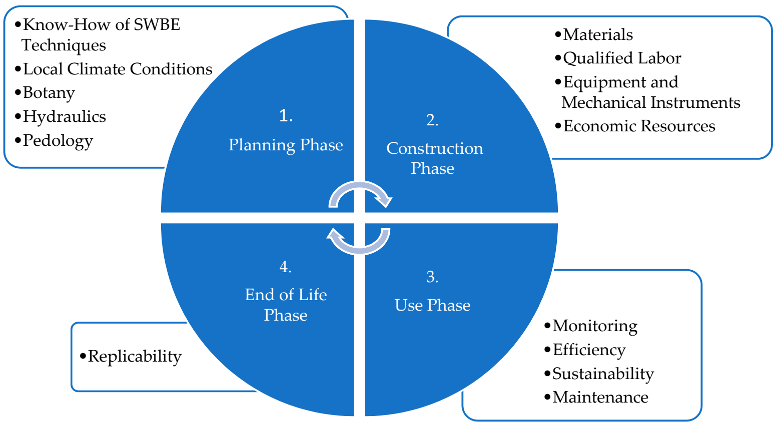


Figure 12. Structure of step 4 of the transferability analysis for soil and water bioengineering.

The main phases were defined as follows:

1. Planning Phase
2. Construction Phase
3. Use Phase
4. End of Life Phase

These main phases of the transferability analysis are divided by components. After the identification of an erosion problem various necessities during the initial Planning Phase appear, such as knowledge about SWBE techniques, local climate conditions, botany, hydraulics or pedology. In the Construction Phase the availability of construction materials, qualified labor, equipment and mechanical instruments, as well as economic resources has to be kept in mind. During the Use Phase of the SWBE constructions the components monitoring, efficiency, sustainability, and maintenance are important. In the End of Life Phase, after or during the decay of the construction, rebuilding depends on various factors, such as replicability.

The selection of the components to be assessed depends on the experiences made at the Leading Sites [29]. Therefore, for each component various questions have been developed. The answers help to establish the basis for assessing the different components and their contribution to success or failure of transferability.

2.4.1. Planning Phase

After the identification of an erosion problem at a site, the aim to prevent further instabilities and soil movements leads to the Planning Phase. In this phase, Know-How is important to be able to decide if and what type of SWBE techniques can alleviate the problem and halt the erosion process. Further, the planner has to select the best possible solution depending on the capacity of the individual techniques, local climate conditions, botanical conditions, hydraulics in case of WBE and pedology.

Know-How of SWBE Techniques

Know-How of SWBE Techniques presents the basis for the transfer to the Take-Up Site. To assess the component's importance, as well as its support or constraint within the Transferability Analysis, the following questions had to be answered:

- *Is SWBE as a topic present at local universities' curricula, as well as implemented at public or private agencies which are dealing with erosion, protection of settlements or NBS area-wide within the Take-Up Site?*
- *What are the possibilities to transfer Know-How of SWBE to the Take-Up Site?*
- *Are experts in the field able and willing to promote and impart Know-How of SWBE techniques at the Take-Up Site?*

Local Climate Conditions

The main questions to clarify regarding Local Climate Conditions were:

- *How are climate conditions influencing the transferability of SWBE techniques to the Take-Up Site?*
- *Does the moment of the construction's implementation influence the development of plants, and therefore the stability?*

Botany

The botanical knowledge regarding the requirements for the plants' utilization in SWBE contexts is one main aspect for a successful transfer of the techniques, as the vegetation should take over the stabilizing function after the decay of e.g., implemented wooden structures. The following questions had to be answered:

- *Is sufficient botanical knowledge available regarding the necessities for the plants' implementation in the constructions?*
- *Is it necessary to carry out further research regarding plants and their ability to fulfill the required standard for SWBE?*
- *Which plant species have been used for implementation at the Leading Sites and are they suitable for the Take-Up Site?*

Hydraulics

Hydraulic aspects which influence the transferability of SWBE had to be considered by answering the following questions:

- *What are the main hydraulic aspects which could negatively influence the stability of a SWBE technique?*
- *How can these aspects be overcome?*

Pedology

To be aware of pedological aspects influencing the transferability of SWBE, the following questions had to be considered:

- *What are the main pedological aspects which could negatively influence the stability of a SWBE technique?*
- *How can these aspects be overcome?*

2.4.2. Construction Phase

For the assessment of the Construction Phase, the availability of diverse parameters needed to be clarified. To guarantee a good work flow, the accessibility to sufficient and high-quality material is important. Qualified labor, as well as accessibility to equipment and mechanical instruments were key aspects to implement the aims defined in the Planning Phase properly. Further, the availability of sufficient economic resources was an important consideration in this section.

Materials

The used material was one main aspect for SWBE and therefore a component in the Construction Phase. The main questions regarding used material were:

- *What type of materials have been used for the constructions at the Leading Sites?*
- *What species for the wooden logs has been used?*
- *What additional material has been used?*
- *Was wild vegetative material available at the sites?*

Qualified Labor

For the transferability of SWBE the training of Qualified Labor was of utmost importance.

- *Are operators familiar with SWBE?*
- *How can inhabitants be involved in the planning or construction process?*

Equipment and Mechanical Instruments

The feasibility of SWBE techniques was strongly dependent on the availability of equipment and mechanical instruments. Answers to the following questions helped to assess the transferability of SWBE.

- *Is it possible to rent or repair specific specialized equipment, mechanical material or vehicles?*
- *Are any differences regarding the availability of equipment within regions observed?*
- *How can be dealt with missing equipment or mechanical instruments?*

Economic Resources

The component Economic Resources was one main aspect for the transferability of SWBE to the Take-Up Site. This paragraph should treat the construction costs of SWBE techniques, depending on the availability of data, to be able to compare different regions within the Leading Sites. For the present analysis a double crib wall was chosen, as it is a typical and effective technique in SWBE.

- *What are the costs for a double crib wall in different regions of the Leading Sites?*
- *What has to be considered in addition to the construction costs?*

2.4.3. Use Phase

For the assessment within the transferability analysis the components during the Use Phase were monitoring, efficiency, sustainability and maintenance of the constructions. This assessment-phase provided information regarding the construction's development and functionality.

Monitoring

Generally, monitoring processes are important as they provide insight into the momentary condition of the plants or constructions. They can contribute to the development of SWBE and therefore to its transferability. With monitoring procedures valuable information regarding the development of the plants or the materials may be gained. When carried out over a certain period, conclusions regarding the development of the monitored object can also be drawn. The following questions had to be answered for the Transferability Analysis:

- *What kind of monitoring data exists from the Leading Sites?*
- *What are the results of the existing monitoring data from the Leading Sites?*

Efficiency

The efficiency of the constructions in the Leading Sites was determined by the person in charge of the project.

- *Did the constructions at the Leading Sites effectively halt soil erosion and resolve the initial problem?*

Efficiency was assessed after the following criteria: (a) Elevated efficiency was assessed if the structure stopped soil erosion completely, (b) moderate efficiency if the erosion had been partially halted and (c) low efficiency if the intervention did not resolve the initial problem.

Sustainability

Further, the person in charge of the project answered the following question:

- *Are the implemented SWBE constructions at the Leading Sites able to sustain themselves?*

The sustainability of the constructions in the Leading Sites was assessed according to the following criteria: (a) the construction is able to maintain its efficiency over time; maintenance can be realized autonomously by the local residents (technically and economically) (*high*); (b) the construction is able to maintain its efficiency over time; maintenance can be realized autonomously by local residents but the availability of financial resources may be problematic (*moderate*); (c) the construction is not able to maintain its efficiency over time; the local residents possess neither technical knowledge nor the required financial resources (*low*).

Maintenance

- *What measures must be carried out to maintain the plants' functionality and therefore the construction's stability?*

2.4.4. End of Life Phase

In the construction's End of Life Phase, the stability and protective function against erosion is not given anymore and a decision regarding a reconstruction should be taken. For the Transferability Analysis itself, information concerning the replicability of the constructions at the Leading Sites was collated.

Replicability

To acquire information regarding the replicability of the constructions at the Leading Sites the person in charge of the project was asked to analyze the situation quantitatively and answer the following question:

- *Are the implemented SWBE constructions at the Leading Sites replicable for local residents?*

The assessment followed the listed criteria: (a) the replication of the construction can be realized autonomously by the local residents (*high*); (b) the replication of the construction can be realized with accompaniment of technicians and financial resources of the municipality (*moderate*); (c) the replication is not possible due to missing technicians and financial resources (*low*).

2.5. Identification of the Level of Importance of the Components

In this step the importance of the components was defined from the viewpoint of the Take-Up Site and rated as high, medium or low. The experience acquired in the Leading Sites, as well as the advice received from experts may be helpful in judging the importance of each point. Additionally, the chosen level of significance can be reinforced by comments [29].

2.6. Assessment of the Components in the Context of the Take-Up Site

A subjective assessment scheme, based on the experience regarding difficulties or positive outcomes made in the Leading Sites, evaluates the various components descriptively and numerically. For the assessment a scale from +2 to −2 was used.

+2 strong support for transferability
+1 moderate support for transferability
0 no support or no constraints
−1 moderate constraint for transferability
−2 strong constraint for transferability

To provide a good overview of the interaction between importance of the components in the Take-Up Site and experience gained in the Leading Site, steps 5 and 6 can be merged by creating a table containing information stemming from both issues.

2.7. Conclusions

For the last step of the Transferability Analysis, it was important to draw conclusions regarding the conceivable transferability of SWBE to the Take-Up Site, based upon the considerations derived from the identified and interacting factors and assessment values. All key success factors and key barriers, as well as probable mitigating actions to overcome barriers should be thoroughly discussed. The concluding estimation regarding the probability of a successful transferability of SWBE to the Take-Up Site was based upon this discussion.

Gyergyay and Boehler-Baedeker [29] stated three rules of thumb for the concluding assessment:

1. If one or more strong constraints appear, it is likely that the solution will not be transferable without overcoming these conditions in the Take-Up Site.
2. If no strong constraints, but one or two moderate constraints appear, it is likely to be challenging to transfer the policy. Therefore, the constraining conditions have to be addressed effectively.
3. If no constraints appear, it is likely that the transfer of the measure performs successfully and satisfying results are yielded.

3. Results

The following chapter shows the results of the Transferability Analysis for SWBE to Central and South America.

3.1. Objectives of the Procedure (Step 1)

The objective of the Transferability Analysis is to assess Central and South America (Take-Up Site) as regions for the implementation of SWBE techniques at a large scale. The needed information for the assessment is taken from representative construction sites at a small scale in Mexico, Nicaragua, Guatemala, Colombia, Ecuador, and Brazil (Leading Sites) built in the last decades. These sites provide local information regarding Planning Phase, Construction Phase, Use Phase and End of Life Phase.

3.2. Impacts of the Measure (Step 2)

The impacts, when implementing SWBE measures in the Take-Up Site, range from increasing safety and environmental benefits to the continued support of ecosystem services. Further, ecological advantages, increasing biodiversity of flora and fauna, as well as the enhancement of awareness regarding environment protection can also be achieved. Table 3 describes the impacts of SWBE solutions.

Table 3. Impacts of SWBE constructions on the environment.

Impacts	Description
Safety	SWBE constructions under good conditions prevent slopes and banks from erosion, protecting settlements and agriculture.
Environment and ecosystem services	Plants used for the constructions are filtering air and water. Effective in cities with high particulate pollution. A cooling effect of the adjacent microclimate can be achieved and therefore the health of inhabitants increased.
Ecology	Due to the selection of construction materials (wooden logs, plants etc.) SWBE conserves resources in comparison with other civil engineering techniques of slope stabilization. The production of resource intensive materials (e.g., concrete) or accumulation of construction waste are omitted.
Biodiversity of flora and fauna	SWBE constructions can provide new habitats for flora and fauna.
Awareness Enhancement	Including local inhabitants in the planning and construction process may lead to increased awareness by the population regarding environment protection.

3.3. Identification of Up-Scaling/Down-Scaling Need (Step 3)

The information for the Transferability Analysis is taken from individual SWBE construction sites (Leading Sites) and used to draw conclusions for Central and South America (Take-Up Site). Single constructions have been carried out at the Leading Sites on a small-scale, where it is generally easier e.g., to establish contact with engineers or to customize the constructions individually. On a large-scale, regulations regarding sustainable constructions, for example, could help to implement SWBE. Further, the development of guidelines or standards regarding regional implementation of SWBE could positively influence labor, ecological effects, or biodiversity within the region. A policy up-scaling should concern various points which go beyond the engineering effects themselves.

3.4. Identification of the Main Phases and Its Components (Step 4)

As Figure 12 illustrated, the definitions of the main phases and its components contribute to the identification of success or failure of a measure. The main phases are based upon the life cycle of a construction and consists of a Planning Phase, Construction Phase, Use Phase and End of Life Phase. The information regarding the assessment of the components is taken from the Leading Sites and therefore from the experiences made with the constructions in question or further knowledge from the Take-Up Site.

3.4.1. Planning Phase

Know-How of SWBE Techniques

- *Is SWBE as a topic present at local universities' curricula, as well as implemented at public or private agencies which are dealing with erosion, protection of settlements or NBS area-wide within the Take Up Site?*

The experience from the Leading Sites, as well as the experience from the authors show, that SWBE as part of the universities' curricula is sparsely existent in Central and South America. Within urban regions civil engineering solutions for any type of erosion problem is still preferred, also due to missing knowledge regarding the ability of NBS.

- *What are the possibilities to transfer Know-How of SWBE to the Take-Up Site?*

The transfer of Know-How to the Take-Up Site depends on the creation of networks within universities, planning agencies or governments throughout the area. Workshops, projects participation processes, guidelines or laws can help to transfer SWBE to the Take-Up Site.

- *Are experts in the field able and willing to promote and impart Know-How of SWBE techniques at the Take-Up Site?*

The interest from students, as well as academic staff in Central and South America in the topic is high, what results in a good basis for future projects undertaken by experts in the field. Further, heads of communities are interested in SWBE as it provides an economic preferable solution for erosion control.

Local Climate Conditions

- *How are climate conditions influencing the transferability of SWBE techniques to the Take-Up Site?*

Due to the presence of the Andes and therefore a difference in altitude of about 6000 m from the coast to the highest peaks, Central and South America is characterized by various different climate zones, primarily defined by a series of droughts and rainy seasons throughout the year. Therefore, species selection must be adapted to the preferred location.

- *Does the moment of the construction's implementation influence the development of plants, and therefore its stability?*

After analyzing the experiences of the Leading Sites, it appears to be crucial to choose the correct time for the implementation of the measures. Especially in zones where irrigation in the first weeks is not possible, the development of the vegetation and therefore the stability of different SWBE techniques will strongly suffer if it is implemented during or before a local drought season. On the other hand, it can be difficult to establish a construction during a rainy season, as extreme precipitation could wash out soil or plants.

Botany

- *Is sufficient botanical knowledge available regarding the necessities for the plants' implementation in the constructions?*

Due to the high biodiversity in Central and South America and a high availability of plants with the ability to reproduce vegetatively, the pool for the choice of suitable species is widespread. Within the available species in an area, it is necessary to select the most adapted ones regarding the ability of fast rooting, bending capacity or vegetative reproduction.

- *Is it necessary to carry out further research regarding plants and their ability to fulfill the required standard for SWBE?*

As SWBE is not frequently used in the Take-Up Site, scientific studies dealing with bending capacity, pull out resistance or root development etc. of the mentioned plants are rare. Closing this knowledge gap can support the transfer of SWBE significantly. Hörbinger (2013), for example, carried out a pull-out test of *Phyllanthus sellowianus* and *Sebastiania schottiana* in South Brazil [37].

Nevertheless, the site-experience with some species shows the usability for SWBE techniques.

- *Which plant species have been used for implementation at the Leading Sites and are they suitable for the Take-Up Site?*

At the Leading Sites, numerous plant species, used for the implementation, have been determined. In total, 33 different species were planted in the 19 sites of soil bioengineering and 47 species in the 12 sites of water bioengineering, using cuttings. Due to the high availability of wild living cuttings in these areas, the necessity to implement rooted shrubs from tree nurseries was low and therefore used on two sites of soil bioengineering (Colombia and Ecuador) and 1 site of water bioengineering (Brazil) only. The great variety of the species used for the cuttings reflects the high biodiversity of the tropical and subtropical regions. Being able to use wild vegetative material represents an uncommon opportunity compared to European conditions, for example.

Tables 4–7 show the number of sites where the particular planted species were used in form of cuttings, divided per geographic area.

Table 4. Used species (in form of cuttings) in the Central American area and the number (#) of sites where the plants were utilized.

Soil Bioengineering (89–691 m. a.s.l.—7 Sites) *				Water Bioengineering (17–698 m. a.s.l.—5 Sites)	
	#Sites		#Sites		#Sites
Gliciridia sepium	5	*Morus alba*	1	*Gliciridia sepium*	3
Erythrina fusca	3	*Plumeria rubra*	1	*Bursera sima ruba*	2
Tabebuia rosea	3	*Salix humboldtiana*	1	*Cordia dentata*	2
Bursera simaruba	1	*Spondia dulcis*	1	*Erythrina fusca*	2
Conutia pyramidata	1	*Spondias purpurea*	1	*Salix humboldtiana*	2
Cordia allodora	1			*Erythrina poeppigiana*	1
Cordia dentata	1			*Jatropha curcas*	1
Erythrina poeppigiana	1			*Pachira aquatica*	1
Lantana camara	1			*Tabebuia rosea*	1

* From two sites of soil bioengineering (Mexico) the names of the species planted are not available.

Table 5. Used species (in form of cuttings) in the Tropical Andes and the number of sites where the plants were utilized.

Soil Bioengineering (2094–3007 m. a.s.l.—*8 Sites*)		*Water Bioengineering* (2563 m. a.s.l.—*1 Site*)			
	#Sites		#Sites		#Sites
Mimosa quitoense	5	*Alnus acuminata*	1	*Macleania rupestres*	1
Delostoma roseum	4	*Baccharis latifolia*	1	*Miconia aspergilaris*	1
Alnus acuminata	2	*Viburnum triphyllum*	1	*Mimosa andina*	1
Baccharis latifolia	2	*Aegiphila ferrugineo*	1	*Morella parviflora*	1
Polyletis incana	2	*Ambrosia arborescens*	1	*Myrsine andina*	1
Sambucus racemosa	2	*Barnadesia arborea*	1	*Myrsine dependens*	1
Sambucus sp.	2	*Berberius pindilincensis*	1	*Phyllantus salvifolius*	1
Viburnum triphyllum	1	*Cantua pyrifolia*	1	*Rubus floribundus*	1
Abutilon sp.	1	*Cestrum peruvianum*	1	*Sambucus mexicano*	1
Erythrina sp.	1	*Citharexylum* sp.	1	*Schinus molle*	1
Euphorbia cotinifolia	1	*Cordateria cubata*	1	*Vallea stipularis*	1
Euphorbia lactifera	1	*Coriaria ruscifolia*	1		
Tibouchina mollis	1	*Erythrina edulis*	1		
Tournefortia fuliginosa	1	*Euphorbia laurifolia*	1		
Verbesina arborea	1	*Ferreyranthus verbasifolius*	1		

Table 6. Used species (in form of cuttings) in the Subtropics (influenced by the Atlantic) and the number of sites where the plants were utilized.

***Water Bioengineering* (35–75 m. a.s.l.—*4 Sites*)**					
	#Sites		**#Sites**		**#Sites**
Phyllantus sellowianus	2	*Salix rubens*	2	*Hedychium coronarium*	1
Salix humboldtiana	2	*Sebastiania schottiana*	2	*Puteria salicifolia*	1
Salix viminalis	1	*Terminalia australis*	1		

Table 7. Used species (in form of cuttings) in the Subtropics Tropics (influenced by the Pacific) and the number of sites where the plants were utilized.

***Soil Bioengineering* (206–887 m. a.s.l.—*4 Sites*) ***				***Water Bioengineering* (220508 m. a.s.l.—*2 Sites*)**	
	#Sites		**#Sites**		**#Sites**
Cordia lutea	2	*Trichanthera gigantea*	1	*Brugmansia versicolor*	1
Jatropha curcas	2	*Malvaviscus pendulifloris*	1	*Sambucus* sp.	1
Spondias purpurea	2			*Trichanthera gigantea*	1
Brugmansia versicolor	1			*Cordia lutea*	1
Euphorbia cotinifolia	1			*Crescentia cujete*	1

* For one site of soil bioengineering (Ecuador) the names of the planted species are not available.

Hydraulics

- *What are the main hydraulic aspects which could negatively influence the stability of a SWBE technique?*

Experiences in the Leading Sites show, that in combination with the climate conditions in Central and South America and the extreme precipitation experienced during rainy seasons, hydraulics play a crucial role, especially in WBE along river courses where the water level may rise strongly within a short time.

- *How can these aspects be overcome?*

With a higher discharge, the WBE constructions must be built to withstand higher drag or shear forces which leads to the need of higher durability. Therefore, in some cases, more durable constructions must be implemented to guarantee the stability of riverbanks or slopes. Further, maintenance measures of the vegetation layer can sustain the flexibility of the branches which protects the riverbank in case of inundation.

Pedology

- *What are the main pedological aspects which could negatively influence the stability of a SWBE technique?*

The experience acquired in the Leading Sites demonstrates that geological properties of the specific regions have to be considered carefully as influencing powers, such as tectonic movements and resulting earthquakes. Further, pedological aspects regarding the behavior of soil, inter alia in cases of high surface runoff during or after rain events or slope stability have to be considered.

- *How can these aspects be overcome?*

Within the Planning Phase, a slope stability analysis can clarify what kind of technique must be chosen. Tendentially, larger techniques should be considered. Vegetated wooden double crib walls, can secure slopes or riverbanks until the planted vegetation takes over the stabilizing function at the site.

As SWBE has an estimated (European) efficiency depth of about 2 m [8], depending on the development of the plants' roots and their pull-out resistance or shear strength, one advantage compared to civil engineering works, is the availability of autonomous recovery after e.g., soil movements, which could be beneficial in rural regions where access with heavy equipment can be difficult to achieve. A further approach to overcome destructively influencing pedological aspects is to implement effective draining systems to drain surface or soil water.

3.4.2. Construction Phase

Materials

- *What type of materials have been used for the constructions at the Leading Sites?*

In the Leading Sites natural and artificial materials which were used for the constructions have been identified. As a result, 30 of 76 realized SWBE techniques are classifiable within the combined techniques, whereby plants are combined with wooden logs.

- *What species for the wooden logs has been used?*

For five techniques (17%), data regarding the used wood are missing, for the construction of 22 (73%) techniques, Eucalyptus was used. In a number of cases the Eucalyptus was treated to be long-lastingly preserved and to increase the durability of the recently cut logs (Figure 13a). Due to missing alternatives, the choice for Eucalyptus (allochthonous and widespread species) resulted in an obligatory decision. Wooden logs were also used in 19 construction sites. In 13 cases (68%) data regarding the type of wood are missing, for the remaining ones Eucalyptus or Bamboo has been used.

(**a**) (**b**)

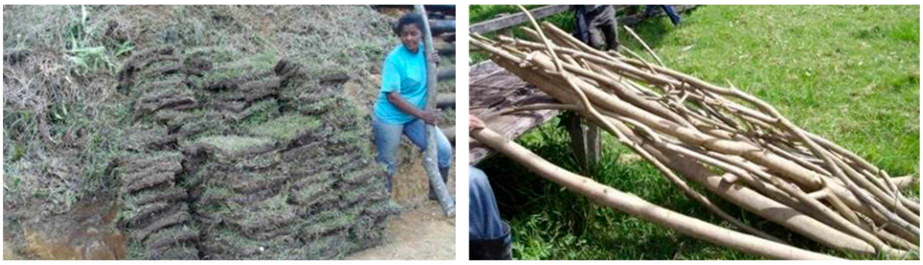
Figure 13. (**a**) Logs of Eucalyptus after borate treatment (Petrone, 2010); (**b**) Reconstruction of vegetational cover with fabrics of Agave or Sisal and plantation of herbaceous' rhizomes (Petrone, 2010) (Colombia).

- *What additional material has been used?*

On 6 sites (1 WBE, 5 SBE) the reconstruction of vegetational cover was experimented with by employing fabrics of Agave (Cubuya) or Sisal (Figure 13b). Additionally, in one case a wire mesh was also used in combination with the above. Agave or Sisal are natural fibers, extracted mainly from *Furucrea andina* (Cubuya) and *Agave sisalana*, both used for the production of artisanal products and sacks for coffee beans. At one site PVC tubes for the drainage of a slope has been used.

- *Was wild vegetative material available at the sites?*

Generally, the good disposability of wild, vegetative material was determined in the Leading Sites. Due to environmental conditions and high biodiversity, rapid growth of the vegetation was favorable (Figure 14). Therefore, the availability of rooted bushes or shrubs from local tree nurseries was given. Main natural dead materials used for constructions were available in the environs of the sites, but the procurement sometimes proved to be difficult e.g., in cases where the harvest and the transportation of logs are undertaken manually, and the transportation thereof is carried out with the help of draft animals.



(**a**) (**b**)

Figure 14. Vegetative material extracted from the surroundings (**a**) sod slabs (Petrone, 2010); (**b**) cuttings (Petrone, 2010) (Colombia).

Qualified Labor

- *Are operators familiar with SWBE?*

Experience gained from the Leading Sites showed that operators are not familiar with individual SWBE techniques. Nevertheless, inhabitants mostly from rural areas, use plants in a technical way, due to various traditional techniques, which were employed over decades in these areas [35]. This fact provides a good basis for the transfer of SWBE.

- *How can inhabitants be involved in the planning or construction process?*

Inhabitants can be involved in the planning and/or construction phase with participation processes, workshops or even citizen science. Nevertheless, experts and scientists with sufficient knowledge are rare and the development of a network will be a key issue to train inhabitants and operators for the successful implementation of SWBE in areas of interest.

Equipment and Mechanical Instruments

- *Is it possible to rent or repair specific specialized equipment, mechanical material or vehicles?*

Work at the Leading Sites indicated that repairing specific specialized equipment, mechanical materials or vehicles may present problems. Tools, e.g., drilling machines with adequate power or boring bits in suitable lengths, can be difficult to find.

- *Are any differences regarding the availability of equipment within regions observed?*

Work machines for excavation are generally available in urban areas, the rental in rural areas is more expensive, depending also upon possible difficulties regarding site access and therefore the additional time this requires. Transportation to the site may therefore represent some weakness regarding the technical feasibility of some projects in rural areas as the material costs increase, and various logistical problems may manifest themselves for engineers and operators.

- *How can be dealt with missing equipment or mechanical instruments?*

The problem of missing equipment or mechanical instruments can be partly resolved, as the cost for manual labor is generally low at the Take-Up Site. When using manual labor instead of mechanical instruments, an extension of the overall construction time for the project must be accepted, remaining aware of the strongly increased exposure of the workers thereby.

Economic Resources

- *What are the costs for a double crib wall in different regions of the Leading Sites?*

Data regarding the costs of the implementation at the Leading Sites at the moment of construction were available for three countries: Nicaragua, Colombia and Ecuador. On many sites the excavations were undertaken manually, with low costs per hour, but increased construction time. Considering the low price of labor this solution can be economically competitive when the safety of the workers can be guaranteed. Table 8 shows a cost comparing analysis [38] regarding the construction of a double log crib wall. With the rental of an excavator in Central and South America the highest construction costs were estimated in Colombia (50.1 EUR/m^3), followed by Nicaragua (47.1 EUR/m^3) and Ecuador (44.0 EUR/m^3). In the case of manual excavation, the costs of a double log crib wall decrease in Colombia (31.4 EUR/m^3), Ecuador (29.8 EUR/m^3) and Nicaragua (18.0 EUR/m^3).

Table 8. Cost analysis of a double log crib wall (rental of excavator and manual excavation) per cubic meter of the construction.

	Unit	Quantity	Nicaragua	Colombia	Ecuador	Nicaragua	Colombia	Ecuador
With rental of excavator			Basic price (Euro)			Total amount (Euro)		
LABOR								
Common operators	hour	0.8	0.5	1.8	2.4	0.4	1.4	1.9
Qualified operator (master builder)	hour	0.7	1.0	2.1	3.1	0.7	1.5	2.2
		SUBTOTAL				**1.1**	**2.9**	**4.1**
RENTAL								
Excavator (with operator)	hour	0.7	45.0	38.5	36.0	31.5	26.9	25.2
Motor saw	hour	0.3	3.5	3.5	4.5	1.1	1.1	1.4
Drilling machine	hour	0.1	1.0	1.0	1.0	0.1	0.1	0.1
Power generator	hour	0.1	6.0	6.5	7.0	0.6	0.7	0.7
		SUBTOTAL				**33.3**	**28.8**	**27.4**
MATERIALS								
Logs (Ø 20 cm)	m	4	2.5	2.5	1.6	10.0	10.0	6.4
Nailing	ppu	4	0.3	0.6	0.4	1.2	2.4	1.6
Cuttings	ppu	15	0.1	0.4	0.3	1.5	6.0	4.5
		SUBTOTAL				**12.7**	**18.4**	**12.5**
		Sum of construction costs (EUR/m^3)				**47.1**	**50.1**	**44.0**
Manual excavation			Basic price (Euro)			Total amount (Euro)		
LABOR								
Common operators	hour	5	0.5	1.8	2.4	2.5	9.0	12.0
Qualified operator (master builder)	hour	1	1.0	2.1	3.1	1.0	2.1	3.1
		SUBTOTAL				**3.5**	**11.1**	**15.1**
RENTAL								
Motor saw	hour	0.3	3.5	3.5	4.5	1.1	1.1	1.4
Drilling machine	hour	0.1	1.0	1.0	1.0	0.1	0.1	0.1
Power generator	hour	0.1	6.0	6.5	7.0	0.6	0.7	0.7
		SUBTOTAL				**1.8**	**1.9**	**2.2**
MATERIALS								
Logs (Ø 20 cm)	m	4	2.5	2.5	1.6	10.0	10.0	6.4
Nailing	ppu	4	0.3	0.6	0.4	1.2	2.4	1.6
Cuttings	ppu	15	0.1	0.4	0.3	1.5	6.0	4.5
		SUBTOTAL				**12.7**	**18.4**	**12.5**
		Sum of construction costs (EUR/m^3)				**18.0**	**31.4**	**29.8**

The cost comparing analysis assumes the use of wild cuttings and excludes refill of soil (other than that from the excavation) and postulates interventions designed to prevent complete erosion (semination/planting of sods). Security costs, general expenses, commercial profit, planification and management are excluded. The reported values therefore represent the actual costs for the construction work. The basic price is indicated, as influenced by local conditions such as transport, and as applicable to each individual country.

- *What has to be considered in addition to the construction costs?*

Especially in Amazonian areas, the presence of poisonous animals must also be considered, and adequate security measures taken. Generally, the required economic resources for the implementation of a SWBE construction project depend on both the location (e.g., accessibility) and the circumstances (e.g., altitude).

3.4.3. Use Phase

Monitoring

- *What kind of monitoring data exists from the Leading Sites?*

From the Leading Sites botanical monitoring data were available from three locations. A survey regarding the development of the implemented plants has been carried out in five sites in Nicaragua and two sites in Ecuador from the research group DAGRI (former GESAAF) [18,19,23,24]. The following constructions were implemented at these sites:

(a): (1) (WBE): Living wooden double crib wall for riparian protection, living wooden slope grid and coverage with net of Cabuya (agave fiber), Nr. of implemented cuttings: not available (NA); (2) (WBE): Living wooden double crib wall for riparian protection and living wooden grid, Nr. of implemented cuttings: NA.

(b): (1) (SBE): Drainage with living fascines, Nr. of implemented cuttings: NA; (2) (SBE): Living wooden palisade over the slope, Nr. of implemented cuttings: 447; (3) (WBE): Living wooden double crib wall, Nr. of implemented cuttings: 1120.

(c): (1) (SBE): Living wooden palisade and various rows of living wooden contour structures, Nr. of implemented cuttings: 2780; (2) (WBE): Living wooden double crib wall, hedge brush layers and seeding of herbaceous species for a new sward, Nr. of implemented cuttings: 1280.

- *What are the results of the existing monitoring data from the Leading Sites?*

The monitoring of the cuttings' development in León (Nicaragua) was carried out in time stages of 45 months at the first and 32 months at the second site after their implementation. The sprouts of *Jatropha curcas* show a total average rooting percentage of 53%, *Cordia dentata* of 58% and *Gliciridia sepium* of 66%. The cuttings of *Bursera simaruba* did not root at the two sites.

At Rio Blanco (Nicaragua), after a development time of 18 months, the lowest average rooting percentage showed *Erythrina fusca* with 14%. As the maximum values of rooting (42%), average diameter (3.5 cm) and length (282.8 cm) for this species show a higher than average growth rate, Table 9 also lists these values to show the probable local usability of this plant species for SWBE techniques. The species *Tabebuia rosea* showed a rooting percentage of 63% and *Gliciridia sepium* of 100%, which makes them—at this point of our knowledge—a good choice for implementation in SWBE constructions in the Centro American area.

Table 9. Significant parameters of the implemented cuttings at the particular last realized monitoring.

	Nr. of Implemented Cuttings	Length of Cutting (cm)	Months after Final Completion	Percentage of Rooting in Total	Av. Diameter Main Shoot (cm)	Av. Length Main Shoot (cm)
(a) LEON: Nicaragua; Construction (1) Jan 2004—WBE **(2)** May 2005—WBE						
Gliciridia sepium	(1) NA (2) NA	(1) 160 *, 60 ** (2) 200 *, 60 **	(1) 45 (2) 32	66%	10	211.6
Cordia dentata	(1) NA (2) NA	(1) 140 *, 60 ** (2) 200 *, 60 **	(1) 45 (2) 32	58%	8.3	178.9
Jatropha curcas	(1) NA (2) NA	(1) 150 *, 60 ** (2) NA	(1) 45 (2) 32	53%	8.8	179.9
Bursera simaruba	(1) NA (2) NA	(1) 140*, 60 ** (2) 200 *, 60 **	(1) 45 (2) 32	0%	0	0
*: cuttings in crib wall **: cuttings in living wooden grid.						
(b) RIO BLANCO: Nicaragua: Construction Jan 2006: **(1)** SBE **(2)** SBE **(3)** WBE						
Erythrina fusca	(1) NA (2) 373 (3) 1116	(1) 200 (2) 90 (3) 130	18	14%/42% *	2.2/3.5 *	82.3/282.8 *
Tabebuia rosea	(1) NA (2) 46 (3) 4	(1) 200 (2) 90 (3) 130	18	63%	1.9	88.7
Gliciridia sepium	(1) NA (2) 21 (3) NA	(1) 200 (2) 90 (3) NA	18	100%	2.68	134.1
* The second value of rooting, average diameter and length shows the value for the highest shoot.						
(c) S. DOMINGO: Ecuador: Construction July 2010: **(1)** SBE **(2)** WBE						
Brugnansia versicolor	(1) 540 (2) 48 **	(1) 60 (2) 100	5	88%	12.1	40.4
Euphorbia cotinifolia	(1) 200 (2) NA	(1) 60 (2) NA	5	41%	10.1	58.1
Malaviscus pendulifloris	(1) 1390 (2) 488 **	(1) 60 (2) 100	5	92%	11.9	71.8
Trichanthera gigantea	(1) 650 (2) 648 *	(1) 60 (2) 200	5	73%	12.4	40.8
*: cuttings in crib wall **: cuttings hedge brush layers.						

The plant species used at the sites in Santo Domingo (Ecuador) were monitored 5 months after the implementation of the cuttings. At this time *Euphorbia cotinifolia* showed an average rooting percentage of 41%. The development of the rooting of *Trichanthera gigantea* (73%), *Brugnansia versicolor* (88%) and *Malaviscus pendulifloris* (92%) was satisfactory. According to Preti F. and Petrone A. [24] at this site one of the primary influences hindering a more rapid development of the cuttings was the usage of the construction area as pastureland by a neighbor, thereby diminishing the sprouting of the cuttings significantly.

Efficiency

- *Did the constructions at the Leading Sites effectively halt soil erosion and resolve the initial problem?*

The efficiency of the constructions in the Leading Sites was assessed as *high* in 74% of the interventions (23), in 10% (3) as *moderate* and in 3% (1) as *low*. For the remaining 13% (4) information was not available due to missing data (2) or the only recently completed construction of the interventions (2) (Table 10).

Table 10. Efficiency of SWBE constructions at the Leading Sites.

	EFFICIENCY					
	Soil Bioengineering		Water Bioengineering		**TOTAL**	
Elevated	13	68%	10	83%	23	74%
Moderate	3	16%	-	-	3	10%
Low	-	-	1	8%	1	3%
Not available	3	16%	1	8%	4	13%
TOT.	**19**	**100%**	**12**	**100%**	**31**	**100%**

Sustainability

- *Are the implemented SWBE constructions at the Leading Sites able to sustain themselves?*

The sustainability of the constructions has been assessed as *high* in 94% (29), as *moderate* in 3% (1) and as *low* in 3% (1) of the cases. To achieve a sustainable SWBE intervention, the site needs to be maintained in the first years of the life cycle, particularly the living part of the construction. These necessities tend to diminish with the development of the biocenosis (Table 11).

Table 11. Sustainability of SWBE constructions at the Leading Sites.

SUSTAINABILITY						
	Soil Bioengineering		Water Bioengineering		TOTAL	
Elevated	18	95%	11	92%	29	94%
Moderate	1	5%	-	-	1	3%
Low	-	-	1	8%	1	3%
Not available	-	-	-	-	-	-
TOT.	**19**	**100%**	**12**	**100%**	**31**	**100%**

Maintenance

- *What measures must be carried out to maintain the plants' functionality and therefore the construction's stability?*

Experience gained from the Leading Sites indicate that maintenance of the vegetation, especially in the first years after the implementation, is important for favorable development of the plants and therefore the stability of the construction. Measures undertaken to ensure this can be the replacement of dead plants, as well as pruning to maintain the flexibility of the trunks.

3.4.4. End of Life Phase

Replicability

- *Are the implemented SWBE constructions at the Leading Sites replicable for local residents?*

The replicability of the constructions was assessed as *high* in 35% (11) and *medium* in 65% (20) (Table 12). Generally, the formation and inclusion of the local residents is important to secure the continuity of the implementation in situ and for the dissemination of SWBE techniques. At various Leading Sites, the social context was often characterized by local communities through an autonomous organization. This fact supports the replicability of the interventions if help from trained, local technicians is provided.

Table 12. Replicability of SWBE constructions at the Leading Sites.

REPLICABILITY						
	Soil Bioengineering		Water Bioengineering		TOTAL	
Elevated	7	37%	4	33%	11	35%
Moderate	12	63%	8	67%	20	65%
Low	-	-	-	-	-	-
Not available	-	-	-	-	-	-
TOTAL	**19**	**100%**	**12**	**100%**	**31**	**100%**

3.5. Assessment of the Components (Step 5 and 6)

Table 13 shows the assessment of the components, which is performed by grading their level of importance, as well as their likely support or constraint for transferability, based on the elaborated results from the Leading Sites.

Table 13. Assessment of the components.

Components	Level of Importance in Central and South America (Take-Up Site)	Likely Support or Constraint for Transferability to the Take-Up Site	Comments
Know-How of SWBE Techniques	High	0	An expert with knowledge of SWBE techniques is needed
Local climate conditions	Medium	0	Possible water shortage or abundance
Botany	High	+2	A key benefit for SWBE in CSA
Hydraulics	Medium	−1	Depends on extreme precipitation
Pedology	Low	−1	Depends on tectonic movements
Materials	Medium	+1	High availability of plants, moderate availability of wooden logs
Qualified Labor	High	−1	Formation courses and training is needed
Equipment and Mechanical Instruments	High	−1	Mostly available in urban areas, more difficult in rural areas
Economic resources	Medium	0	The building-costs of SWBE constructions are economically competitive but not in every case of need money can be raised by municipalities or public administrations
Monitoring	Medium	+1	Important to share experiences within the SWBE field
Efficiency	High	+1	Good technical results can be expected
Sustainability	Medium	+1	SWBE Interventions are able to maintain the efficiency over time; the maintenance can be realized autonomously from the local residents (technically and economically)
Maintenance	Medium	+1	Living part of the construction should be maintained, especially in the first years
Replicability	Medium	+1	Replication is simplified when inhabitants are included in the first construction process (participation)

When assessing the components, based on the experiences made in the Leading Sites, it becomes obvious that the botanical circumstances in Central and South America support the transfer of SWBE strongly (+2). In total, six components, such as Materials, Monitoring, Efficiency, Sustainability, Maintenance and Replicability, were assessed with +1 and therefore indicate moderate support for a transfer. Know-How, Local Climate Conditions and Economic Resources have been evaluated to be without either support or constraint. (0). Further, four components—Hydraulics, Pedology, Qualified Labor and Equipment/Mechanical Instruments—were assessed with −1, as they comprise moderate constraints for the transfer of SWBE to Central and South America. No components with a strong constraint (−2) regarding the transferability was detected.

3.6. Conclusions of the Transferability Analysis (Step 7)

Comparing the assessment values to the level of importance of the components in Central and South America, Qualified Labor and Equipment/Mechanical Instruments appear as probable barriers, as they show high importance but modest constraints for the transfer. To overcome the constraint of sparsely existent Qualified Labor regarding SWBE in Central and South America, workshops or seminars held by experts should be implemented in universities, public agencies or at construction companies. Similarly, the level of importance for the component Equipment/Mechanical Instruments is high, though the assessment shows a modest constraint. Especially in rural areas, site access with heavy equipment can therefore be problematic, which may result in longer construction times.

The component Know-How in SWBE was assessed with high importance but possessed neither support nor constraint in the category of transferability (0) with regard to the Take-Up Site. An increase of the supportive effect (e.g., participation processes within construction projects) could help to spread knowledge regarding SWBE.

The component Hydraulics in water bioengineering was assessed with medium importance but moderate constraint, taking into account extreme rainfall events and a higher water level on riverbanks over a longer period during rainy seasons, possibly exerting forces on a construction which could result in its destruction. To overcome this barrier, massive types of WBE constructions such as double crib walls should be the preferred choice.

The level of importance of the component Efficiency was evaluated as high and its transferability assessed with moderate support. To raise the efficiency of SWBE constructions in Central and South America, additional experience could benefit further positive development of the discipline.

The assessment of the component Pedology could be improved by clarifying the influence of earthquakes on SWBE constructions. The Local Climate Conditions have to be considered when implementing SWBE at new sites. In Central and South America, it may be challenging to receive sufficient Economic Resources for erosion protection projects. Nonetheless, experience has shown that the construction costs of SWBE are lower than the costs for equivalent civil engineering constructions.

Supporting key factors for the transfer were detected within the components Materials, Monitoring, Sustainability, Maintenance and Replicability. The most influencing key factor of success is the component Botany, as the number of usable plant species for SWBE is high in Central and South America. In some cases, the usage of fast-growing plant species could compensate e.g., the lack of equipment, qualified labor, efficiency or economic resources.

A graphical overview of the analysis is shown in Figure 15.

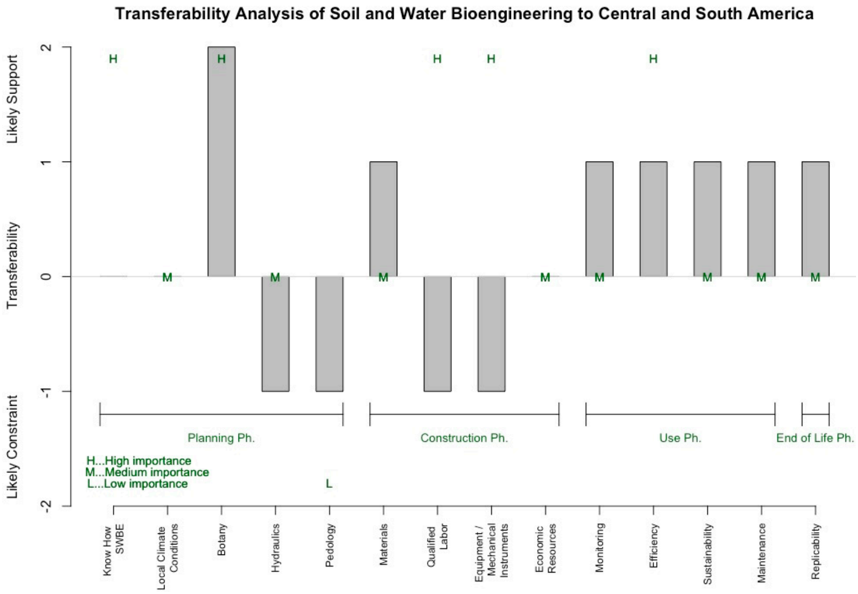


Figure 15. Comparison of level of importance and assessment value of the components.

4. Discussion

In general, the transferability analysis undertaken supports the assumption that SWBE techniques can be transferred to Central and South America on a large scale. Challenges could appear in the Planning Phase when superficial techniques are planned in locations, where massive types should have been preferred and the intervention therefore fails. According to Mickovski and Van Beek [39] the local and regional environmental conditions must be considered carefully in order to create a sustainable system with SWBE.

In Central and South America, the most important considerations are therefore the increasing hydraulic forces with higher discharge during extreme rain events at water bioengineering constructions and pedologic aspects, which could influence the consolidation works. During the Construction Phase labor's level of education regarding SWBE, as well as the availability of equipment may influence the success of implementation. With sufficient preparation and education these problems can be sustainably solved.

The control of natural hazards using herbaceous species remains a challenge in areas where technical, socioeconomic and ecological issues are hindering factors [40], especially in rural areas. Nevertheless, success can be achieved when compromises such as longer construction times or manual excavations are taken into consideration. The lack of economic resources in some parts of Central and

South America often results in difficulties towards investing in construction projects carried out for civil protection. Therefore, it is fundamental to investigate techniques of low environmental impact and high socio-economic sustainability, using solutions that are economically sustainable for local communities without dependence upon national or international institutions, as well as to maximize the use of local work power and local materials.

SWBE techniques therefore constitute an effective approach which allows for the obtainment and utilization of socio-economic and environmental advantages. Regarding the availability of plants, the open access plant species database, developed by Perez et al. [41], could be an appropriate instrument towards documenting and detecting vegetation for SWBE in Central and South America in existing and future applications. Generally, depending on the site, native species should be selected to avoid the introduction of invasive neophytes.

An important aspect for a comparison with traditional reinforcement constructions against erosion is the inclusion of an assessment of the construction's endurance as well as its impact on the environment and its eventual disposal. Therefore, a Life Cycle Assessment of SWBE constructions can provide valuable information concerning the entire life cycle of an object, as well as the impact of a construction on the environment, the consumption of resources as well as landscape esthetics.

Von der Thannen et al. [10] states that the hotspot of energy consumption for SWBE constructions are the operating machines. When carrying out the construction process with manual excavation, as was undertaken a number of times in the mentioned Leading Sites, this impact would be significantly reduced. A further important advantage of a living SWBE construction is the development of vegetation during its lifetime, absorbing CO_2 from the surroundings with the plants' growth, as well as the vegetations' filtering capacity along surface waters.

5. Conclusions

This study has demonstrated that a successful implementation of SWBE in Central and South America is possible. Very important will be the implementation of further research on botanical questions regarding e.g., development of various species and the behavior and endurance of inert material in different regions and climate conditions. To gain further knowledge on the performance of SWBE constructions in Central and South America one option would be to include local universities and companies to implement experimental and in situ experiences. Further, the European status quo of knowledge in SWBE can support the development of the discipline in Central and South America, but must be analyzed and carefully adapted to the needs of the region of interest. Generally, under European conditions a simple revegetation is often sufficient to stop erosion while in some parts of Central and South America the implementation of more massive constructions e.g., a living wooden double crib wall would be more appropriate, depending on the overall conditions, such as the amount of rainfall during extreme events or geological processes such as tectonic movements. The influence of earthquakes on the SWBE techniques and their stability is in need of further study and clarification.

However, the most important aspect will be long-term experience acquired when applying SWBE techniques in addition to follow-up monitoring, as these provide the possibility of reviewing and adapting the constructions towards improving results. Therefore, the organization and inclusion of the local residents and their participation during the planning and construction, as well as in the maintaining process, can also create a positive impact on the development of the scientific field.

The participation processes can highlight the benefits of the constructions in the minds of the residents, which may lead to increased personal identification, protection and good maintenance of the site instead of e.g., cutting the sprouts or using the inert materials for personal purposes. To be able to apply SWBE in Central and South America thoroughly, the creation of a dedicated network, as well as a constant exchange of practical experience and new insights will be factors importance.

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References

1. United Nations Office for Disaster Risk Reduction (UNDRR). *Global Assessment Report on Disaster Risk Reduction*; UNDRR: Geneva, Switzerland, 2019.
2. Petrone, A.; Preti, F. *Ingenieria Naturalistica en Centroamerica, Manuali Tecnici per la Cooperazione allo Sviluppo*; Istituto Agronomico per l'Oltremare, Società Editrice Fiorentina: Firenze, Italy, 2005; p. 108.
3. European Commission. The EU and Nature-Based Solutions. Available online: https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en (accessed on 1 December 2020).
4. Stokes, A.; Sotir, R.; Chen, W.; Ghestem, M. Soil bio- and eco-engineering in China: Past experience and future priorities. *Ecol. Eng.* **2010**, *36*, 247–257. [CrossRef]
5. Rauch, H.P.; Rey, F.; Graf, F.; Preti, F. NH10.4/BG2.18/GM4.4/SSS1.12—Mitigating against natural hazards: Biological contribution to sustainable soil bio-engineering in a changing world (coorganized). In Proceedings of the European Geosciences Union General Assembly, Vienna, Austria, 3–8 April 2011.
6. Lammeraner, W.; Rauch, H.P.; Laaha, G. Implementation and monitoring of soil bioengineering measures at a landslide in the Middle Mountains of Nepal. *Plant Soil* **2005**, *278*, 159–170. [CrossRef]
7. Florineth, F. Stabilization of gullies with soil—Bioengineering methods in the Alps and in Nepal. In *Gully Erosion under Global Change*; Li, Y., Poisen, J., Valentin, C., Eds.; Sichuan Science and Technology Press: Chengdu, China, 2004; pp. 315–339.
8. Florineth, F. *Pflanzen statt Beton—Handbuch zur Ingenieurbiologie und Vegetationstechnik*; Patzer: Berlin, Germany, 2004.
9. Weissteiner, C.; Schenkenbach, N.; Lammeranner, W.; Kalny, G.; Rauch, H.P. Cutting diameter on early growth performance of purple willow (*Salix purpurea* L.). *J. Soil Water Conserv.* **2019**, *74*, 380–388. [CrossRef]
10. Von der Thannen, M.; Hoerbinger, S.; Paratscha, R.; Smutny, R.; Lampalzer, T.; Strauss, A.; Rauch, H.P. Development of an environmental life cycle assessment model for soil bioengineering constructions. *Eur. J. Environ. Civil Eng.* **2017**. [CrossRef]
11. Schlüter, U. Zur Geschichte der Ingenieurbiologie. *Landschaft und Stadt* **1984**, *16*, 2–9.
12. Schiechtl, H.M. *FAO Watershed Management Field Manual. Vegetative and Soil Treatment Measures*; FAO Conservation Guide; Food and Agriculture Organization (FAO): Italy, Rome, 1985; Volume 13/1.
13. Evette, A.; Labonne, S.; Rey, F.; Liebault, F.; Jancke, O.; Girel, J. History of bioengineering techniques for erosion control in rivers in western Europe. *Environ. Manag.* **2009**, *43*, 972–984. [CrossRef]

14. Ghimire, S.K.; Karki, K.K. Mitigation of soil erosion hazards through bio-engineering: A case study of Mid-Himalaya, Nepal. In *Eco-and Ground Bio-Engineering: Use of Vegetation to Improve Slope Stability: Proceedings of the International Conference Eco-Engineering, Thessaloniki, Greece, 13–17 September 2004*; Stokes, A., Spanos, I., Norris, J.E., Cammeraat, L.H., Eds.; Springer: Dordrecht, The Netherlands, 2007.
15. Reubens, B.; Windey, J.; Danjon, F.; Poesen, J.; Muys, B. Root system architecture of woody species important for erosion control in Tigray, Northern Ethiopia. In Proceedings of the 4th International Symposium on Dynamics of Physiological Processes in Roots of Woody Plants, Bangkor, UK, 16–19 September 2007.
16. Sutili, F.J.; Durlo, M.A.; Bressan, D.A. Bio-technical capability of "sarandi-branco" (*Phyllanthus sellowianus* Müll. Arg.) and "vime" (*Salix viminalis* L.) for revegetation water course edges. *Ciencia Florest.* **2004**, *14*, 13–20. [CrossRef]
17. Rivera Posada, H.R.; Sinisterra Reyes, J.A. *Uso Social de la Bioingeniería para el Control de la Erosión Severa*; Corporación Autonoma Regional del Valle del Cauca: Cali, Coumbia, 2006.
18. Petrone, A.; Preti, F. Suitability of soil bio-engineering techniques in Central America: A case study in Nicaragua. *Hydrol. Earth Syst. Sci.* **2008**, *12*, 1241–1248. [CrossRef]
19. Petrone, A. Realización de obras de mitigación con técnicas de ingenería naturalistica en el Cerro Musún-Río Blanco, published in the framework of the DIPECHO Project "Sistema de prevención antes desatres naturales en 7 comunidades rurales del area del cerro Musún", Nicaragua 2006.
20. Petrone, A.; Matassoni, P.; Preti, F. Sperimentazioni con talee di specie autoctone in interventi di ingegneria naturalistica in Nicaragua. *Quaderni di Idronomia Montana* **2006**, *26*, 477–488.
21. Petrone, A.; Ferrari, R.; Preti, F. La rinascita dell'America. *Acer-Il Verde Ed.* **2005**, 74–79.
22. Borja, P.; Vanacker, V.; Alvarado, D.; Govers, G. Restoration of badlands through applying bio-engineering techniques in active gully systems: Evidence from the Ecuadorian Andes. In Proceedings of the European Geosciences Union General Assembly, Vienna, Austria, 22–27 April 2012.
23. Petrone, A.; Preti, F. Soil bio-engineering for risk mitigation and environmental restoration in a humid tropical area. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 239–250. [CrossRef]
24. Preti, F.; Petrone, A. Soil bio-engineering for watershed management and disaster mitigation in South America: Local species survivability and growth rates in Ecuador. *iFOREST Biogeosci. For.* **2013**, *6*, 95–99. [CrossRef]
25. Acharya, M.S.; Lammeranner, W. How to Select the Appropriate Techniques and Suitable Plant Species for Soil Bioengineering Works?—An Application Example from Nepal. In *Geophysical Research Abstracts*; EGU General Assembly: Vienna, Austria, 2011; Volume 13, EGU2011-11381.
26. Maffra, C.R.B.; Sousa, R.d.S.; Sutili, F.J.; Pinheiro, R.J.B. Evaluation of Live Cuttings Effect on Slope Stability. *Floresta e Ambiente* **2019**, *26*. [CrossRef]
27. Maffra, C.R.B.; Sutili, F.J. The use of soil bioengineering to overcome erosion problems in a pipeline river crossing in South America. *Innov. Infrastruct. Solut.* **2020**, *5*, 24. [CrossRef]
28. 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]
29. Gyergyay, B.; Boehler-Baedeker, S. Transferability Analysis: Innovative Sustainable Urban Solutions from Europe, Singapore, China and Latin America. Rupprecht Consult. 2014. Available online: http://www.rupprecht-consult.eu/uploads/tx_rupprecht/SOLUTIONS_D1.3_Transferability_Analysis.pdf (accessed on 30 August 2020).
30. Bößner, S.; Suljada, T.; Johnson, F.X.; Bruno, A.; Rodriguez Morales, J.; Hu, M.; Lakshmi Bhamidipati, P.; Haselip, J. Policy transfer processes and renewable energy penetration: A comparative analysis of Peru, Thailand, and Uganda. *Sustain. Earth* **2020**, *3*, 1–18. [CrossRef]
31. Schloemer, T.; Schröder-Bäck, P. Criteria for evaluating transferability of health interventions: A systematic review and thematic synthesis. *Implement. Sci.* **2018**, *13*. No. 88. [CrossRef]
32. Dolowitz, D.P.; Marsh, D. Learning from Abroad: The Role of Policy Transfer in Contemporary Policy-Making. *Governance* **2000**, *13*, 5–23. [CrossRef]
33. Petrone, A. Identificación de practicas inovadoras para la mitigación del riesgo a nivel regional latinoamericano con enfoque de ingenieria naturalistica. *Inf. CRIC* **2013**.
34. Cornelini, P. La palificata viva Latina. *Acer-Il Verde Ed.* **2007**, 61–65.
35. Cornelini, P.; Ruggieri, L.; Crocetti, C. Palificata viva Latina. *Acer-Il Verde Ed.* **2009**, 61–63.

36. Zentralanstalt für Meteorologie und Geodynamik (ZAMG). Available online: http://www.zamg.ac.at/geophysik/Reports/Monatsberichte/K16-04.pdf (accessed on 14 June 2020).
37. Hörbinger, S. A Pull Out Test of Phyllanthus Sellowianus and Sebastiania Schottiana and Development of Soil Bioengineering Constructions in Southern Brazil. Master's Thesis, University of Natural Resources and Life Sciences, Vienna, Austria, 2013.
38. Sauli, G.; Binazzi, P. *Linee Guida per Capitolati Speciali per Interventi di Ingegneria Naturalistica*; Ministero dell'Ambiente e della Tutela del Territorio: Rome, Italy, 2006.
39. Mickovski, S.B.; Van Beek, L.P.H. A decision support system for the evaluation of eco-engineering strategies for slope protection. *Geotech. Geol. Eng.* **2006**, *24*, 483–498. [CrossRef]
40. Phillips, C.J.; Rey, F.; Marden, M.; Lièbault, F. Revegetation of steeplands in France and New Zealand: Geomorphic and policy responses. *N. Z. J. For. Sci.* **2013**, *43*, 1–16. [CrossRef]
41. Perez, J.; Condes Salazaar, R.; Stokes, A. An open access database of plant species useful for controlling soil erosion and substrate mass movement. *Ecol. Eng.* **2017**, *99*, 530–534. [CrossRef]

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7.2 Article 2

Analyzing fire severity and post-fire vegetation recovery in the temperate Andes using earth observation data.

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Article

Analyzing Fire Severity and Post-Fire Vegetation Recovery in the Temperate Andes Using Earth Observation Data

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Abstract: In wildfire areas, earth observation data is used for the development of fire-severity maps or vegetation recovery to select post-fire measures for erosion control and revegetation. Appropriate vegetation indices for post-fire monitoring vary with vegetation type and climate zone. This study aimed to select the best vegetation indices for post-fire vegetation monitoring using remote sensing and classification methods for the temperate zone in southern Ecuador, as well as to analyze the vegetation's development in different fire severity classes after a wildfire in September 2019. Random forest classification models were calculated using the fire severity classes (from the Relativized Burn Ratio—*RBR*) as a dependent variable and 23 multitemporal vegetation indices from 10 Sentinel-2 scenes as descriptive variables. The best vegetation indices to monitor post-fire vegetation recovery in the temperate Andes were found to be the Leaf Chlorophyll Content Index (LCCI) and the Normalized Difference Red-Edge and SWIR2 (NDRESWIR). In the first post-fire year, the vegetation had already recovered to a great extent due to vegetation types with a short life cycle (seasonal grass-species). Increasing index values correlated strongly with increasing fire severity class (fire severity class vs. median LCCI: 0.9997; fire severity class vs. median NDRESWIR: 0.9874). After one year, the vegetations' vitality in low severity and moderate high severity appeared to be at pre-fire level.

Keywords: wildfire; remote sensing; Sentinel-2; fire severity; vegetation indices; random forest; vegetation recovery; northern South America

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1. Introduction

While the analysis of the fourth-generation global fire emission database (GFED4) [1], between the years 2000 and 2012, shows a modest decrease in global wildfire incidences, the amount of burned areas in most environments increased, whereby the most affected ecosystems were savannahs, open shrubland and subtropical grasslands. Climate change and the resulting extreme weather events, such as droughts, influence the intensity of fires. In total, 13.3 million individual fires, globally, were reported by the Global Fire Atlas between 2003 and 2016 [2]. The estimated direct average carbon emission into the atmosphere from the burned biomass between 1997 and 2016 was 2.2×10^{15} g of carbon per year (Pg C yr^{-1}) [3], whereby the process of decay of the burned trunks in some regions indirectly releases further emissions years after the wildfire event [4]. Supporting measures for the fast recovery of the vegetation after a wildfire are therefore important to bind CO_2 from the atmosphere, and several authors have conducted work on this topic [5–8]. The fire severity (FS) is an important indicator regarding the post-fire vitality of the affected vegetation, as well as probable necessary supportive measures for recovery. Space Agencies, such as NASA [4] and ESA (Copernicus program with two equal satellites—Sentinel 2A and 2B) [9], document the wildfire phenomena around the planet with earth observation data. They deliver an important and open access base to elaborate remotely sensed information regarding FS, as well as the recovery of vegetation. In many affected areas, the increase in the intensity of the fires decreases the ability to resprout, as the soil seed banks are diminished during the wildfire [10], or vegetation parts at the subsurface, such as rhizomes, are damaged by the heat. The required time of the vegetations' recovery depends on the vegetation type itself and differs strongly between forest areas and grassland due to their different life cycles. Certain weed species found in some fire prone areas, particularly in Savannahs, are adapted to frequent wildfires and are therefore stimulated positively by heat and smoke [11], and some even require fire to geminate [12]. FS is therefore an important parameter when assessing the impact of a wildfire on vegetation. For the definition of the FS through earth observation data, the differenced Normalized Burn Ratio (*dNBR*) [13] derived from pre- and post-fire satellite imagery, as well as the Relativized Burn Ratio (*RBR*) [14] in cases of areas with low or sparse vegetation before the fire event [15], are frequently used spectral indices. They aim to determine the extent of the wildfire area, as well as the degree of change in vegetation caused by the fire [13]. Further, the mentioned burn ratios help to immediately identify fire effects, as well as to assess vegetative recovery potential and delayed mortality during the following growing season [13]. However, follow-up monitoring of vegetation recovery in post-fire years is usually undertaken using vegetation indices (VI), such as the Normalized Difference Vegetation Index (NDVI) [16], or the Soil Adjusted Vegetation Index (SAVI) [17], etc., calculated from multitemporal satellite scenes from the affected area over a number of years. These VIs map the vitality of the vegetation and serve municipalities, planning parties or forest management institutions to classify and define the development or stadium to which extent the burnt area recovered, and maintenance steps can be evaluated accordingly. The maintenance of fire prone areas to support vegetation recovery after wildfires can speed up the recovery process of the vegetation by up to 10 years [18]; however, accurate measures differ according to region, climate, as well as vegetation composition, and are therefore an important topic to work on [5]. Various investigations address the vegetation's recovery after wildfires in the Mediterranean area [19,20], northern America [8,21,22], Siberia [23], as well as Australia [24]. Further studies were developed for the humid tropics [5], as well as the Páramo region [25–27], the latter covering areas in northern South America from Venezuela, Colombia, Ecuador, and Peru. In Ecuador, scientific studies have been conducted using remote sensing methods e.g., modeling and simulation of wildfires next to urban areas [28], forest fire susceptibility monitoring using machine learning techniques [29], as well as fire severity effects on physical-chemical soil properties in southern Ecuador [30]. To the current knowledge of the authors, scientific publications defining the best VIs for the monitoring of vegetation recovery in post-fire conditions are not existent. Moreover, studies investigating the correlation between FS and vegetation recovery in the temperate climate (no dry season, warm summer—Cfb, Köppen-Geiger-Classification) in southern Ecuador were not found. The Loja province is covered by various climate zones, which leads to different combinations of vegetation and different needs when developing effective restoration methods after wildfires. Therefore, further studies are required to better understand and predict the responses of vegetation to fire, as well as to define the restoration measures necessary in the area. As already mentioned, VIs derived from remote sensing methods are a useful and open access tool to better understand the post-fire vegetation recovery. However, the choice to use an appropriate VI for vegetation recovery monitoring depends on the vegetation composition and climate zone of the area in question, as different VIs provide different levels of sensitivity for grassland, canopy moisture or plant structures [31]. For post-fire vegetation recovery monitoring using VIs, the correlation to FS is an important aspect, as it strongly influences the regrowth rate. The present study investigates the best VIs for fire prone areas at the Cfb climate zone in southern Ecuador using random forest classification models. Furthermore, the autonomous vegetation recovery capacity is assessed using remote sensing techniques by analyzing a fire event which occurred in September 2019 in the canton Quilanga. The results can support municipalities or planning parties to better understand the vegetation's behavior in post-fire conditions, as well as to estimate whether recuperating measures are necessary at the area in question.

The primary objectives of the present investigation were:

- To elaborate the FS of the fire event in September 2019 at the El Saco basin.
- To identify the most appropriate VIs derived from Sentinel-2 (S2) images for the monitoring of vegetation recovery after wildfires in the temperate climate zone in southern Ecuador.
- To assess the vegetation recovery in the different FS classes based on the previous selection of the best VIs for post-fire monitoring at the area in question.

2. Materials and Methods

2.1. Study Site

The investigated wildfire area is located in a mountainous, temperate zone (Cfb) in the southern Andes (Sierra) of Ecuador in the canton Quilanga, which is part of the province of Loja on the Peru border. It is characterized by grass- and shrub-land, as well as some forest patches with non-native tree species, such as pine or eucalyptus, which tend to dry out the soil and therefore influence the development of native vegetation. Further, coffee production, farming and pastureland characterize the landscape. In the area of concern, the precipitation value is approximately 1100 mm per year, whereby the months from December to April/May are characterized by intense rain events [32]. From June to November, the risk of fires increases due to the decline in precipitation; in recent years, three intense wildfires have been reported: in 2012 (Parroquia Fundochamba, sector Collingora, Quilanga); 2016 (Parroquia Fundochamba, sector Guaguasaco, Quilanga); and the investigated event, in 2019 [33]. The last wildfire, caused by farmers intending to prepare farmland in the beginning of September 2019, affected more than 8000 ha and lasted for more than two weeks (Figure 10). For the present study, the basin of the river El Saco (Figure 1), with a linear distance of 2500 m southeast from the center of Quilanga to the outflow point, was chosen. It covers an area of 984.3 ha, reaches from 1520 m at the outflow point to 2680 m a.s.l. at the highest point and includes one main and two micro basins; the length of the mainstream is 4.83 km. Table 1 shows the different climate zones in Loja/Ecuador according to the Köppen-Geiger-Classification.

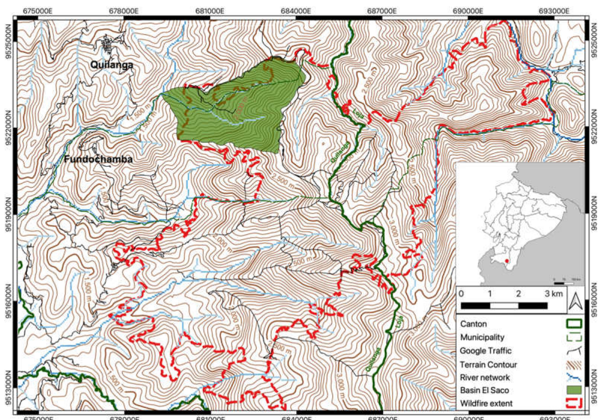

Figure 1. Location and extent of the wildfire area (red), as well as the river El Saco basin (green) in Quilanga, Ecuador; Background: contour map of elevation and river network derived from DEMs (credit: Marc Souris, IRD), Road network: Google Traffic.

Table 1. Climate zones in Loja (Ecuador), according to Köppen-Geiger-Classification.

Climate Zones in the Province of Loja	
Aw	Tropical, savannah
BSh	Arid, steppe, hot
BWh	Arid, desert, hot
Cfb	Temperate, no dry season, warm summer
Cfc	Temperate, no dry season, cold summer
Csb	Temperate, dry summer, warm summer
Cwb	Temperate, dry winter, warm summer
ET	Polar, tundra

2.2. Workflow

The investigation of the wildfire area in this temperate zone of southern Ecuador is based on various elaborations from the data, gained remotely (Figure 2). In the first step the *RBR*, the FS was calculated, providing the basis for further evaluation. The second step consisted of the identification of the best VIs for the monitoring of vegetation recovery in the study area. In total, 23 VIs (Appendix A, Table A1) were calculated from atmospherically corrected, multitemporal S2 scenes (Level 2A products). In addition, random forest classification models (with feature selection) describing the FS class were set up for every used S2 scene at the El Saco basin to identify the most influencing VIs within the models. In the third step, the selected VIs were used for the analysis of the post-fire vegetation recovery within the different FS classes.

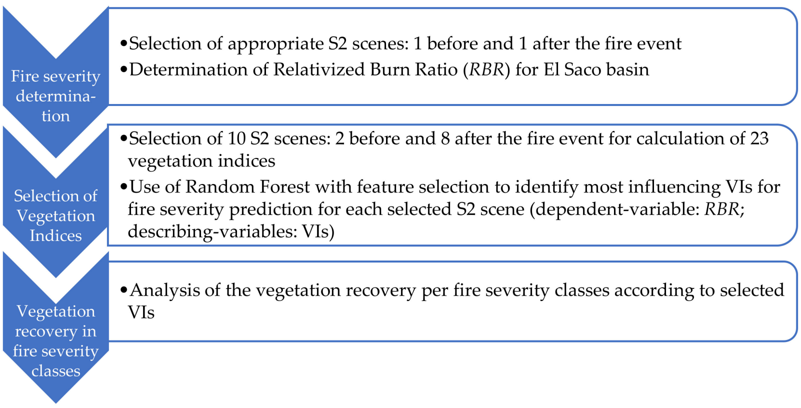

Figure 2. Workflow of the analysis of vegetation recovery at each fire severity class in the temperate (Cfb) zone in northern South America.

2.2.1. Elaboration of the Fire Severity

For the present investigation, the FS was assessed and remotely sensed from S2 images with a spatial resolution of 10 m. Atmospherically corrected S2 images (Level 2A products), taken on 31 July 2019 and 29 September 2019, were selected for the evaluation, considering the cloud coverage at the time of the recordings above the El Saco basin. In the first step, the *NBR* [34] was calculated for both images using the freely accessible SNAP program. Furthermore, the *dNBR* between the two scenes, as well as the *RBR* (Equation (1) [15]), were calculated.

$$RBR = \left(\frac{dNBR}{\left(NBR_{pre-fire} + 1001 \right)} \right) = \left(\frac{NBR_{pre-fire} - NBR_{post-fire}}{\left(NBR_{pre-fire} + 1001 \right)} \right) \quad (1)$$

A water and cloud mask of the images was created with the help of the *NDWI* (Equation (2) [15]) as water bodies can have a similar *NBR* difference.

$$NDWI = \frac{Green - NIR}{Green + NIR} = \frac{B3 - B8}{B3 + B8} \tag{2}$$

As the absolute *dNBR* may misclassify pixels in areas with little vegetation before the fire event and because the first image of the El Saco basin was captured during the season with less precipitation, the *RBR* was chosen for further usage in the following models. After exporting the calculated *RBR* image as a GeoTIFF file, the pixels were classified in QGIS, based on fire intensity (Table 2). The higher the value in a pixel, the lower the vitality of the vegetation in that location.

Table 2. Classification of the fire severity from the Relativized Burn Ratio according to United States Geological Survey—USGS [35].

Classification	*RBR*-Value
High regrowth	−0.500 to −0.251
Low regrowth	−0.250 to −0.101
Unburned	−0.100 to 0.099
Low severity	0.100 to 0.269
Moderate low severity	0.270 to 0.439
Moderate high severity	0.440 to 0.659
High severity	0.660 to 1.300

2.2.2. Identification of the Best VIs for the Monitoring of Vegetation Recovery in Different Fire Severity Classes

In the study area, no supporting post-fire measures regarding vegetation or erosion protection were carried out by the municipality. Therefore, the natural recovery capacity of the vegetation located at the El Saco basin, without anthropogenic influence, within the first two years after the fire event, could be analyzed. Ten atmospherically corrected Level 2A products (two before and eight after the fire event) of the S2A and S2B platform were chosen, taking into consideration cloud coverage and the change of vegetation in the area over a year. From the eight scenes chosen after the fire event, two scenes were selected within the first two months after the fire event (Nr. 3, 4; Table 3) to monitor the short-term development of the vegetation. Moreover, three scenes were chosen for each of the following years (2020: Nr.5–7 and 2021: Nr.8–10; Table 3), starting from the end of the rainy season (April/May) until one and two years after the fire event.

Table 3. Summary of selected Sentinel-2 scenes; Granule: T17MPR.

Nr.	Sentinel-2 Satellite	Date	Sun Zenith Angle	Sun Azimuth Angle
1	A	6 June 2019	35.06	39.19
2	B	31 July 2019	33.31	47.13
		Fire Event		
3	B	29 September 2019	21.12	86.18
4	B	18 November 2019	24.54	129.68
5	A	21 April 2020	28.19	54.44
6	A	10 June 2020	35.50	38.95
7	B	24 August 2020	28.19	57.90
8	A	26 May 2021	33.78	40.46
9	A	5 July 2021	36.06	40.83
10	A	3 September 2021	25.91	63.91

Spectral indices derived from satellite images are widely used to map burned areas [36–38], as well as to monitor the vegetation's development after a fire event [23,37,39,40]. For this study, 23 VIs (Appendix A, Table A1) were calculated for every S2 scene and databases were created by extracting the VI-values according to the FS class (unburned, low severity, moderate low severity, moderate high severity) derived from the *RBR* at the El Saco basin. To determine the best VIs for the vegetation monitoring at the study area, a pixel-based classification was carried out using the Random Forest approach, after Breiman [41], with the FS class from the *RBR* (classified after USGS [35]) as the dependent variable. This approach is frequently used for FS mapping [16], as well as for the classification of vegetation or tree species [42]. For this study, the parameter *mtry* (number of predictors samples randomly for each node) was taken as the square root of the number of input parameters and *ntree* (number of trees) was set to 500 at each classification (default values). In addition, a recursive feature selection process was applied using the mean decrease in accuracy (MDA), which is used to measure the performance of the model without a specific describing variable. The removal of a variable with a high MDA value would cause the model to lose accuracy in prediction. The higher the MDA value, the higher the importance of the variable to the accuracy of the model. Further, the results of the classification models were assessed by the out of bag (OOB) error [42]. The classification of the FS class with feature selection was run with every database containing the data of the VIs of every S2-scene. The BEST model (according to the overall accuracy (OA)) was chosen to be representative for the respective date. The variables (=VIs) of these BEST models were checked regarding matching VIs between the different dates to obtain a preselection of VIs. To prove that these matching VIs are suitable for post-fire vegetation monitoring in the temperate Andes, new databases were set up for model calculation at each date, containing the FS class as the dependent variable and the matching VIs as the describing variables. Further, four additional databases were set up for the scenes of the years: (I) 2020; (II) 2021; (III) eight scenes (not using the scenes nr. 2 and 3, which were part of the *RBR* calculation); and (IV) all ten scenes containing the FS class as the dependent variable and the matching VIs as the describing variables. With these 10 single-date and four multi-date databases, the Random Forest classification of the FS class was repeated and the two best performing VIs in these models were used to analyze the vegetation development in the FS classes. Figure 3 illustrates the identification process of the best VIs for the monitoring of the post fire vegetation recovery.

2.2.3. Analysis of Vegetation Recovery in Different Fire Severity Classes

The vegetation recovery in the different FS classes at the El Saco basin was studied using boxplot diagrams, descriptive statistics, and time series. The VIs selected in the previous step were analyzed at one pre- and three post-fire moments from 2018 to 2021, (around the month of the fire event, with a maximum difference of two months due to cloud coverage) to understand the post-fire development of the vegetation at the El Saco basin in the different FS classes. Further, the delta of the VIs for the first, the second, and the first two post-fire years was calculated and statistically analyzed. While the analysis of the VIs' delta shows the recovery at each FS class within the first and the second post-fire year, another important question was whether the pre-fire level of the vegetation's vitality could be obtained again according to the VIs. As it was not possible to obtain cloud free S2 scenes from the El Saco basin for the same month over four years (2018–2021), the median values at the unburned area were used as reference values to understand the phenological change, which influenced the post-fire images. The pre-fire medians of the VI values at each FS class were set to a reference level of 100% and the difference in the following years was calculated as percentage points [PP].

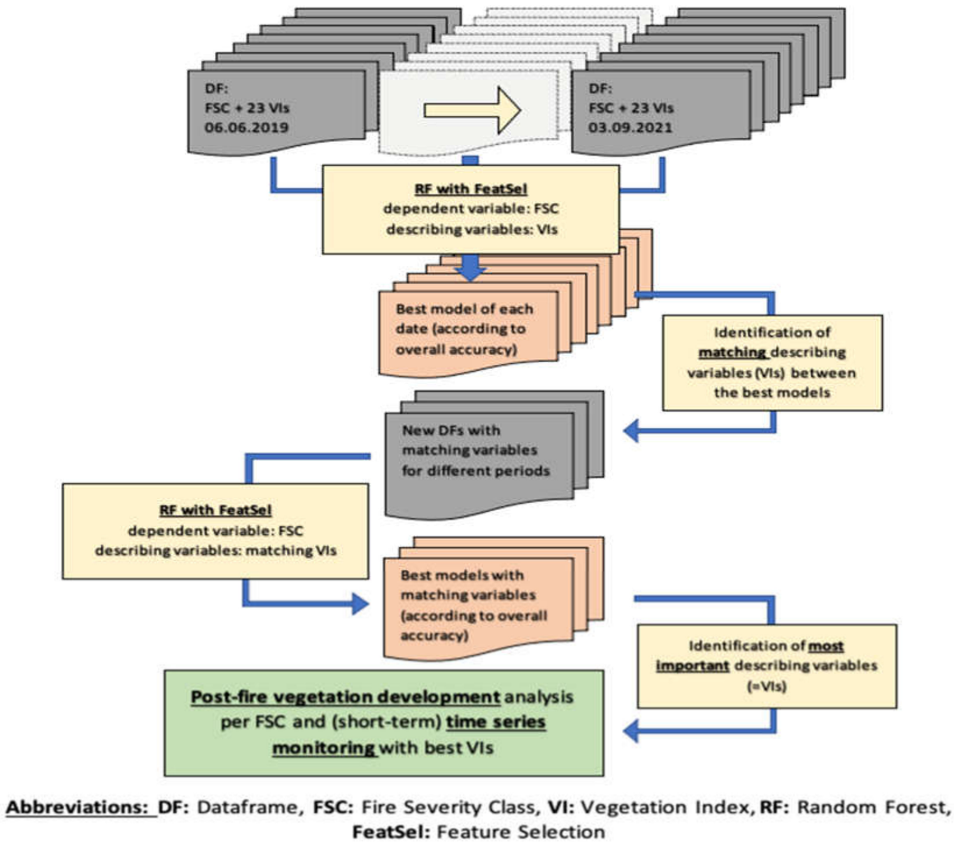

Figure 3. Identification of vegetation indices for post-fire vegetation development analysis per fire severity class and time series monitoring in the temperate Andes.

3. Results

3.1. Elaboration of the Fire Severity

The FS elaborated from S2 images with the formula of the *RBR* is shown in Figure 4a,c. From the total size of the El Saco basin (984.30 ha), 781.25 ha and, therefore, 79.37% were affected by the fire event. In the northeastern part of the basin, 0.07% and 0.30% of the pixels were classified as “high regrowth” and “low regrowth”. These fragments can be defined as misinterpretation as the calculated water and cloud mask (*NDWI*) did not cover some parts of the cloud shadows and thus led to this misclassification. The class “unburned” (UB) covers 4.54% and was classified mainly along the river courses of the basin. Further, “low severity” (LS) was determined at 18.82% of the pixels. The biggest part of the area was classified as “moderate low severity” (MLS), with 54.74%, and the class “moderate high severity” (MHS) achieved 21.38%. The maximum FS class “high severity” (HS) was classified at 0.15% of the burned area in the El Saco basin (Figure 4b). With the exception of the mentioned misclassification due to cloud shadows, the field investigation mostly confirmed the FS map. The vegetation in areas with HS or MHS showed the complete destruction of the biomass on the surface. MLS or LS were classified in areas where higher vegetation, such as shrubs or trees, were burned at the base with intact, green parts on the crown, as well as in areas of the grassland, where some ferns and grass species sprouted again one month after the fire event.

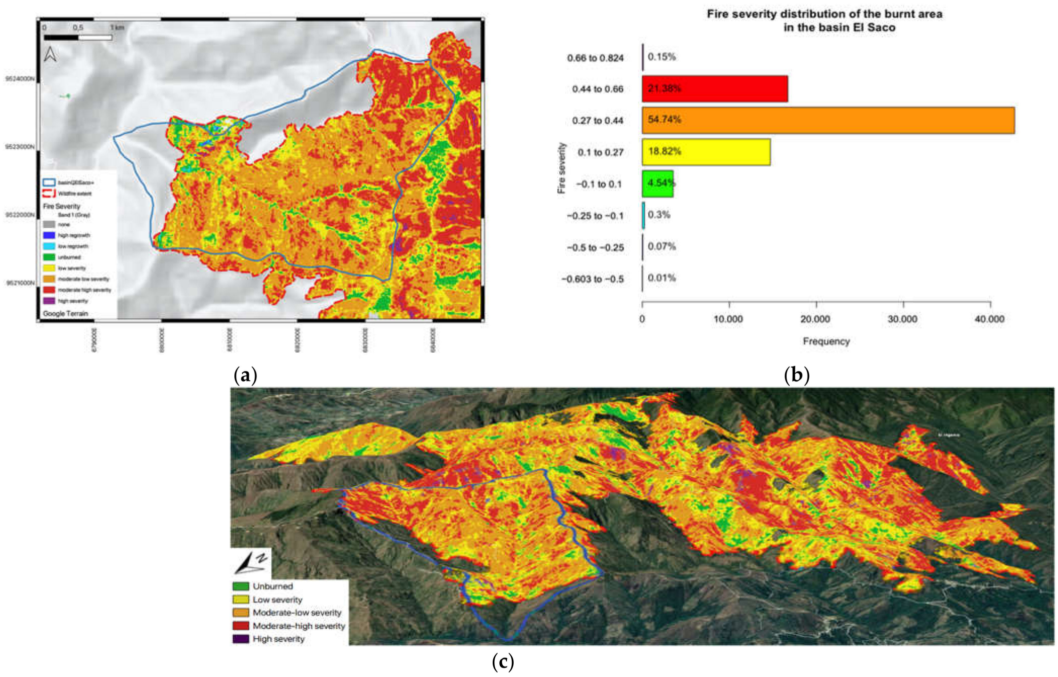

Figure 4. (**a**) Fire severity after the wildfire in September 2019 at the El Saco basin, canton Quilanga/Ecuador. Base map: Google Terrain; (**b**) Distribution of the fire severity within the burnt area of El Saco at the canton Quilanga/Ecuador after the wildfire in September 2019; (**c**) Overview of the wildfire area 2019 from the viewpoint Quilanga in Google Earth Pro.

3.2. Identification of the Best VIs for Post-Fire Monitoring in the Temperate Andes

To identify the best VIs for the monitoring of the vegetation recovery at each FS class, ten BEST simple models using the VIs of each date were calculated (Table 4). The OA resulted between 57.8% and 84.9%, with a median of 63.4%. The most significant model predicting the *RBR* was the one of 29 September 2019 (84.9%), two weeks after the wildfire. This can be explained as this scene was used for the *RBR* calculation, as well as the low time lag from the fire event. The OA of the two scenes before the fire event is around 67% and the worst classified model derives from the S2-scene on 10 June 2020 (OA 57.8%). From the three S2-scenes in 2020 and 2021, the ones at the end of the rainy season achieved an OA of 67.7% and 63.1%, respectively. The number of variables for each BEST model differs due to the applied feature selection function. Therefore, the occurrence of the same Vis in the different BEST models was checked. As a result, the Leaf Chlorophyll Content Index (LCCI), the Normalized Difference Red-Edge and SWIR2 (NDRESWIR), as well as the Red Edge Peak Area (REPA), were part of every model.

To verify that these matching VIs were suitable for post-fire vegetation monitoring at the area in question, new databases were set up containing only LCCI, NDRESWIR and REPA. As a result, the OA ranged between 75.0% and 81.3%, with a median of 76.8%, for these models (Table 5); a minimum increase of 7.8% and a maximum increase of 17.3% in OA compared to the BEST models appeared. The model from September 29, 2019, again showed the highest OA, but decreased by 3.6% compared to the BEST model. While the model from this date achieved 81.3% in OA with the three descriptive variables LCCI, NDRESWIR and REPA, the BEST model used 12 VIs as descriptive variables to achieve an OA of 84.9%.

Table 4. BEST Random Forest models based on OOB results after Feature Selection using 23 Vegetation Indices from single Sentinel-2 data recording dates.

BEST MODELS: Dependent Variable: *RBR*; Descriptive Variables: 23 Vegetation Indices Classification: Random Forest with Feature Selection					
Scene Nr:	**S2 Acquisition Date**	***n* Variables after Feature Selection**	**Split**	**Overall Accuracy**	**Kappa**
1	6 June 2019	4	2	67.1%	0.503
2	31 July 2019	4	2	67.5%	0.508
Fire Event					
3	29 September 2019	12	3	84.9%	0.779
4	18 November 2019	9	3	63.7%	0.444
5	21 April 2020	4	2	67.7%	0.511
6	10 June 2020	6	2	57.8%	0.342
7	24 August 2020	5	2	61.4%	0.408
8	26 May 2021	5	2	63.1%	0.436
9	5 July 2021	5	2	60.6%	0.401
10	3 September 2021	7	2	60.0%	0.383
Result: LCCI, NDRESWIR, REPA were part of every BEST model					

Table 5. Random Forest models using three Vegetation Indices (LCCI, NDRESWIR, REPA) from single Sentinel-2 data recording dates.

MODELS: Dependent Variable: *RBR*; Descriptive Variables: LCCI, NDRESWIR, REPA Classification: Random Forest						
Scene Nr:	**S2 Acquisition Date**	***n* Variables**	**Split**	**Overall Accuracy**	**Change in Accuracy Compared to BEST Models**	**Kappa**
1	6 June 2019	3	1	75.5%	+8.4%	0.636
2	31 July 2019	3	1	75.3%	+7.8%	0.634
Fire Event						
3	29 September 2019	3	1	81.3%	−3.6%	0.725
4	18 November 2019	3	1	76.6%	+12.9%	0.654
5	21 April 2020	3	1	77.0%	+9.3%	0.660
6	10 June 2020	3	1	75.0%	+17.2%	0.628
7	24 August 2020	3	1	76.9%	+15.5%	0.660
8	26 May 2021	3	1	77.0%	+13.9%	0.661
9	5 July 2021	3	1	76.4%	+15.8%	0.651
10	3 September 2021	3	1	77.3%	+17.3%	0.666

The additional model calculations from the databases containing the VIs for the S2-scenes in 2020, 2021, as well as combinations of eight and all ten scenes, helped to understand the change in OA where multitemporal Sentinel scenes were used (Table 6). The best combined models from both individual years showed an OA of approximately 82% using all nine input variables. The model derived from the eight S2 scenes (without the scenes from *RBR* calculation) showed an OA of 83.5%, using 22 variables (of 24). The best combined model from all ten scenes and, therefore, with the ones used for the *RBR* calculation, resulted with an OA of 86.3% (eleven input variables). According to the

MDA of the combined models, the most important input variables were the LCCI and the NDRESWIR. These VIs were used for the monitoring of the vegetation recovery.

Table 6. Best Random Forest models based on OOB results after Feature Selection using three Vegetation Indices (LCCI, NDRESWIR, REPA) from different Sentinel-2 data recording series.

BEST MODELS: Dependent Variable: *RBR*; Descriptive Variables: LCCI, NDRESWIR, REPA Classification: Random Forest with Feature Selection						
Scene Nr:	Vegetation Indices from Different S2 Scenes	*n* Variables after Feature Selection	Split	Overall Accuracy	Kappa	3 Most Influencing Variables According to Mean Decrease Accuracy
5–7	LCCI, NDRESWIR, REPA 3 SC 2020	9	3	82.4%	0.744	LCCI 24 August 2020 NDRESWIR 21 April 2020 LCCI 21 April 2020
8–10	LCCI, NDRESWIR, REPA 3 SC 2021	9	3	82.6%	0.746	LCCI 03 September 2021 LCCI 26 May 2021 NDRESWIR 3 September 2021
1 and 4–10	LCCI, NDRESWIR, REPA 8 SC 2019 to 2021 (no scenes from *RBR* calculation)	22	4	83.5%	0.760	NDRESWIR 21 April 2020 LCCI 18 November 2019 LCCI 26 May 2021
1–10	LCCI, NDRESWIR, REPA 10 SC 2019 to 2021 (with scenes from *RBR* calculation)	11	3	86.3%	0.800	NDRESWIR 31 July 2019 NDRESWIR 29 September 2019 REPA 29 September 2019

3.3. Analysis of the Vegetation Recovery in Different Fire Severity Classes

3.3.1. LCCI and NDRESWIR in One Pre- and Three Post-Fire Scenes

Immediately after the fire event, the two analyzed VIs showed that with the increasing FS class, the lower and the upper quartiles converged, and the median decreased (Appendix A: Tables A2 and A3; Figures 5 and 6). At the VIs from the S2 scene of 24 August 2020, about one year after the fire event, the medians in all four FS classes were higher compared to the pre-fire year; thus, the time difference of two months (August and October) and the phenological development due to the rainy season from December to May must be considered (Section 3.3.3.). Figures 5 and 6 show the boxplots of the VI values per FS class in the different years.

3.3.2. Development of the LCCI and the NDRESWIR in the First Two Post-Fire Years

When analyzing the vegetation's development using the delta of the VIs between post-fire scenes, the median values showed a high positive correlation with increasing FS classes in the first year (LCCI: 0.9997, NDRESWIR: 0.9874). At the MHS area, the recuperation appeared to be the highest, followed by MLS and LS (Figures 7 and 8). The second post-fire year showed continuously equilibrated, slightly decreasing median dLCCI, as well as dNDRESWIR values with increasing FS. The vegetation at the study area seemed to be recuperating strongly in the first post-fire year.

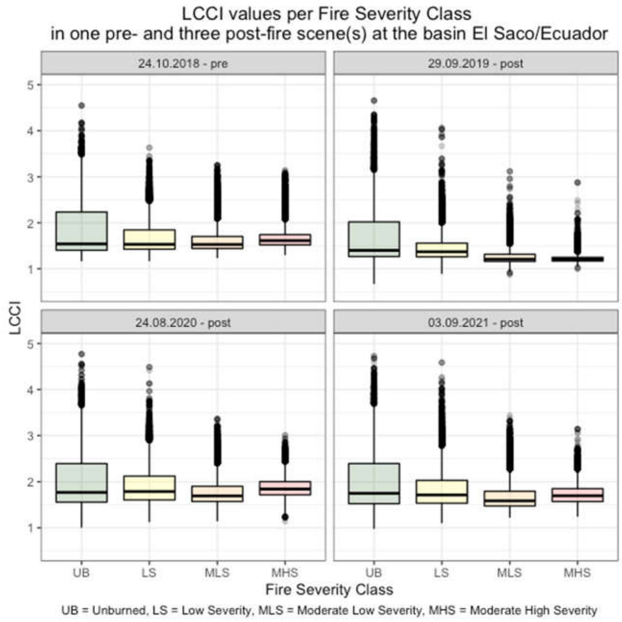

Figure 5. Boxplots of LCCI values in the fire severity classes at the El Saco basin in one pre- and three post-fire Sentinel 2 scenes.

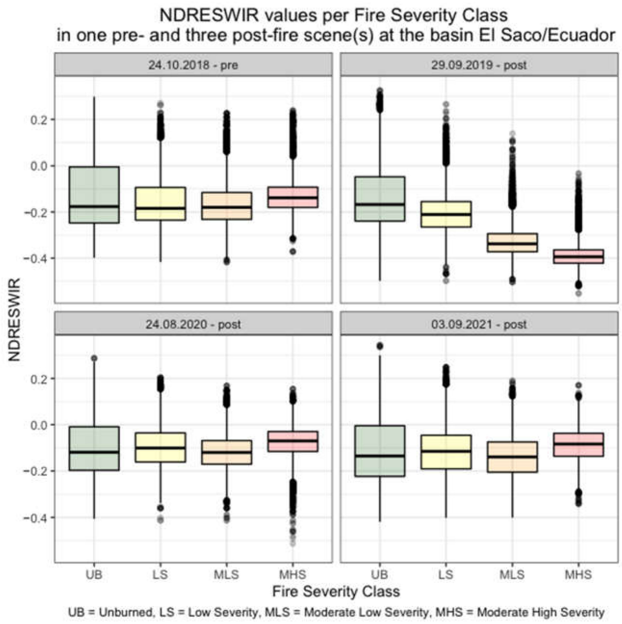

Figure 6. Boxplots of NDRESWIR values in the fire severity classes at the El Saco basin in one pre- and three post-fire Sentinel 2 scenes.

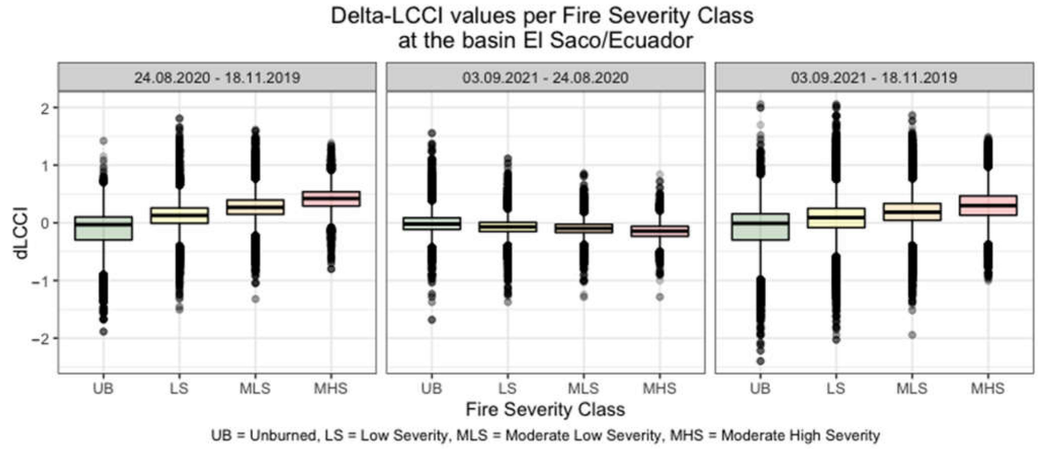

Figure 7. Boxplots of dLCCI values per fire severity classes from the first two post-fire years at the El Saco basin.

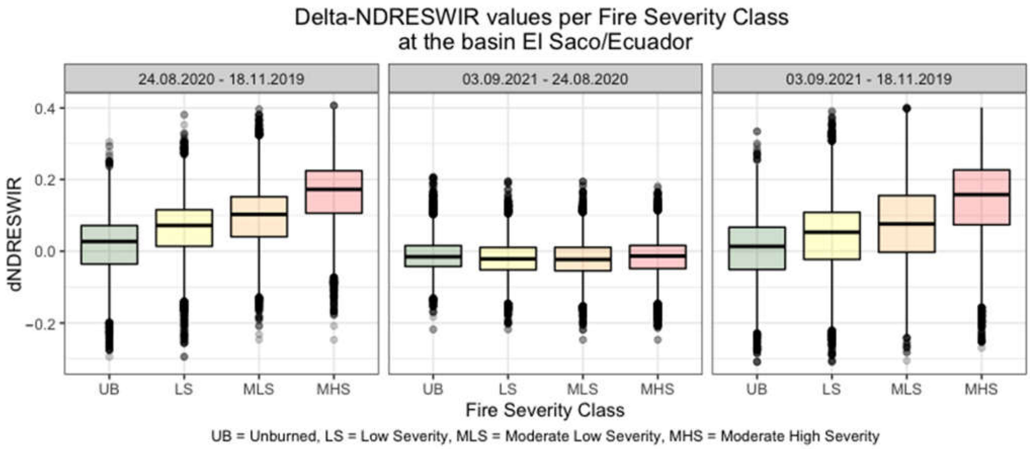

Figure 8. Boxplots of dNDRESWIR values per fire severity classes from the first two post-fire years at the El Saco basin.

3.3.3. Relative Post-Fire Development of LCCI and NDRESWIR Per Fire Severity Class

Due to the different acquisition times of the S2 images (cloud-free data), which were used for the analysis of the vegetation's post-fire development, the UB area served as a reference to understand the relative change of the median within the FS classes. Comparing the two post-fire years with the pre-fire year 2018 showed that the LCCI median in the UB area in 2020 was +14.87 PP higher. due to the two months of difference with the pre-fire scene, and caused by the different influence of the phenology (Table 7). The chosen S2 scene in 2021 had a similar LCCI median value in the UB area (+13.57 PP) compared to the pre-fire year in 2018. The NDRESWIR median in the UB area, showing a +32.76 PP of relative increase in 2020 and +23.72 PP in 2021 related to pre-fire conditions (Table 8). When relativizing the time difference, the LCCI showed an increase in 2020 of +1.92 PP at the area with LS, a decrease of −4.00 PP at the MLS, as well as a decrease of −0.54 PP at the MHS compared to the pre-fire image in 2018 (Table 9). According to the LCCI, the vegetation in LS and the MHS areas recovered one year after the fire event to about the same level as was measured in the pre-fire conditions in 2018. In the second post-fire year, the LCCI indicated a decrease in all FS classes, whereby the MLS again showed the lowest value, with −9.71 PP. Interpreting the relativized data from the NDRESWIR (Table 10), the LS and MHS areas performed better compared with MLS, whereby all three FS classes were at least around the same level as the pre-fire year in 2018.

Table 7. Vegetation recovery according to the median LCCI per fire severity class compared to the pre-fire year in percentage points (PP) at the El Saco basin.

Change of LCCI Median with Year and Fire Severity				
	Pre-Fire 24 October 2018	**Post-Fire 29 September 2019**	**Post-Fire 24 August 2020**	**Post-Fire 3 September 2021**
Unburned	100.00 PP	−9.09 PP	+14.87 PP	+13.57 PP
Low severity	100.00 PP	−10.58 PP	+16.79 PP	+11.95 PP
Moderate low severity	100.00 PP	−20.96 PP	+10.87 PP	+3.86 PP
Moderate high severity	100.00 PP	−25.62 PP	+14.33 PP	+5.27 PP

Table 8. Vegetation recovery according to the median NDRESWIR per fire severity class compared to the pre-fire year in percentage points (PP) at the El Saco basin.

Change of NDRESWIR Median with Year and Fire Severity				
	Pre-Fire 24 October 2018	**Post-Fire 29 September 2019**	**Post-Fire 24 August 2020**	**Post-Fire 3 September 2021**
Unburned	100.00 PP	+5.08 PP	+32.76 PP	+23.72 PP
Low severity	100.00 PP	−14.05 PP	+45.41 PP	+37.84 PP
Moderate low severity	100.00 PP	−87.78 PP	+33.33 PP	+22.78 PP
Moderate high severity	100.00 PP	−185.51 PP	+49.28 PP	+39.13 PP

Table 9. LCCI time series: relativizing the phenological difference of the selected vegetation index dates at the El Saco basin.

Relativized Change of LCCI Median			
	Post-Fire 29 September 2019	**Post-Fire 24 August 2020**	**Post-Fire 3 September 2021**
Unburned	0.00 PP	0.00 PP	0.00 PP
Low severity	−1.49 PP	+1.92 PP	−1.62 PP
Moderate low severity	−11.87 PP	−4.00 PP	−9.71 PP
Moderate high severity	−16.53 PP	−0.54 PP	−8.30 PP

Table 10. NDRESWIR time series: relativizing the phenological difference of the selected vegetation index dates at the El Saco basin.

Relativized Change of NDRESWIR MEDIAN			
	Post-Fire 29 September 2019	**Post-Fire 24 August 2020**	**Post-Fire 3 September 2021**
Unburned	0.00 PP	0.00 PP	0.00 PP
Low severity	−19.13 PP	+12.65 PP	+14.12 PP
Moderate low severity	−92.86 PP	+0.57 PP	−0.94 PP
Moderate high severity	−190.59 PP	+16.52 PP	+15.41 PP

The calculated PP cannot be compared directly between the two selected VIs, as they refer to different benchmarks, derived from different S2 bands and formulas. Nevertheless, both VIs show a similar, V-shaped trend (Figure 9), as the LS and MHS have a higher relative increase than the MLS area when comparing it with pre-fire conditions.

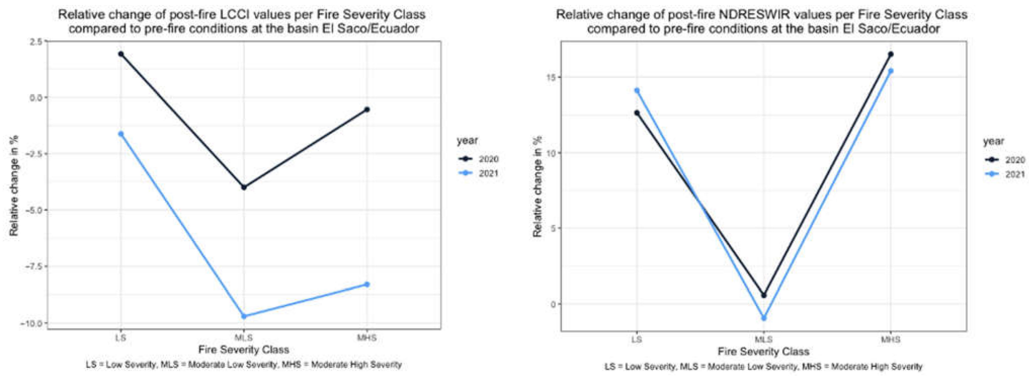

Figure 9. Relative change of post-fire vegetation index values per fire severity class compared to pre-fire conditions at the El Saco basin.

4. Discussion

When classifying the FS using Random Forest for every single scene of the used dates, before and after the fire event, widely used VIs for time series monitoring, such NDVI, or Soil Adjusted Vegetation Index (SAVI) [8,40,43,44], were not part of the final models. The *NBR*, which is frequently used for post-fire vegetation monitoring [22], was part of one model (29 September 2019), which questions the application of this index for grassland-dominated areas. The understanding that the optimal spectral or VIs for quantifying FS depends on vegetation composition or forest type is reported in different studies [24,34,45]. Tran et al. (2018) [24] considers the different spectral indices for FS assessment; namely, NDVI, *NBR*, Normalized Difference Water Index (NDWI), Normalized Difference Vegetation Index Thermal (NDVIT), Normalized Burn Ratio Thermal (NBRT), Vegetation Index 6 Thermal (VI6T), Burned Area Index (BAI), Modified Soil Adjusted Vegetation Index (MSAVI), Mid InfraRed Burn Index (MIRBI) and Char Soil Index (CSI). While the best performing VI for open forests with mixed fire responses (resprouters and seeders) in the Australian temperate forests was the dNDVI, the most accurate VI for obligate seeder closed forests was found to be the delta Normalized Difference Water Index (dNDWI) [24]. In 2001, Trigg and Flasse [46] developed the Mid-Infrared Burn Index (MIRBI) for savannahs, using the short wavelength and long-wavelength mid-infrared bands from MODIS. A further study, assessing VIs for post-fire vegetation recovery monitoring in grass- and/or shrubland was found in China/Mongolia by Qin et al. (2021), who recommended the Normalized Difference Phenology Index (NDPI) [47]. One problem when comparing these studies is that there are numerous VIs from different sources (Sentinel, Landsat, MODIS, etc. [47,48]), with different recording conditions, as well as different temporal and spatial resolution. This fact leads to a certain variance between the central wavelengths of the input bands and, therefore, to probable deviations in the calculated VIs. Another problem is that there is some ambiguity regarding the abbreviations of spectral and VIs used in scientific studies. For example, BAI is short for Burned Area Index [49], but also for Built-up Area Index [50]. The authors therefore recommend strongly to report used formulas, as well as names, when using VIs. Globally, with the increasing number of open access earth observation data, the remote sensing of fire events is gaining increasing attention. Numerous VIs are being developed or revised [51,52]; leading, on one hand, to more accurate tools, but on the other hand, to probable oversupply and user confusion. In addition, when assessing different VIs for the specific use in certain areas, it can be challenging to cover all important aspects for post-fire monitoring. However, this study presents a scalable methodology to assess VIs for post-fire vegetation recovery monitoring, applicable on other vegetation and climate conditions, using also additional VIs. Compared to other reported studies, the number of VIs examined (n = 23) in this paper is relatively high. The importance of LCCI, NDRESWIR and REPA to monitor vegetation recovery after wildfires in the temperate zone in southern Ecuador, with sparse tree vegetation and broad grassland, was shown as they conclude to FS class prediction. The RED, all RED EDGE, as well as the NEAR INFRARED (SHORTWAVE INFRARED) bands of the S2 satellite images, contributed to the post-fire vegetation development analysis in this study. This result should be considered in future studies when monitoring vegetation recovery in former wildfire areas in the temperate zone (Cfb), as well as areas with similar vegetation types. The vegetation recovery analysis in the different FS classes showed that within the first two years, the vegetation recovered to a great extent. In particular, the grassland recovered fully within the first post-fire year, which coincides with a study from Li and Guo (2018) in a North American mixed prairie [44]. At the El Saco basin, areas with higher severity and, therefore, a higher incision in the vegetation, developed faster in post-fire conditions. Nevertheless, LS and MHS seemed to recover better, equalizing or surpassing the pre-fire level within the first post-fire year. This is most likely due to the release of nutrients, which changes with fire severity [53]. The time of vegetation recovery varies with different biomes. Therefore, the recovery period required in forests and riparian vegetation types to regrow to pre-fire conditions is higher compared to grasslands and steppe areas, where fires potentially increase the amount of biomass [54]. Asrar et al. (1989) [55] stated that burned prairie grassland showed higher leaf production in burned areas. Further studies showed that more severely damaged areas recover faster after the fire event than areas with lower severity [54,56]. As vegetation monitoring with satellite data provides information regarding the amount of biomass, or the leaf area at the location, one important note is that the present analysis does not specify the type of vegetation if no reference data is given. In some cases, it could therefore be possible that the values of the VIs may be higher than before the fire event, leading to a better evaluation of the situation as it is. Some densely growing ferns, which are facilitated by fires or pioneer vegetation, could be the reason for higher VI values, indicating good recovery in areas where trees are burned, for which recuperation time is higher due to a longer life cycle and therefore slower growth compared to pioneer vegetation. One possible solution could be to use multitemporal S2 scenes with reference data regarding the vegetation types at the area in question to classify the vegetation [42] and acquire information regarding the development of vegetation types or species after the wildfire. This implies, further, that the classification model of the vegetation type depends on monitoring in the field or the exact interpretation of orthophotos. While short-term monitoring can be sufficient for grass- or shrub-land, higher growing vegetation with a longer recuperation time will not be covered within two years.

(**a**) (**b**)

Figure 10. (**a**) Fire-affected shrub and tree vegetation layer (**b**) Impact of the wildfire on the landscape one month after the event in the canton Quilanga/Ecuador [57].

Globally, the effects of wildfires are receiving increasing attention with the increasing number of extreme weather events and droughts. Being able to estimate the numerous consequences can help to diminish and minimize post-fire effects on landscapes, ecosystems, and/or settlements. Post-fire vegetation monitoring with adequate VIs from satellite data, according to climate zone and vegetation type, can help planning parties to assess these effects properly and determine suitable measures. When implementing post-fire measures using soil and water bioengineering techniques to revegetate or mitigate erosion [57–59], the use of time series from VIs can help to understand where to place the measures, spatially, at the area in question. Knowing from experience, or from post-fire monitoring with satellite data, that, for example, the vegetation in high severity areas recovers fast, can help planning parties to decide whether to apply measures in the area or not. The financial and time effort for planning and applying post-fire measures can be made more effective by using remote sensing data and VIs. However, in addition to monitoring or recuperation strategies for vegetation, educational work could have a high impact on the prevention of fire events and, therefore, the preservation of an intact vegetation cover. As farmers in the area use fire frequently (traditional slash and burn method [60]) to remove vegetation from the surface of their land to prepare it for seeding [61], days with a high risk of wildfires during the season with less precipitation should be avoided. Most of the residents have access to internet with their smartphones. Therefore, the development and promotion of an application such as the Fire Weather Index (FWI) [62], tuned for the area in question, showing the daily wildfire risk due to various meteorological variables, such as air temperature, relative humidity, wind speed and total precipitation, could help to prevent the spreading of uncontrolled fire events. Further, the extension of infrastructure for fire departments could have a high impact towards successfully limiting the spread of wildfires.

5. Conclusions

This study showed that for the monitoring of the post-fire vegetation recovery with sparse tree vegetation and broad grassland in the temperate Andes (Cfb), LCCI, as well as NDRESWIR, were the best VIs. Widely used VIs such as NDVI or SAVI were not part of the calculated final models. It underlines the assumption that the VI used for the monitoring of post-fire vegetation development should be selected according to the main vegetation type. As VIs do not indicate the vegetation type, there is no information regarding the development of specific species at the area in question. The short-term monitoring (<2 years) of vegetation recovery can be sufficient for grassland but must be extended for several years in areas with higher vegetation, such as shrubs or trees. According to vegetation monitoring with the selected VIs, the plants' recovery showed a strong positive correlation with the increasing FS class within the first two post-fire years at the investigated area. A repetition of the study within the following years may provide further information regarding the recovery of different vegetation types. Possible restauration strategies for the area should refer to the vegetation recovery, combining remote sensing methods with as field monitoring. By providing these answers to the research questions, a solid basis for possible landscape and forest restoration strategies after wildfires in the temperate (Cfb) zone in northern South America is delivered and the need for supporting or revegetating interventions can be evaluated. Municipalities or planning parties can use this information as a basis to develop further post-fire recuperation strategies. According to the knowledge of the authors, to date, no such study has been carried out for the temperate zone in southern Ecuador. The result of the present investigation is therefore an important contribution to recovering landscapes after fires in this region.

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Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1. Formulas used for the calculation of the vegetation indices using Sentinel-2 scenes from the wildfire area in Quilanga/Ecuador.

Nr.	Name	Formula	Source
1	Built-up Area Index (BAI)	$\frac{BLUE-NIR}{BLUE+NIR}$	[50]
2	Chlorophyll Green index (CGI)	$\frac{NIR}{GREEN+RE1}$	[63]
3	Global Environmental Monitoring Index (GEMI)	$\eta - 0.25\eta^2 - \frac{RED-0.125}{1-RED}$ $\eta = \frac{2(NIR^2-RED^2)+1.5NIR+0.5RED}{NIR+RED+0.5}$	[64]
4	Greenness Index (GI)	$\frac{GREEN}{RED}$	[65]
5	Green Normalized Difference Vegetation Index (gNDVI)	$\frac{NIR-GREEN}{NIR+GREEN}$	[66]
6	Leaf Chlorophyll Content Index (LCCI)	$\frac{RE3}{RE1}$	[67]
7	Normalized Difference Red-Edge and SWIR2 (NDRESWIR)	$\frac{RE2-SWIR2}{RE2+SWIR2}$	[68]
8	Normalized Difference Vegetation Index (NDVI)	$\frac{NIR-RED}{NIR+RED}$	[69]
9	Red-Edge Normalized Difference Vegetation Index (reNDVI)	$\frac{NIR-RE1}{NIR+RE1}$	[66]
10	Normalized Burn Ratio (NBR)	$\frac{NIR-SWIR2}{NIR+SWIR2}$	[13,15]
11	Red-Edge Peak Area (REPA)	$RED + RE1 + RE2 + RE3 + NIR$	[68,70]
12	Red-Edge Triangular Vegetation Index (RETVI)	$100(NIR - RE1) - 10(NIR - GREEN)$	[71]
13	Soil Adjusted Vegetation Index (SAVI)	$\frac{NIR-RED}{NIR+RED+0.5}1.5$	[17]
14	Blue and RE1 ratio (SRBRE1)	$\frac{BLUE}{RE1}$	[65]
15	Blue and RE2 ratio (SRBRE2)	$\frac{BLUE}{RE2}$	[72]
16	Blue and RE3 ratio (SRBRE3)	$\frac{BLUE}{RE3}$	[68]
17	NIR and Blue ratio (SRNIRB)	$\frac{NIR}{BLUE}$	[73]
18	NIR and Green ratio (SRNIRG)	$\frac{NIR}{GREEN}$	[65]
19	NIR and Red ratio (SRNIRR)	$\frac{NIR}{RED}$	[73]
20	NIR and RE1 ratio (SRNIRRE1)	$\frac{NIR}{RED1}$	[63]
21	NIR and RE2 ratio (SRNIRRE2)	$\frac{NIR}{RED2}$	[68]
22	NIR and RE3 ratio (SRNIRRE3)	$\frac{NIR}{RED3}$	[68]
23	Water Body Index (WBI)	$\frac{BLUE-RED}{BLUE+RED}$	[74]

Table A2. Statistics of pre- and post-fire LCCI in different fire severity classes at the El Saco basin.

LCCI								
		Min	**Median**	**Mean**	**Max**	**Standard Deviation**	**Skewness**	**Kurtosis**
24.October 2018	UB	1.165	1.540	1.860	4.546	0.615	1.210	3.437
	LS	1.165	1.531	1.684	3.629	0.365	1.463	4.642
	MLS	1.232	1.527	1.613	3.257	0.262	1.938	7.757
	MHS	1.298	1.612	1.672	3.141	0.245	2.283	10.032
29.September 2019	UB	0.668	1.400	1.700	5.244	0.650	1.434	4.641
	LS	0.887	1.369	1.456	4.072	0.314	1.761	7.854
	MLS	0.867	1.207	1.261	3.124	0.157	2.306	12.066
	MHS	0.993	1.199	1.225	2.876	0.103	3.809	33.201
24.August 2020	UB	1.002	1.769	2.024	5.751	0.623	1.228	4.058
	LS	1.124	1.788	1.911	4.487	0.425	1.228	4.377
	MLS	1.141	1.693	1.774	3.369	0.292	1.392	5.250
	MHS	1.141	1.843	1.880	3.007	0.230	0.840	3.953
3.September 2021	UB	0.978	1.749	2.024	6.069	0.674	1.283	4.184
	LS	1.100	1.714	1.841	4.585	0.435	1.454	5.423
	MLS	1.222	1.586	1.678	3.437	0.290	1.613	5.920
	MHS	1.240	1.697	1.733	3.140	0.216	1.129	5.065

Table A3. Statistics of pre- and post-fire NDRESWIR in different fire severity classes at the El Saco basin.

NDRESWIR								
		Min	**Median**	**Mean**	**Max**	**Standard Deviation**	**Skewness**	**Kurtosis**
24 October 2018	UB	−0.398	−0.177	−0.125	0.298	0.153	0.663	2.267
	LS	−0.417	−0.185	−0.158	0.271	0.112	0.760	3.008
	MLS	−0.417	−0.180	−0.168	0.227	0.088	0.760	3.687
	MHS	−0.373	−0.138	−0.132	0.238	0.078	0.975	5.448
29 September 2019	UB	−0.498	−0.168	−0.134	0.325	0.141	0.807	2.969
	LS	−0.498	−0.211	−0.204	0.265	0.090	0.643	3.880
	MLS	−0.504	−0.338	−0.327	0.139	0.066	1.101	5.119
	MHS	−0.553	−0.394	−0.389	−0.033	0.054	1.329	7.360
24 August 2020	UB	−0.406	−0.119	−0.098	0.287	0.126	0.459	2.479
	LS	−0.413	−0.101	−0.097	0.205	0.093	0.204	2.763
	MLS	−0.413	−0.120	−0.118	0.168	0.075	0.179	2.899
	MHS	−0.513	−0.070	−0.075	0.154	0.071	−0.548	4.371
3 September 2021	UB	−0.419	−0.135	−0.105	0.344	0.147	0.576	2.491
	LS	−0.402	−0.115	−0.115	0.248	0.111	0.190	2.815
	MLS	−0.401	−0.139	−0.137	0.190	0.092	0.194	2.683
	MHS	−0.344	−0.084	−0.087	0.170	0.072	−0.139	2.909

References

1. Giglio, L.; Randerson, J.T.; van der Werf, G.R. Analysis of Daily, Monthly, and Annual Burned Area Using the Fourth-Generation Global Fire Emissions Database (GFED4). *J. Geophys. Res. Biogeosci.* **2013**, *118*, 317–328. [CrossRef]
2. Andela, N.; Morton, D.C.; Giglio, L.; Paugam, R.; Chen, Y.; Hantson, S.; van der Werf, G.R.; Randerson, J.T. The Global Fire Atlas of Individual Fire Size, Duration, Speed and Direction. *Earth Syst. Sci. Data* **2019**, *11*, 529–552. [CrossRef]
3. van der Werf, G.R.; Randerson, J.T.; Giglio, L.; van Leeuwen, T.T.; Chen, Y.; Rogers, B.M.; Mu, M.; van Marle, M.J.E.; Morton, D.C.; Collatz, G.J.; et al. Global Fire Emissions Estimates during 1997–2016. *Earth Syst. Sci. Data* **2017**, *9*, 697–720. [CrossRef]
4. NASA's Jet Propulsion Laboratory Satellite Data Record Shows Climate Change's Impact on Fires. Available online: https://climate.nasa.gov/news/2912/satellite-data-record-shows-climate-changes-impact-on-fires/ (accessed on 30 September 2021).

5. Scheper, A.C.; Verweij, P.A.; van Kuijk, M. Post-Fire Forest Restoration in the Humid Tropics: A Synthesis of Available Strategies and Knowledge Gaps for Effective Restoration. *Sci. Total Environ.* **2021**, *771*, 144647. [CrossRef]
6. Rodrigues, M.; Ibarra, P.; Echeverría, M.; Pérez-Cabello, F.; de la Riva, J. A Method for Regional-Scale Assessment of Vegetation Recovery Time after High-Severity Wildfires: Case Study of Spain. *Prog. Phys. Geogr.* **2014**, *38*, 556–575. [CrossRef]
7. Shive, K.L.; Sieg, C.H.; Fulé, P.Z. Pre-Wildfire Management Treatments Interact with Fire Severity to Have Lasting Effects on Post-Wildfire Vegetation Response. *For. Ecol. Manag.* **2013**, *297*, 75–83. [CrossRef]
8. van Leeuwen, W.J.D. Monitoring the Effects of Forest Restoration Treatments on Post-Fire Vegetation Recovery with MODIS Multitemporal Data. *Sensors* **2008**, *8*, 2017–2042. [CrossRef]
9. European Space Agency. European Union Copernicus Open Access Hub. Available online: https://scihub.copernicus.eu/twiki/do/view/SciHubWebPortal/TermsConditions (accessed on 30 September 2021).
10. Maia, P.; Pausas, J.G.; Arcenegui, V.; Guerrero, C.; Pérez-Bejarano, A.; Mataix-Solera, J.; Varela, M.E.T.; Fernandes, I.; Pedrosa, E.T.; Keizer, J.J. Wildfire Effects on the Soil Seed Bank of a Maritime Pine Stand—The Importance of Fire Severity. *Geoderma* **2012**, *191*, 80–88. [CrossRef]
11. Davies, R.J.P.; Whalen, M.A.; Mackay, D.A.; Taylor, D.; Pisanu, P. Does Soil Seed Bank Diversity Limit Post-Fire Regeneration in Small, Fragmented, Long-Unburnt Remnants of Fire Adapted Vegetation? *Biol. Conserv.* **2013**, *158*, 287–295. [CrossRef]
12. Vallejo, V.R.; Arianoutsou, M.; Moreira, F. Fire Ecology and Post-Fire Restoration Approaches in Southern European Forest Types. In *Post-Fire Management and Restoration of Southern European Forests*; Moreira, F., Arianoutsou, M., Corona, P., de las Heras, J., Eds.; Springer: Dordrecht, The Netherlands, 2012; Volume 24, pp. 93–119. ISBN 978-94-007-2207-1.
13. Key, C.H.; Benson, N.C. Landscape Assessment (LA) Sampling and Analysis Methods. In *FIREMON: Fire Effects Monitoring and Inventory System*; Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., Gangi, L.J., Eds.; Rocky Mountain Research Station, U.S. Department of Agriculture, Forest Service: Fort Collins, CO, USA, 2006; pp. LA 1–LA 55.
14. Parks, S.A.; Dillon, G.K.; Miller, C. A New Metric for Quantifying Burn Severity: The Relativized Burn Ratio. *Remote Sens.* **2014**, *6*, 1827–1844. [CrossRef]
15. RUS Copernicus Burned Area Mapping with Sentinel-2 Using SNAP. Available online: https://rus-copernicus.eu/portal/wp-content/uploads/library/education/training/HAZA02_BurnedArea_Portugal_Tutorial.pdf (accessed on 4 December 2022).
16. Collins, L.; Griffioen, P.; Newell, G.; Mellor, A. The Utility of Random Forests for Wildfire Severity Mapping. *Remote Sens. Environ.* **2018**, *216*, 374–384. [CrossRef]
17. Huete, A.R. A Soil-Adjusted Vegetation Index (SAVI). *Remote Sens. Environ.* **1988**, *25*, 295–309. [CrossRef]
18. Wohlgemuth, T.; Wasem, U.; Hester, C. Waldverjüngung nach Feuer—Konkurrenzstarke Lärche. *Bündnerwald* **2010**, *63*, 28–33.
19. Gemitzi, A.; Koutsias, N. Assessment of Properties of Vegetation Phenology in Fire-Affected Areas from 2000 to 2015 in the Peloponnese, Greece. *Remote Sens. Appl.* **2021**, *23*, 100535. [CrossRef]
20. Francos, M.; Úbeda, X.; Tort, J.; Panareda, J.M.; Cerdà, A. The Role of Forest Fire Severity on Vegetation Recovery after 18 Years. Implications for Forest Management of *Quercus suber* L. in Iberian Peninsula. *Glob. Planet. Chang.* **2016**, *145*, 11–16. [CrossRef]
21. Vanderhoof, M.K.; Hawbaker, T.J.; Ku, A.; Merriam, K.; Berryman, E.; Cattau, M. Tracking Rates of Postfire Conifer Regeneration vs. Deciduous Vegetation Recovery across the Western United States. *Ecol. Appl.* **2021**, *31*, e02237. [CrossRef]
22. Bright, B.C.; Hudak, A.T.; Kennedy, R.E.; Braaten, J.D.; Henareh Khalyani, A. Examining Post-Fire Vegetation Recovery with Landsat Time Series Analysis in Three Western North American Forest Types. *Fire Ecol.* **2019**, *15*, 8. [CrossRef]
23. Cuevas-González, M.; Gerard, F.; Balzter, H.; Riaño, D. Analysing Forest Recovery after Wildfire Disturbance in Boreal Siberia Using Remotely Sensed Vegetation Indices. *Glob. Chang. Biol.* **2009**, *15*, 561–577. [CrossRef]
24. Tran, B.N.; Tanase, M.A.; Bennett, L.T.; Aponte, C. Evaluation of Spectral Indices for Assessing Fire Severity in Australian Temperate Forests. *Remote Sens.* **2018**, *10*, 1680. [CrossRef]
25. Ramsay, P.M. Giant Rosette Plant Morphology as an Indicator of Recent Fire History in Andean Páramo Grasslands. *Ecol. Indic.* **2014**, *45*, 37–44. [CrossRef]
26. Borrelli, P.; Armenteras, D.; Panagos, P.; Modugno, S.; Schütt, B. The Implications of Fire Management in the Andean Paramo: A Preliminary Assessment Using Satellite Remote Sensing. *Remote Sens.* **2015**, *7*, 11061–11082. [CrossRef]
27. Zomer, M.A.; Ramsay, P.M. Post-fire Changes in Plant Growth Form Composition and Diversity in Andean Páramo Grassland. *Appl. Veg. Sci.* **2021**, *24*, e12554. [CrossRef]
28. Lara, J.G.M.; Mendoza, C.I.Á.; Coronel, L.J.J. Assessment of Fuel Related Data in the Metropolitan District of Quito for Modeling and Simulation of Wildfires, Case Study: Atacazo Hill Wildfire. *Granja* **2022**, *34*, 43–59. [CrossRef]
29. Reyes-Bueno, F.; Loján-Córdova, J. Assessment of Three Machine Learning Techniques with Open-Access Geographic Data for Forest Fire Susceptibility Monitoring—Evidence from Southern Ecuador. *Forests* **2022**, *13*, 474. [CrossRef]
30. Carrión-Paladines, V.; Hinojosa, M.B.; Álvarez, L.J.; Reyes-Bueno, F.; Quezada, L.C.; García-Ruiz, R. Effects of the Severity of Wildfires on Some Physical-Chemical Soil Properties in a Humid Montane Scrublands Ecosystem in Southern Ecuador. *Fire* **2022**, *5*, 66. [CrossRef]
31. Pérez-Cabello, F.; Montorio, R.; Alves, D.B. Remote Sensing Techniques to Assess Post-Fire Vegetation Recovery. *Curr. Opin. Environ. Sci. Health* **2021**, *21*, 100251. [CrossRef]
32. Gobierno Autónomo Descentralizado del Canton Quilanga. Plan de Ordenamiento Territorial Del Cantón Quilanga, Tema: Precipitación. 2014.

33. Alcaldia del Cantón Quilanga Incendio Forestal en Quilanga. Available online: https://www.facebook.com/fredy.cuevarojas.1/videos/145016750072990/ (accessed on 17 October 2021).
34. Keeley, J.E. Fire Intensity, Fire Severity and Burn Severity: A Brief Review and Suggested Usage. *Int. J. Wildland Fire* **2009**, *18*, 116–126. [CrossRef]
35. UN-SPIDER Knowledge Portal Normalized Burn Ratio (NBR). Available online: https://un-spider.org/advisory-support/recommended-practices/recommended-practice-burn-severity/in-detail/normalized-burn-ratio (accessed on 17 October 2021).
36. Mpakairi, K.S.; Ndaimani, H.; Kavhu, B. Exploring the Utility of Sentinel-2 MSI Derived Spectral Indices in Mapping Burned Areas in Different Land-Cover Types. *Sci. Afr.* **2020**, *10*, e00565. [CrossRef]
37. Chen, X.; Vogelmann, J.E.; Rollins, M.; Ohlen, D.; Key, C.H.; Yang, L.; Huang, C.; Shi, H. Detecting Post-Fire Burn Severity and Vegetation Recovery Using Multitemporal Remote Sensing Spectral Indices and Field-Collected Composite Burn Index Data in a Ponderosa Pine Forest. *Int. J. Remote Sens.* **2011**, *32*, 7905–7927. [CrossRef]
38. Efthimiou, N.; Psomiadis, E.; Panagos, P. Fire Severity and Soil Erosion Susceptibility Mapping Using Multi-Temporal Earth Observation Data: The Case of Mati Fatal Wildfire in Eastern Attica, Greece. *Catena* **2020**, *187*, 104320. [CrossRef] [PubMed]
39. Hislop, S.; Jones, S.; Soto-Berelov, M.; Skidmore, A.; Haywood, A.; Nguyen, T.H. Using Landsat Spectral Indices in Time-Series to Assess Wildfire Disturbance and Recovery. *Remote Sens.* **2018**, *10*, 460. [CrossRef]
40. Petropoulos, G.P.; Griffiths, H.M.; Kalivas, D.P. Quantifying Spatial and Temporal Vegetation Recovery Dynamics Following a Wildfire Event in a Mediterranean Landscape Using EO Data and GIS. *Appl. Geogr.* **2014**, *50*, 120–131. [CrossRef]
41. Breiman, L. Random Forests. *Mach. Learn.* **2001**, *45*, 5–32. [CrossRef]
42. Immitzer, M.; Neuwirth, M.; Böck, S.; Brenner, H.; Vuolo, F.; Atzberger, C. Optimal Input Features for Tree Species Classification in Central Europe Based on Multi-Temporal Sentinel-2 Data. *Remote Sens.* **2019**, *11*, 2599. [CrossRef]
43. Romo Leon, J.R.; van Leeuwen, W.J.D.; Casady, G.M. Using MODIS-NDVI for the Modeling of Post-Wildfire Vegetation Response as a Function of Environmental Conditions and Pre-Fire Restoration Treatments. *Remote Sens.* **2012**, *4*, 598–621. [CrossRef]
44. Li, M.; Guo, X. Evaluating Post-Fire Vegetation Recovery in North American Mixed Prairie Using Remote Sensing Approaches. *Open J. Ecol.* **2018**, *8*, 646–680. [CrossRef]
45. Hammill, K.A.; Bradstock, R.A. Remote Sensing of Fire Severity in the Blue Mountains: Influence of Vegetation Type and Inferring Fire Intensity. *Int. J. Wildland Fire* **2006**, *15*, 213–226. [CrossRef]
46. Trigg, S.; Flasse, S. An Evaluation of Different Bi-Spectral Spaces for Discriminating Burned Shrub-Savannah. *Int. J. Remote Sens.* **2001**, *22*, 2641–2647. [CrossRef]
47. Qin, Q.; Xu, D.; Hou, L.; Shen, B.; Xin, X. Comparing Vegetation Indices from Sentinel-2 and Landsat 8 under Different Vegetation Gradients Based on a Controlled Grazing Experiment. *Ecol. Indic.* **2021**, *133*, 108363. [CrossRef]
48. Steiner, J.L.; Wetter, J.; Robertson, S.; Teet, S.; Wang, J.; Wu, X.; Zhou, Y.; Brown, D.; Xiao, X. Grassland Wildfires in the Southern Great Plains: Monitoring Ecological Impacts and Recovery. *Remote Sens.* **2020**, *12*, 619. [CrossRef]
49. Liu, J.; Maeda, E.E.; Wang, D.; Heiskanen, J. Sensitivity of Spectral Indices on Burned Area Detection Using Landsat Time Series in Savannas of Southern Burkina Faso. *Remote Sens.* **2021**, *13*, 2492. [CrossRef]
50. Shahi, K.; Shafri, H.Z.M.; Taherzadeh, E.; Mansor, S.; Muniandy, R. A Novel Spectral Index to Automatically Extract Road Networks from WorldView-2 Satellite Imagery. *Egypt. J. Remote Sens. Space Sci.* **2015**, *18*, 27–33. [CrossRef]
51. Alcaras, E.; Costantino, D.; Guastaferro, F.; Parente, C.; Pepe, M. Normalized Burn Ratio Plus (NBR+): A New Index for Sentinel-2 Imagery. *Remote Sens.* **2022**, *14*, 1727. [CrossRef]
52. Liu, S.; Zheng, Y.; Dalponte, M.; Tong, X. A Novel Fire Index-Based Burned Area Change Detection Approach Using Landsat-8 OLI Data. *Eur. J. Remote Sens.* **2020**, *53*, 104–112. [CrossRef]
53. Caon, L.; Vallejo, V.R.; Coen, R.J.; Geissen, V. Effects of Wildfire on Soil Nutrients in Mediterranean Ecosystems. *Earth Sci. Rev.* **2014**, *139*, 47–58. [CrossRef]
54. White, J.D.; Ryan, K.C.; Key, C.C.; Running, S.W. Remote Sensing of Forest Fire Severity and Vegetation Recovery. *Int. J. Wildland Fire* **1996**, *6*, 125–136. [CrossRef]
55. Asrar, G.; Myneni, R.B.; Li, Y.; Kanemasu, E.T. Measuring and Modeling Spectral Characteristics of a Tallgrass Prairie. *Remote Sens. Environ.* **1989**, *27*, 143–155. [CrossRef]
56. Gordon, C.E.; Price, O.F.; Tasker, E.M. Mapping and Exploring Variation in Post-Fire Vegetation Recovery Following Mixed Severity Wildfire Using Airborne LiDAR. *Ecol. Appl.* **2017**, *27*, 1618–1632. [CrossRef] [PubMed]
57. Maxwald, M.; Crocetti, C.; Ferrari, R.; Petrone, A.; Rauch, H.P.; Preti, F. Soil and Water Bioengineering Applications in Central and South America: A Transferability Analysis. *Sustainability* **2020**, *12*, 10505. [CrossRef]
58. Girona-García, A.; Vieira, D.C.S.; Silva, J.; Fernández, C.; Robichaud, P.R.; Keizer, J.J. Effectiveness of Post-Fire Soil Erosion Mitigation Treatments: A Systematic Review and Meta-Analysis. *Earth Sci. Rev.* **2021**, *217*, 103611. [CrossRef]
59. Zaimes, G.N.; Kasapidis, I.; Gkiatas, G.; Pagonis, G.; Savvopoulou, A.; Iakovoglou, V. Targeted Placement of Soil Erosion Prevention Works after Wildfires. *IOP Conf Ser Earth Environ Sci* **2020**, *612*, 12050. [CrossRef]
60. Bandy, D.; Garrity, D.P.; Sánchez, P. EL Problema Mundial de La Agricultura de Tala y Quema. *Agroforestería Américas* **1994**, *1*, 14–20.
61. Armenteras, D.; González, T.M.; Ríos, O.V.; Elizalde, M.C.M.; Oliveras, I. Fire in the Ecosystems of Northern South America: Advances in the Ecology of Tropical Fires in Colombia, Ecuador and Peru. *Caldasia* **2020**, *42*, 1–16. [CrossRef]

62. Copernicus Climate Change Service Fire Weather Index. Available online: https://climate.copernicus.eu/fire-weather-index (accessed on 21 June 2022).
63. Datt, B. A New Reflectance Index for Remote Sensing of Chlorophyll Content in Higher Plants: Tests Using Eucalyptus Leaves. *J. Plant Physiol.* **1999**, *154*, 30–36. [CrossRef]
64. Pinty, B.; Verstraete, M.M. GEMI: A Non-Linear Index to Monitor Global Vegetation from Satellites. *Vegetatio* **1992**, *101*, 15–20. [CrossRef]
65. le Maire, G.; François, C.; Dufrêne, E. Towards Universal Broad Leaf Chlorophyll Indices Using PROSPECT Simulated Database and Hyperspectral Reflectance Measurements. *Remote Sens. Environ.* **2004**, *89*, 1–28. [CrossRef]
66. Gitelson, A.A.; Kaufman, Y.J.; Merzlyak, M.N. Use of a Green Channel in Remote Sensing of Global Vegetation from EOS-MODIS. *Remote Sens. Environ.* **1996**, *58*, 289–298. [CrossRef]
67. Wulf, H.; Stuhler, S. Sentinel-2: Land Cover, Preliminary User Feedback on Sentinel-2A Data. In Proceedings of the Sentinel-2A Expert Users Technical Meeting, Frascati, Italy, 29–30 September 2015; pp. 29–30.
68. Radoux, J.; Chomé, G.; Jacques, D.C.; Waldner, F.; Bellemans, N.; Matton, N.; Lamarche, C.; D'Andrimont, R.; Defourny, P. Sentinel-2's Potential for Sub-Pixel Landscape Feature Detection. *Remote Sens.* **2016**, *8*, 488. [CrossRef]
69. Tucker, C.J. Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. *Remote Sens Environ* **1979**, *8*, 127–150. [CrossRef]
70. Filella, I.; Peñuelas, J. The Red Edge Position and Shape as Indicators of Plant Chlorophyll Content, Biomass and Hydric Status. *Int. J. Remote Sens.* **1994**, *15*, 1459–1470. [CrossRef]
71. Chen, P.; Tremblay, N.; Wang, J.; Vigneault, P.; Huang, W.; Li, B. New Index for Crop Canopy Fresh Biomass Estimation. *Spectrosc. Spectr. Anal.* **2010**, *30*, 512–517.
72. Lichtenthaler, H.K.; Lang, M.; Sowinska, M.; Heisel, F.; Miehé, J.A. Detection of Vegetation Stress via a New High Resolution Fluorescence Imaging System. *J. Plant Physiol.* **1996**, *148*, 599–612. [CrossRef]
73. Alan Blackburn, G. Quantifying Chlorophylls and Caroteniods at Leaf and Canopy Scales: An Evaluation of Some Hyperspectral Approaches. *Remote Sens. Environ.* **1998**, *66*, 273–285. [CrossRef]
74. Domenech, E.; Mallet, C. Change Detection in High-Resolution Land Use/Land Cover Geodatabases (At Object Level). In *European Spatial Data Research*; EuroSDR: Vienna, Austria, 2014; Volume 64, pp. 9–57.

7.3 Article 3

Post-fire erosion and sediment yield in a Mediterranean forest catchment in Italy.

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Research article

Post-fire erosion and sediment yield in a Mediterranean forest catchment in Italy

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Abstract

Wildfires are an increasingly alarming phenomenon that affects forests and agro-ecosystems, generating several cascade effects among which soil erosion is one of the most deleterious. A robust body of data-based evidence on post-fire soil erosion and sediment yield at watershed scale is thus required, especially dealing with areas where wildfires are particularly frequent, such as the Mediterranean Basin. This study analyses the impact of the first rains after a large wildfire in terms of soil erosion and sediment yield at watershed scale in a Mediterranean area, the Pisan Mountains, Central Italy. Here about 1,000 ha of olive groves, maquis, maritime pine and chestnut forests burned in late summer. Fire severity was mapped by remote sensing and checked by a field survey. Sediment yield was assessed by sampling the earthy material deposited upstream a check dam at the outlet of the watershed. Finally, a hydrological model was developed in HEC-HMS environment for exploring the relationship between the erosion-deposition events observed in the watershed and the rainfall-induced hydrological processes. The first two post-fire rainy events relocated a high amount of sediments, mostly non-organic, perhaps already in the stream before the fire, while the subsequent four rains deposited materials rich in pyrogenic organic matter. Overall, the soil erosion caused by such six main post-fire rains – the larger of which had a return time of one year – was estimated to amount to 7.85 t ha^{-1}, corresponding to 42% of the watershed average annual potential erosion rate in normal conditions. This value is lower than expected and, overall, moderate if compared to other Mediterranean case studies, possibly because of the nature of soils in the studied watershed, i.e. shallow and quite stony, thus poor in fines prone to erosion.

Keywords: Wildfire, Check dams, Post-fire hydrological modelling, Soil loss, Sediment yield, HEC-HMS

1. Introduction

Wildfires are a major concern of our times, with huge amounts of biomass burned and the global average carbon emissions into the atmosphere being estimated to be 2.2 Pg C yr^{-1} (Van Der Werf et al., 2017). Post-fire soil erosion is a negative indirect outcome of wildfires, which make them a hydrological and geomorphological agent (Shakesby and Doerr, 2006; Rulli and Rosso, 2007; Greenbaum et al, 2021; Robinne et al., 2021). Burned areas are prone to soil erosion because of decreased vegetation and litter covers, which would otherwise protect the soil against wind and splash erosion by interception and slow down the surface runoff (Fernandez et al., 2016; Ebel, 2020; Vega et al., 2020). The latter is instead encouraged by fire, which increases topsoil clogging and hydrophobicity, so preventing water infiltration (Rulli et al., 2006; Larsen et al., 2009). Erosion implies a net loss in soil fertility, which is generally greater in the uppermost layers (Thompson et al., 1991; Shakesby, 2011). Furthermore, topsoil erosion implies a net loss of soil organic matter and a reduced potential for soils to act as carbon sinks, which is functional for contrasting the climate change (Powlson et al., 2011). Last, once transported downstream the eroded soil can also cause major hydraulic problems (Stavi, 2019; Robinne et al, 2021). It impacts surface waters with sediments and possible contaminants (Granath et al., 2016; Abraham et al., 2017), and often needs to be collected and disposed in landfills (Köthe, 2003).

Relatively few studies have been carried out to account for the consequences of wildfires in terms of soil erosion and sediment yield at the catchment scale compared to the plot, slope and swale scales, perhaps because of practical and/or economic issues (Shakesby, 2011; Mayor et al., 2011; Robichaud et al., 2016; Weninger et al., 2019; Wu et al., 2021). However, geomorphic and hydrological processes are highly affected by the spatial scale and, therefore, erosion rates at larger scale should not be inferred from plot-scale studies (Parsons et al., 2006). Indeed, plot- and hillslope-scale studies often overestimate hydrological and erosion processes, thus making difficult to assess the real fire impact at larger scale (Mayor et al., 2011; Wagenbrenner and Robichaud, 2014; Wilson et al., 2021). In a synthesis of several field studies on post-fire sediment erosion and deposition measurement across the western United States, Moody and Martin (2009) found significantly different results according to the spatial scale, although opposite to the above-mentioned trend, i.e. lower sediment yield at the plot scale. In fact, keeping into account a certain variability depending on the measurement method, the annual post-fire sediment yield measured by various authors at catchment scale using dams, check dams, debris basins, alluvial fan deposition, and channel erosion was between 14 and 300 t ha^{-1}, with a mean of 240 t ha^{-1} (Moody and Martin, 2009). On the other hand, the annual sediment yield measured at hillslope scale by erosion pin, erosion bridge, survey transect, or grid measurements ranged between 37 and 160 t ha^{-1}, with a mean of 110 t ha^{-1}, or between 6 and 200 t ha^{-1}, with a mean of 62 t ha^{-1}, when sediment yield was measured by bounded hillslope plots, unbounded hillslope plots, and silt fences (Moody and Martin, 2009).

In the Mediterranean Basin, the watershed-scale studies on post-fire soil erosion and sediment yield are relatively less than in other geographic regions (Greenbaum et al., 2021; Wu et al., 2021), in spite of some worrying aspects, such as the high frequency and severity of wildfires or the often thin, steep and highly erodible soils (Poesen and Hooke, 1997; Pausas et al., 2008). Moderate post-fire erosional events seem to be prevalent in the Mediterranean Basin (Shakesby, 2011); however, as highlighted by Esposito et al. (2017), most of the case studies in this region are from experimental plot in Spain and Portugal. The need of larger and more representative datasets is pressing also considering that these are necessary for developing erosion models, which are more and more tested at plot and hillslope scales, but not as much at catchment or landscape scales (Thomas et al., 2021).

In this work we dealt with one of the most devastating recent fires in Italy in terms of rate of spread (up to 500 m h^{-1}), natural damages and structural/infrastructural damages. It occurred in September 2018 and affected an area of about 1,000 ha on Pisan Mountains, Tuscany. We evaluated the short-term impact of this fire in terms of soil erosion and sediment yield, focusing on the first rains after the fire – usually the most problematic ones (Greenbaum et al, 2021). The study was carried out on a single watershed, where post-fire precipitation and the characteristics (soil organic matter and granulometry) of the sediments accumulated at the catchment outlet were investigated. The aim of the study was to provide a valid contribution to the knowledge and measured data of post-fire rainfall-induced runoff processes at the catchment scale in a typical Mediterranean bio-geo-physical setting characterized by stony and shallow soils. With respect to the usually moderate post-fire erosion values reported for Mediterranean soils evaluated from plot studies (Shakesby, 2011), we hypothesize higher degree of soil erosion and sediment yield because of some predisposing factors of the study area (e.g., high rainfall erosivity and steep topography). Indeed, the average annual potential erosion rate of the investigated watershed, estimated with the USLE method in normal conditions, is 18.8 t ha^{-1} y^{-1} (Regione Toscana, 2020), a much higher value than 4.6 t ha^{-1} y^{-1}, the overall erosion mean value of the Mediterranean climatic zone (Panagos et al., 2015). Our study is based on a methodology that takes into account multiple environmental factors (e.g., burn severity, slope, soil characteristics, pre-fire land use, rainfall-runoff transformation, etc.) and takes advantage of a hydrological model for exploring the relationship between the erosion-deposition events and the rainfall-induced hydrological processes.

2. Material and methods

2.1. Study area

The Pisan Mountains are a 15,000-ha wide ridge (maximum height 917 m a.s.l.) made of Triassic Verrucano metasediments consisting of ferriferous quartzites undergone relatively high pressure and low temperature metamorphism (Franceschelli et al., 1986; Giorgetti et al., 1998), located in Central Italy, 5 km north-east of Pisa (Fig. 1). It is a fire-prone environment, having been involved by over 75 large wildfires since 1970, mainly occurring in summertime and linked to the high anthropization of the area, as usual in Mediterranean coastal areas (Pausas et al., 2008). The slope of the area ranges between 30% and 60% and the vegetation is typically Mediterranean, with olive groves and maquis in the basal belt and forests of maritime pine or chestnut above (Fig. 1). The climate is Mediterranean (Csa – "Hot-summer Mediterranean climate" in the Köppen climate classification), i.e. characterized by hot and dry summers, and relatively cold and rainy falls and winters. The mean annual temperature is 14.4 °C and the mean annual precipitation is 883 mm (data source: Climate-Data.org, 2021).

Our study was focused on the Santo Pietro (hereafter SP) watershed, which extends on the west side of the ridge (Fig. 1) and covers an area of 0.408 km^2 with a length of the main stream of 1.12 km and maximum, average and outlet altitudes of 409, 205 and 66 m a.s.l., respectively. According to the 1:250,000 soil map by Regione Toscana (http://sit.lamma.rete.toscana.it/websuoli/) – which refers to the ninth edition of the U.S. Soil Taxonomy (Soil Survey Staff, 2003) – the soils of the area are *Ultic Haplustalfs* (fine-silty, siliceous, mesic) or *Typic Dystrustepts* (loamy-skeletal, siliceous, mesic) near the river bed, and *Lithic Haplustepts* (loamy-skeletal, siliceous, mesic) or *Typic Dystrustepts* at higher elevations. A wooden check dam built right after the fire at the outlet (Figs. 2 and 3), near the small-town of Calci, induced the deposition of the eroded soil transported by the stream, so allowing its quantification and reconstruction of its depositional history (cfr. Par 2.6, Fig. 3).

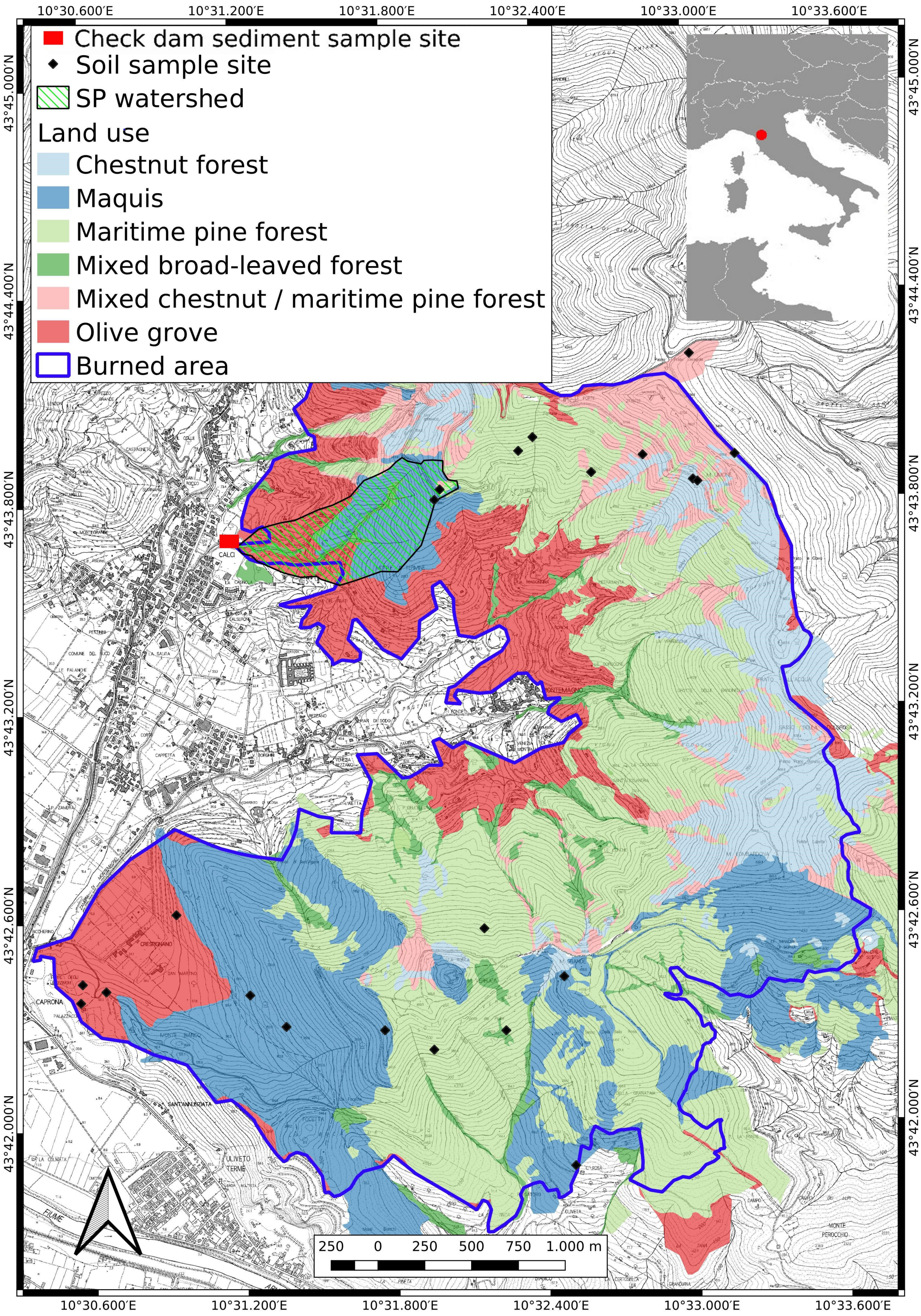

Fig. 1:The perimeter of the Pisan Mountains study area affected by the wildfire and the land uses (traced area on top). The location of the Santo Pietro (SP) watershed, check dam and soil sampling sites are marked.

Fig. 2: Wooden check dam at the outlet of Santo Pietro watershed (photo by P. Trucchi).

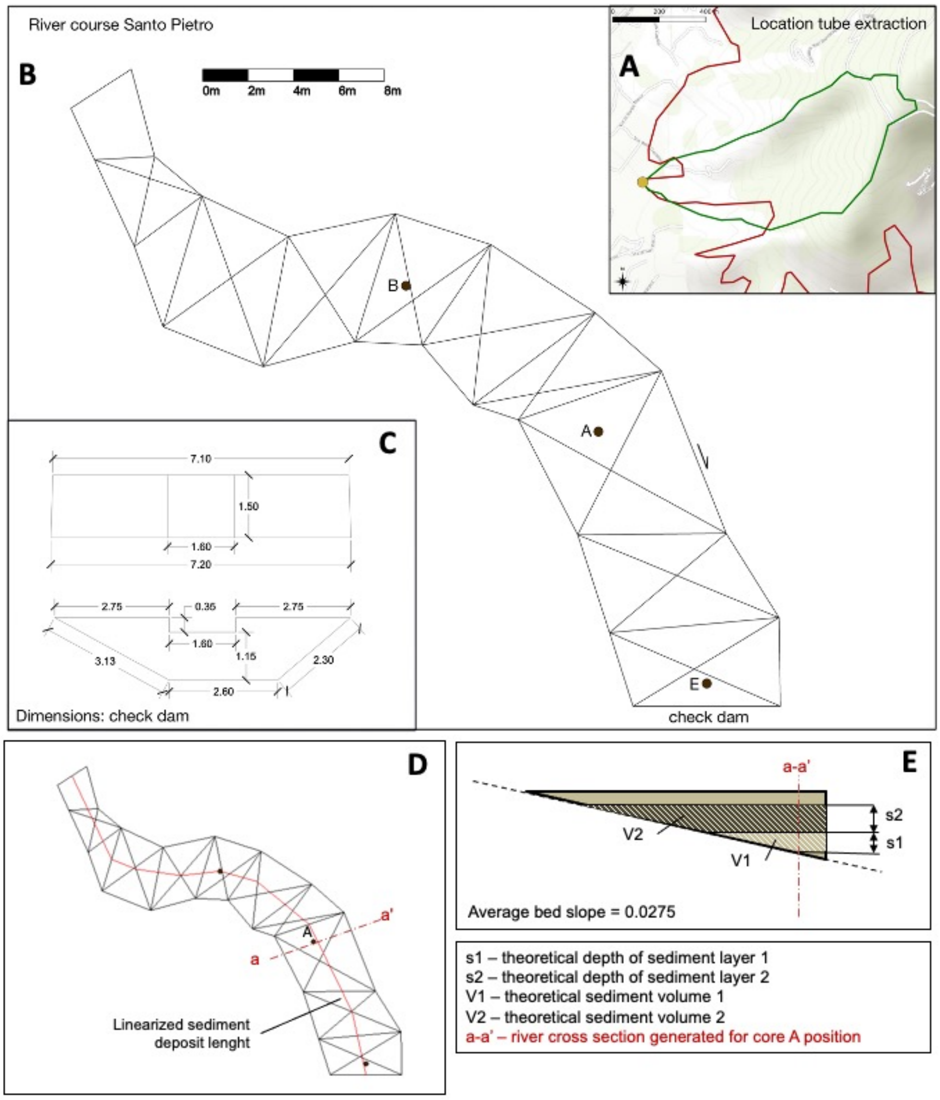

Fig. 3: A) the location of the check dam with respect to the Santo Pietro watershed; B) Geometrical scheme for calculation of the volume of sediment upstream the Santo Pietro watershed check dam, and for the volumes relative to each sediment layer identified i

2.2. Fire description and burn severity assessment

Following several relatively dry days, a fire started at 10 pm of September 24th, 2018. Classified as a strong wind-driven crown-fire with a slope-driven ground component, it burned a total area of 1,148 ha in over three days. Wind blew with gusts of 14 m s^{-1} (50 km h^{-1}), first from North-North-East, then, in the morning of September 25th from East. Wind speed peaks were locally measured at 22 m s^{-1} (80 km h^{-1}) by forest firefighters. Combination of slopes with wind speed and dense forest stand structure, as well as a low relative humidity (40% at 9 pm on September 24th), determined a maximum spread rate of 500 m h^{-1}, generating several spot fires up to 8 km away from the main fire front.
Wildfire spread and intensity were dictated by the combination of several ground fires started from spot events, favored by local topography and a main crown fire front driven by the wind. Fire control was initially restricted to property protection and perimeter containment involving 580 firefighter crews (each one composed by 2-5 operators) and 12 aircrafts.
The assessment of burn severity was carried out using remote sensed data from Sentinel-2 images (spatial resolution scaled at 20 m) recorded at the end of August and the beginning of October, calculating the Relativized Burn Ratio (RBR) index. This index indicates a relative measure of fire severity based on the difference in radiometric response between the near infrared (NIR) and short-wave infrared (SWIR) wavelengths, measured before and after the fire (Parks et al., 2014). To improve readability of burn severity distribution, we applied the United States Geological Survey (USGS) classification to RBR index (Table 1).

Severity class	**RBR values**	**% all burned surface**	**% SP watershed surface**
unburned	–0.1 to 0.099	8.6	16.7
low severity	0.1 to 0.269	19.7	15
moderate severity	0.27 to 0.659	59	65.7
high severity	0.66 to 1.3	12.6	2.6

Table 1: Burn severity classes distribution in the whole Pisan Mountains study site and the Santo Pietro (SP) watershed according to the United States Geological Survey (USGS) classification to Relativized Burn Ratio (RBR) index (modified).

2.3. Field investigation and soil sampling

Fire severity was also checked by a field survey (Fig. 4), done right after the fire on the whole Pisan Mountains range area, according to the visual scale of fire severity proposed by Parsons et al. (2010). During this campaign we randomly selected 20 circular areas, 30 m in diameter, five areas each vegetation stand, i.e. maquis, pine forest, chestnut forest, and olive orchards. Sixteen of these plots were burned, the other four ones unburned (control plots), all located on the two main soil types of the area (i.e. *Typic Dystrustepts* and *Lithic Haplustepts*). At each plot, the following variables were measured in the field:

i) *Stoniness* (presence of rock fragments >1 cm and outcrops on the ground surface), estimated by eye on eight circular mini-plots, with a diameter of 0.3 m, spaced 2 m each other on an alignment;

ii) *Soil depth*, down to the bedrock, determined by a steel auger on nine randomly selected spots.

One soil sample was collected from each plot, bulking together three soil samples taken with a shovel to a depth of 1 cm (ca. 300 g each), for determining the soil texture.

Fig. 4: Some examples of burned areas at Pisan Mountains: a) high burn severity in a pine stand; b) high burn severity in maquis; c) low burn severity in maquis; d) moderate burn severity in a chestnut stand.

2.4. Post-fire rainfall events

We focused our analysis to the first rains after the fire. Rainfall data of interest for our study (Fig. 5) were recorded by a station around 2.5 km from the catchment, at an altitude of 705 m a.s.l (Latitude 43.731°, Longitude 10.553°) and managed by the Hydrologic Regional Service (SIR) of the Tuscany Region. The first precipitation (October 28th to November 3rd, 2018; Fig. 5) occurred about one month after the wildfire, when five distinct intense rainy events were recorded.

We analyzed the return period (Rt) of these events by considering the specific rainfall intensity (h) - duration (t) curve in the form:

$$h = a' \cdot Rt^m \cdot t^n \qquad \text{[Eq. 1]}$$

The parameters of this relationship (a'; m; n) are available from the AlTo database of the Tuscany region (Regione Toscana, 2007; Preti, 2013; Preti et al., 2011). For the specific study case, they were a' = 24.08, m = 0.19, n= 0.31.

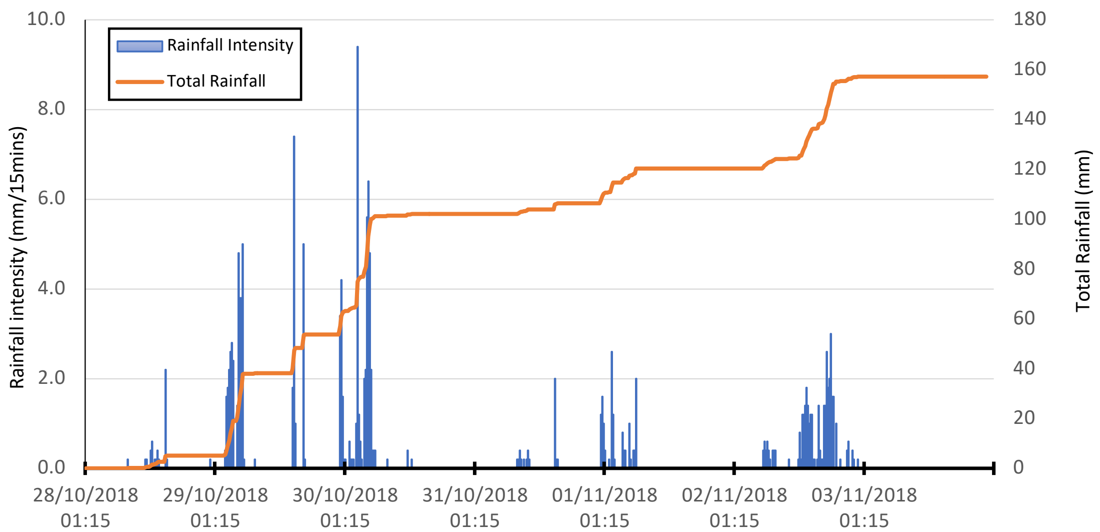

Fig. 5: Rainfall events recorded from October 28th to November 3rd, 2018 at Monte Serra Station, located at around 2.5 km from the SP watershed.

2.5. Rainfall-runoff model

To explore the relationship between the erosion-deposition events monitored in the watershed and the hydrological processes induced by the rains occurred from October 28th to November 3rd, 2018, we implemented a hydrological model of the SP watershed to simulate the discharges at the basin outlet.

A simplified model based on the Hydrologic Modeling System (HEC-HMS, see Scharffenberg et al., 2018) was built starting from static data (land use and soil maps) and dynamics inputs (rainfall). HEC-HMS is a simple, globally available and widely used software that is a well-established standard in hydrology. It simulates a basin-wide dynamic by sub-basins interconnected through a channel network, where rainfall-runoff generation is calculated independently for each sub-basin. The modeling of these hydrological phenomena is obtained by the simulation of the different hydrological processes, such as the rainfall partitioning between runoff, interception and deep basin losses, the successive rainfall-runoff transformation, and the routing of river discharges in schematized flow channels.

In this study, the SP watershed was modeled with a parsimonious strategy, using a single sub-basin scheme and without involving any river channel modelling, given also the small extent of the area. The model was built starting from the rainfall data. Rainfall partitioning and the sub-basin loss, “Loss Method” section in the HEC-HMS interface, were calculated by the application of the SCS Curve Number (CN) method (United States Department of Agriculture, 1986).

For each time interval considered, the CN method calculates the instant runoff generated (Q) with the following equation:

$$Q = \begin{cases} 0 & for P \leq Ia \\ \frac{(P-Ia)^2}{P-Ia+S} & for P > Ia \end{cases} \quad \text{Eq. 2}$$

where:

- P is the rainfall height for the calculation interval (mm)
- S is the potential maximum soil moisture retention after the runoff starts (mm), and is calculated as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad \text{Eq. 3}$$

- Ia is the initial abstraction, namely the depth of water retained by the landscape before the runoff starts, by infiltration or by rainfall interception by vegetation (mm). Ia is generally assumed to be 0.2 S.

The method is based on the CN adimensional parameter that accounts for the physical response of a landscape unit to rainfall, and ranges from 30 to 100. It depends upon the soil type and the land cover, and the higher the CN, the lower the basin losses and, consequently, the larger the runoff generation. Combining data on soil and land cover, an initial CN value, namely CNII, valid for average soil moisture conditions, is calculated. Each CNII value corresponds to a CNI (lower) value, to be used for dry soil conditions, and to a CNIII (higher) value for wet conditions (see United States Department of Agriculture, 1986, for the complete method and CN value parametrization).

In our case, the overall average CN for the SP watershed in post-fire conditions was obtained by an area-weighted average of the CN of all landscape units falling within the watershed, which were extrapolated from the CN map of Tuscany (Castelli, 2014). Since no significant rain was recorded right after the wildfire and before the simulation date, values for CN in dry soil conditions (CNI) were used.

Several CN-based methods are available for the modeling of burned landscape conditions. One of these is BAER (Burned Area Emergency Response, USDA Forest Service, 2006), which prescribes increases in CNII of 15, 10 and 5 for areas affected by high, medium and low severity, respectively. Instead, Coschignano et al. (2019) adopted increases of CN varying from 5 and 20 for growing fire severities. In our case, the burned areas in SP watershed were characterized by a rather homogeneous moderate severity. However, aiming at investigating the short-term effect of fire, therefore with the maximum alteration of CN, we followed Soulis (2018), who assumed an increase of 25 units in CN for burned areas in a catchment in Greece. We made this choice because of the similarities between the Soulis' study site and ours in terms of environment, vegetation and fire impact.

The SCS Unit Hydrograph method (United States Department of Agriculture, 1986) was used as rainfall-runoff transformation method ("Transform Method"). Hence, at each calculation time, the instant runoff generated by the watershed was transformed in a standard hydrograph with peak time 0.6 times that of the basin concentration time, which meant 27 minutes for the SP watershed. The overall sub-basin response was calculated as the convolution of all hydrographs.

The HEC-HMS version 4.3 was used for the modeling process, and no baseflow and evapotranspiration processes simulation were considered, since the model was replicating a peak flow event. The model was not calibrated nor validated, since burned catchments in the area were not gauged at the time of the analysis, while performing a validation of the model some months after the fire would have led to different catchment conditions due to vegetation regrowth.

2.6. Stream sediments quantification and sampling

A few days after the fire, a large wooden check dam was built to act as a sediment trap at the SP watershed outlet, just before the small town of Calci, to prevent streambed aggradation in the urban area in case of post-fire floods (Fig. 2). No rainfall occurred between the fire and the setting up of the structure, while the whole volume of the latter was filled by sediment just after the significant rainfall events described in par. 2.4. Therefore, the sediment volume trapped upstream the check dam corresponded to the sediment produced by the rains occurred from 28.10 to 03.11.2018.

Soon after that time lapse, a detailed topographic survey was carried out to measure location and elevation of a 32-point grid at the surface of the sediment deposit and at the level of the streambed by digging small trenches upstream the check dam. This allowed determining the shape and volume of the deposit (Fig. 3), which was then sampled by metal pipes 12 cm in diameter, driven as deep as possible. The individuation of the boundary between the post-fire sediments and the pre-existing streambed based on the assumption that, due to the relatively high slope of the stream, the original streambed was mainly composed by gravel, which prevented the sampling pipes to be driven deeper. Further discussion on the analysis of the sedimentation dynamics is reported in par. 3.3.

Five deposit cores were taken at five different points and three cores were kept for further analysis (see Fig. 3): one close to the check dam (E), another almost at the opposite extreme of the sedimentation area (B), and the third (A) approximately in between. Core A was the thickest and the one used for the calculation of the volume of the sediment. For each layer individuated in this core, the relative deposited volume was determined with a geometric procedure, considering the widening of the trapezoid section and, at the cut-off length, adjusted layer by layer (Fig. 3). For each layer the respective mass deposited at the check dam site (M_{Di}) was calculated multiplying the estimated volume by the related bulk density measured in the core (see par. 2.7 for the bulk density calculation). The total mass of soil eroded at the catchment scale (M_{Ei}), namely the one flowed up to the check dam site (either deposited before or flowed past it through the overflowing water), was calculated from M_{Di} by the means of the Sediment Trap Efficiency of the check dam at the time of deposition of the uppermost layer of core A (STE_i):

$$M_{Ei} = \frac{M_{Di}}{STE_i}$$

Eq. 4

where STE_i was estimated according to Brown (1943), by the following equation:

$$STE_i = 1 - \left(\frac{1}{1 - 0.0021D\frac{C_i}{W}} \right)$$

Eq. 5

where C_i is the volume capacity upstream the check dam before the deposition of the uppermost layer of core A in m^3, W is the extension of the watershed upstream the check dam, and D is a coefficient assumed to be 1 for watersheds with variable and limited runoff.

By analysing the outputs of the HEC-HMS model (par. 2.5), each sedimentation event (i.e., each layer in the core) was related to a peak flow event during the modelled period, and the sediment concentration was calculated dividing M_{Ei} by the total volume of the flow. Finally, the average post-fire erosion rate was calculated dividing the total sediment eroded by the area of the SP watershed.

2.7. Soil and sediments analysis

The disturbed soil and sediment samples were air-dried and then sieved to 2 mm. The lone fine earth, the smaller than 2-mm fraction, underwent further analysis.
Particle size analysis was performed according to the hydrometer method. The bulk density of collected sediments was determined dividing their weight after oven-drying at 105 °C to constant weight by the known volume of the sediment cores. The organic matter content was measured as Loss On Ignition (LOI) at 480 °C for eight hours.

3. Results

3.1. Burn severity

The burn severity, as registered by remote sensed data from Sentinel-2 images, is shown in Fig. 6. Most of the SP watershed underwent moderately severe fire, as in the other Pisan Mountains catchments involved in the same wildfire. About 12% of the Pisan Mountains area burned with high severity, while just 2% did so in the SP catchment, perhaps because of its proximity to the small town of Calci, where fire suppression efforts were greater than elsewhere. Possibly for the same reason, the unburned surface amounted to over 16% in the SP watershed versus less than 9% in the whole Pisan Mountains area.

Field investigation mostly confirmed the remote-sensed data. In the areas where burn severity was recorded as moderate, most of the litter had completely burned, leaving a mixture of gray ash and black char on the soil surface, while in the understory the shrub skeletons remained. In the areas where fire severity was recorded as high, most of the above ground biomass, including finer fuels and the shrub layer < 2–3 cm, was consumed and turned into a gray or white ash covering the ground, while most of the tree stems were still standing although scorched (Fig. 4). The ash layer, however, did not last for long and was flushed away after the first rains.

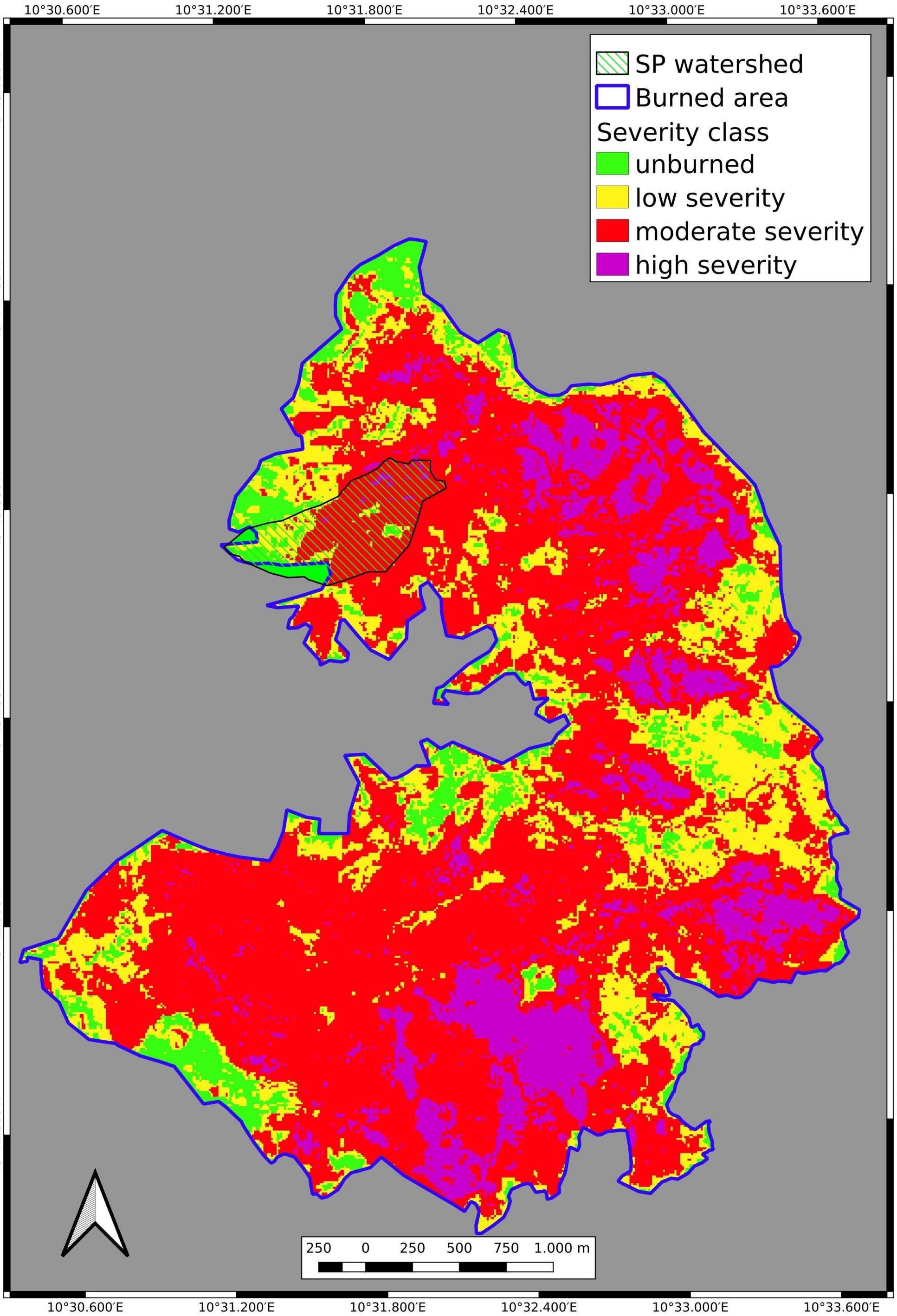

Fig. 6: Fire severity of the study area according to the Relativized Burn Ratio index.

3.2. Soil characteristics

In general, the Pisan mountains' soils were shallow and quite rich in rock fragments. The median depth of soils we measured was 0.4 m, with a minimum value of 0.1 m and a maximum value of over 1.2 m, the latter just in one plot in the maquis stand. The median value of stoniness, estimated by eye on the soil surface, was 16%, with a minimum value of <1% and a maximum value of over 34%. As a reference, a stone cover of 30% has shown to imply a consistent reduction of post-fire soil erosion (Prats et al., 2018). Soil texture was quite uniform in the investigated plots and ranged from sandy loam to loam, being composed by half sand and a third of total by silt on a weight basis.

3.3. Analysis of the sediments

The collected cores of sediments retained by the wooden check dam are shown in Fig. 7, while the organic matter content and particle size distribution of the different layers – confidently corresponding to the main episodes of deposition – are reported in Table 2. The maximum thickness of the sediment deposit, 71.5 cm, was individuated 13 m upstream of the dam. None of the cores contained rock fragments, i.e. larger than 2 mm, or coarse charcoal pieces, which were instead abundant in the ash layer covering the burned soils (Mastrolonardo et al., 2017).

The thickest core, core A, showed six distinct layers (A1 to A6, from the surface downwards). The A1–A4 layers, overall 40.6 cm thick, were clearly made of post-fire eroded soil, as revealed by the blackish colour imposed by the abundant charred material (Table 2). The A4 was much richer in organic matter than all the overlying material, which was of course brought in by subsequent rainfall. The A5–A6 layers, i.e. the bottom of the whole deposit (i.e. the first ones that settled), were much different from the upper ones, i.e. lighter, brownish in colour and poorer in organic matter. However, they differed each other in their organic matter content, the deeper one being poorer. In terms of particle size distribution, there was no clear discontinuity between the A1−A4 and A5-A6 sediment layers (Table 2). Nevertheless, with the subsequent rainy events the deposited eroded soil tended to become increasingly coarser from base upward, i.e. richer in sand and poorer in silt (whereas clay was almost constant and amounting to around 10 %).

Core B was taken several meters upstream of Core A, where the sediment deposit was much thinner. The layers of which it was composed approximately corresponded to the ones in the uppermost 20 cm of core A. However, there were some discrepancies between the two cores, such as the much higher organic matter and sand contents in the deepest layer in core B compared to the relative layer in core A, most probably due to progressive selective deposition of particles on a weight basis.

Core E comprised four layers, including a brownish layer at the bottom, which is a similar material described at the base of core A in terms of thickness, organic matter content and particle size distribution. The blackish material, assumed to be from the burned area, had a more homogeneous appearance than in the other two cores, although still showing three distinct layers; actually, these latter were similar to each other in terms of both organic matter and particle size distribution. This homogeneity could be explained by the flow turbulences acting in the water close to the check dam, where the E core was from.

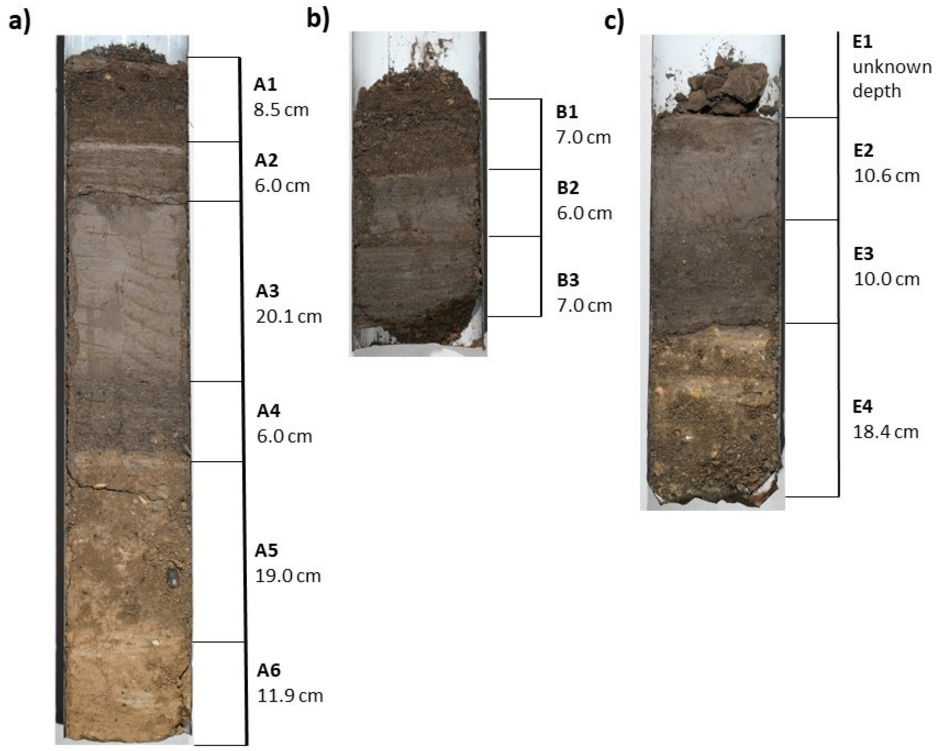

Fig. 7: Sediment cores collected upstream the check dam built immediately after the wildfire at the outlet of the Santo Pietro watershed (see Fig. 3 for the locations of the cores).

Core	Layer	Depth	Thickness	BD g cm^{-3}	Organic matter %	Sand %	Silt %	Clay %
A	A1	0–8.5 cm	8.5 cm	0.53	23.1	64.7	25.5	9.8
	A2	8.5–14.5 cm	6.0 cm	0.49	21.3	53.3	37.2	9.5
	A3	14.5–34.6 cm	20.1 cm	0.66	19.4	41.0	50.8	8.1
	A4	34.6–40.6 cm	6.0 cm	0.56	32.1	46.1	44.1	9.8
	A5	40.6–59.6 cm	19.0 cm	0.93	9.1	45.2	44.1	10.7
	A6	59.6–71.5 cm	11.9 cm	1.02	3.9	32.2	54.7	13.1
B	B1	0–6 cm	6 cm	nd	25.6	70.1	23.3	6.6
	B2	6–13 cm	7 cm	nd	21.7	38.6	55.0	6.4
	B3	13–20 cm	7 cm	nd	26.4	50.2	40.5	9.4
E	E1	0–3 cm	3 cm	nd	16.5	41.0	49.1	9.9
	E2	3–13.6 cm	10.6 cm	nd	16.4	32.2	57.7	10.1
	E3	13.6–23.6 cm	10.0	nd	19.8	47.7	42.7	9.6
	E4	23.6–42 cm	18.4	nd	10.4	46.5	41.0	12.5

nd= not determined

Table 2: Depth, thickness, bulk density, organic matter concentration and particle size distribution of the layers in the investigated sediment cores from the Santo Pietro (SP) watershed.

3.4. Post-fire rainfall-runoff-erosion

The average CNI calculated for the SP watershed was 71, considering the extent of the burned areas according to RBR map. Rainfall and runoff time series, together with the hypothesized deposition events for the SP watershed, are reported in Fig. 8, where the main flow events are associated with the six deposition events detected by the analysis of sediment core A. Coherently, layer A3 was assigned to the largest flow event.

Table 3 shows the overall results of the analysis, including the values used for STE calculation. The latter was performed considering the same C_i for events A4 and A3, and for events A2 and A1, since the two couples of events were very close in time.

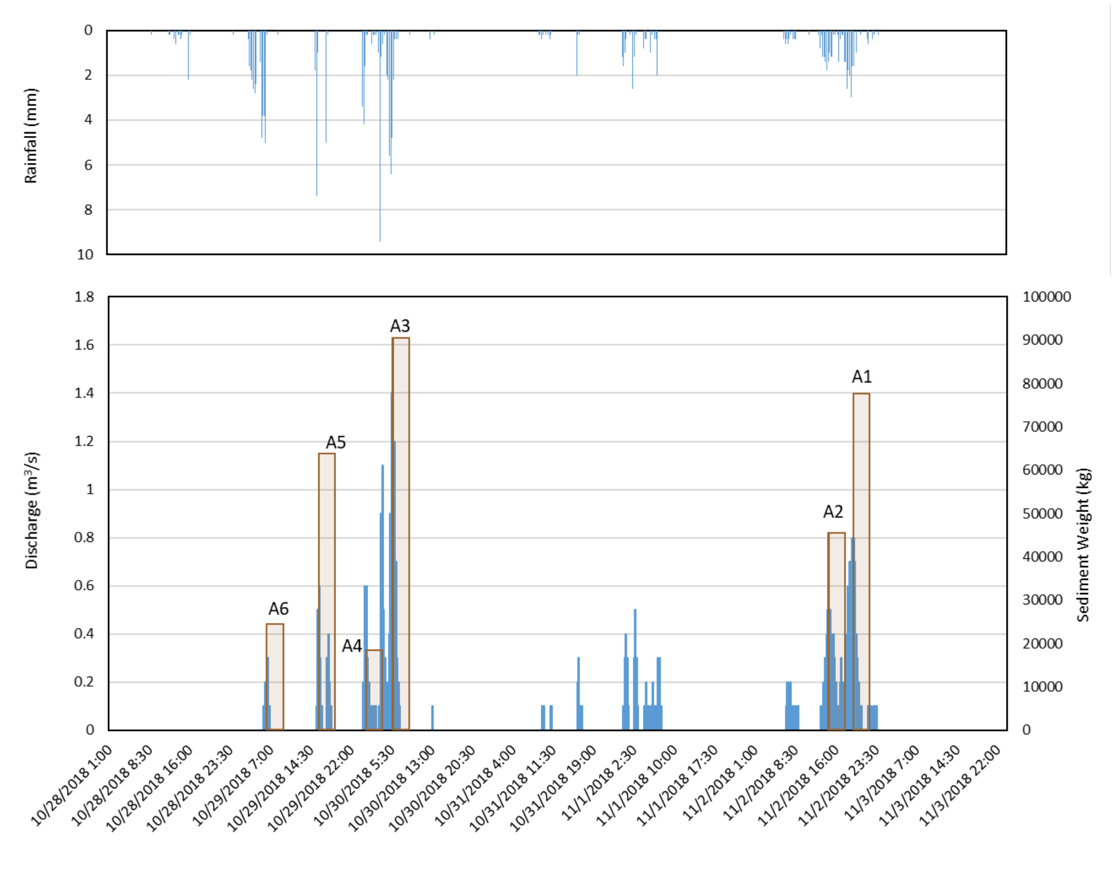

Fig. 8: Rainfall and runoff time series, and amount of sediments transported by flow events (brown bars) at the outlet of the Santo Pietro watershed.

Layer	Peak discharge $m^3\ s^{-1}$	Flow event volume m^3	Sediment volume at check dam site m^3	MD_i t	C_i m^3	STE_i	ME_i t	Sediment concentration $g\ l^{-1}$ - $kg\ m^{-3}$
A6	0.3	900	10.22	10.43	142.60	0.42	24.64	27
A5	0.6	2430	27.86	25.91	132.38	0.41	63.94	26
A4	0.6	1800	11.35	6.36	104.52	0.35	18.17	10
A3	1.6	8910	47.94	31.64	104.50	0.35	90.46	10
A2	0.5	3510	17.57	8.61	45.21	0.19	45.61	13
A1	0.8	5400	27.65	14.65	45.21	0.19	77.61	14

Table 3: Values of peak discharge, flow, sediment concentration, volume and mass (MDi) at check dam site, volume capacity upstream the check dam (Ci), Sediment Trap Efficiency (STEi), sediment eroded at catchment scale (MEi) for the Santo Pietro (SP) watershed.

By equation 1 and the available rainfall data, the Rt of the largest 30-minute event monitored was estimated to be 1 year. The main rainfall-runoff events recorded from October 28th to November 3rd, 2018, showed a significant correlation with the mass calculated for the deposition layers of Core A, when the six events are considered as a whole group (Fig. 9). However, a second interpretation of the results based on the separation of the A6–A5 events from the A4–A1 ones provided a better regression and additional insights. The sediment concentrations in the runoff events related to the A6 and A5 layers were similar (around 26 g l^{-1}) and higher than the ones related to the events generating the A4 to A1 layers. Therefore, the two classes of events could represent two separated groups, both characterized by two linear relationships (forced to pass at 0) with $R^2 \sim 1$ (Fig. 9). The values for the A4 to A1 layers were in line with those from other studies related to post-fire sedimentation (e.g., Ryan et al., 2011; García-Comendador et al., 2017), which amount to 10–14 g l^{-1}. Such relatively low sediment concentrations are due to the shallowness of soils in the study area and the abundance of outcrops and emerging rock fragments.

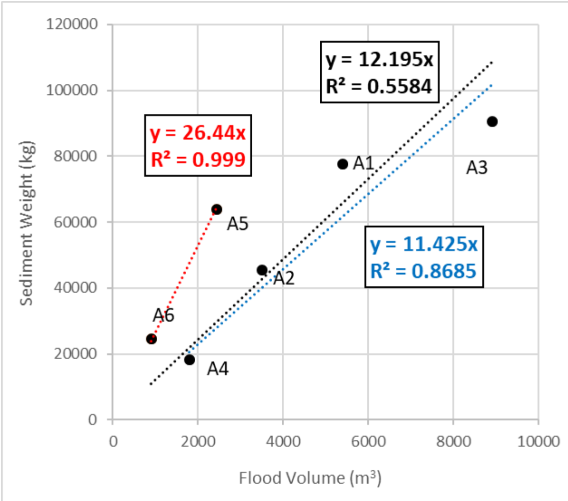

Fig. 9: Correlation of flow and sedimentation events at the outlet of the Santo Pietro watershed. Black trendline: A6–A1 regression; red trendline: A6–A5 regression; blue trendline: A4–A1 regression.

Comparing the precipitation and erosion events at the watershed scale, the soil erosion calculated for the SP basin in occasion of the rains immediately after the fire was 0.26 mm, corresponding to 7.85 t ha^{-1}. This value corresponded to 42% of the watershed average annual potential erosion rate in normal conditions (18.8 t ha^{-1} y^{-1}) estimated with the USLE method (Regione Toscana, 2020).

4. Discussion

4.1. Sedimentation dynamics

The sequence of sedimentary layers of Core A (Table 2 and Fig. 7) is quite counter-intuitive, since the bottom layers (A5-A6), which were deposited before layers A1-A4, are poor in charred residues, which are light and, consequently, more prone to be eroded. In this framework, we hypothesized that the first rainfall events and the subsequent peak flows initially transported to the sedimentation site those fire-unaffected sediments that were close or within the river stream, as found by Esposito et al. (2017) in a burned watershed in Southern Italy. According to such hypothesis, the burned soil eroded from the watershed slopes reached the channel and was consequently trapped by the check dam after some hours from the beginning of the rain. This would explain the virtual lack of organic material in the A6 layer. Layer A5 was richer in organic matter than the underlying one, revealing that some of the burned sediments intermixed with the previously eroded material and reached the check dam site on the occasion of the second deposition event.

The increasing coarseness of texture from the bottom A6 layer to the A1 one could be a consequence of progressive depletion in silt-sized particles of the residual soil of the watershed. Shakesby et al. (2003), studying two small catchments in Australia on sandstone bedrock affected by fires of different severity, found that the sediments transported downstream were richer in organic matter, mostly charred, and contained more fines (<63 µm particles) than those deposited on slopes. Layer A3, the thickest one (20 cm), was rather homogenous and apparently put in place by a single runoff event, fast and uninterrupted. This is confirmed by the HMS model (Fig. 8), which shows that the A3 layer was generated by the largest runoff event, although it comprised two flow peaks induced by a bimodal rainfall pattern. On the contrary, the two overlying layers, A2 and A1, were finely stratified, suggesting a discontinuous deposition.

4.2. Erosion rate and sediment yield

The first two rains analyzed for the SP watershed – those that most plausibly originated the A6 and A5 layers – transported an overall higher concentration of sediments than the subsequent ones, which can be explained by one or both the following reasons: i) the first two floods have remobilized that C-poor material accumulated near the river bed or already in it (as explained in par. 3.3); and ii) the initial sediment yield has been fed by the operations for building some erosion control structures, including the check dams on the SP stream. The second hypothesis is consistent with the lower presence of organic matter in the A6-A5 layers compared the overlying ones. Although the used model was not validated, leading to a relative uncertainty in the estimation of sediment concentrations, the differences between the first two events and the four following ones are consistent and can be considered representative of the overall sediment mobilization dynamics at catchment scale.

The estimated erosion rate in the SP watershed, 7.85 t ha^{-1}, is comparable to that found in other studies, as, for instance, the one by Kampf et al. (2016), who measured an average loss of 5.9 t ha^{-1} after some summer storms, of comparable intensities than those described in this study, observed a couple of months after a fire that affected a forest stand composed predominantly by ponderosa pine on stony sandy loam soils in Colorado. On the other hand, our results are quite lower than those from other studies. For instance, Esposito et al. (2017) observed sediments yield ranging from 19.8 to 33.1 t ha^{-1} in a watershed 11 ha wide in Southern Italy on fresh volcanic deposits because of an intense rainstorm happened one month after a wildfire. Similarly, Robichaud et al. (2013) reported soil losses of 18.6 to 24.4 t ha^{-1} after two high-intensity rainstorms in a previously burned 4.6 ha wide watershed in Colorado. These studies, however, dealt with slightly higher intensity rainfalls than ours. On a longer term, again at the catchment scale, Mayor et al. (2007) measured 35 mm and 4.6 t ha^{-1} as total volume of runoff and sediments during 7 years (from 1999 to 2005) after a wildfire nearby Alicante, Spain. In a 72-km^2 catchment in southern Italy, Grangeon et al. (2021) checked over an entire hydrological year including 21 flood events (from November 2010 to May 2011), finding that the mean sediment yield had increased by 5% and up to a maximum of 37% because of fire, ranging from 2.0 t $ha^{-1}yr^{-1}$ to 2.7 t $ha^{-1}yr^{-1}$ depending on the burned area. However, a comparison of our data with those from longer-term studies could be somewhat improper as we evaluated just the first rain events after the fire. Nonetheless, in the Mediterranean Basin the period of high susceptibility to erosion of burned soils is typically short as the maximum fire potential is during the dry summer (July-August), which is followed by a rainy autumn (Granged et al., 2011; Shakesby, 2011; Lucas-Borja et al., 2019). The fire-induced impact on soil is the combination/interaction of various factors, in particular fire severity and extent, terrain slope, rainfall intensity and soil infiltrability (the "fire nexus" *sensu* Neary, 2019). The Pisan Mountains have steep slopes characterised by high erosion rates and the studied wildfire, whose severity was moderate to high, affected entire watersheds, theoretically triggering conditions for dramatic soil erosion even with relatively modest rainfall events. Nonetheless, this did not happen. Often, post-fire erosion rates in the Mediterranean area have been reported to be relatively modest, ranging from 0.016 to 13.1 t ha^{-1} $year^{-1}$ (Shakesby, 2011), mainly because of the shallow, skeleton-rich soils that: i) provide limited amount of fines and: ii) are endowed of a stony pavement, which protects the underlying soil from erosion (Shakesby, 2011), encourages water infiltration and limits the formation of a continuous fire-induced water repellency layer (Urbanek and Shakesby, 2009; Wu et al., 2021). This could be the case for our study area, indeed.

A relatively moderate soil loss caused by a fire, however, does not necessarily correspond to an equally moderate negative impact on the ecosystem. In fact, most of the organic matter and nutrients are concentrated near the surface, so topsoil erosion negatively affects both soil fertility and water quality, especially in such already degraded, where even small soil losses have serious consequences in terms of land degradation (Shakesby et al., 2015). Here as elsewhere in the Mediterranean regions, the application of soil and water bioengineering solutions, such as cover and barrier treatments, can hinder the progression of erosion in a sustainable way (Florineth, 2012; Girona-García et al., 2021). Particularly in severely burned areas, targeted economically viable and effective measures are strongly requested to stabilize the slopes (Girona-García et al., 2021; Zaimes et al., 2020), as well as to drain and control runoff (Florineth, 2012).

5. Conclusions

This paper inspects the hydrological impacts at watershed scale of a fire of moderate to high severity that involved the Pisan Mountains in central Italy. The high extent of the fire, the marked loss of vegetation cover, and the steep slopes would have suggested substantial post-fire soil erosion. Our watershed-scale investigation, carried out by a HEC-HMS model, and the sediment yields, inferred by sediment cores taken upstream the ultimate dam, allowed estimating the eroded soil through the dynamic calculation of STE. This amounted to 7.85 t ha^{-1}, which is unexpectedly moderate considering the already high average annual potential erosion rate of the watershed.

The comparison of such findings with those from other studies in the Mediterranean area highlights that the post-fire hydrological response can be highly variable, even in comparable conditions of fire severity, wildfire scale, slope and post-fire rainfall. It supports the opportunity to rely on multiple studies targeting all the specific and diverse conditions for the prediction of hydrological and erosive risks and the management in fire-affected environments of Mediterranean regions. The methodology implemented in our study is an example in this sense, taking into account burn severity, slope, soil characteristics, pre-fire land use, rainfall patterns etc., as well as other factors such as the potential downstream off-site damages to valuables. This methodology could be reproduced in all those cases where civil works aiming at retaining sediments are implemented but the available data are scarce. The results from such studies, if well integrated with watershed planning, are useful for indicating how quick check dams built for reducing the risk flood would fill, and if further infrastructures are needed.

REFERENCES

Abraham J, Dowling K, Florentine S (2017) Risk of post-fire metal mobilization into surface water resources: A review. Sci Total Environ 599–600:1740–1755. https://doi.org/10.1016/j.scitotenv.2017.05.096

Brown CB (1943) Discussion of sedimentation in reservoirs, by J. Witzig. Proceedings of the American Society of Civil Engineers 69: 1493–1500.

Castelli F (2014) Implementazione di modello idrologico distribuito per il territorio toscano - Regione Toscana. https://www.regione.toscana.it/-/implementazione-di-modello-idrologico-distribuito-per-il-territorio-toscano

ClimateData.org (2021) https://it.climate-data.org/

Coschignano G, Nicolaci A, Ferrari E, Cruscomagno F, Iovino F (2019) Evaluation of hydrological and erosive effects at the basin scale in relation to the severity of forest fires. iForest 12: 427-434. https://doi.org/10.3832/ifor2878-012

Ebel BA (2020) Temporal evolution of measured and simulated infiltration following wildfire in the Colorado Front Range, USA: Shifting thresholds of runoff generation and hydrologic hazards. J Hydrol 585: 124765. https://doi.org/10.1016/j.jhydrol.2020.124765

Esposito G, Matano F, Molisso F, Ruoppolo G, Di Benedetto A, Sacchi M (2017) Post-fire erosion response in a watershed mantled by volcaniclastic deposits, Sarno Mountains, Southern Italy. Catena 152:227–241. https://doi.org/10.1016/j.catena.2017.01.009

Florineth F (2012) Pflanzen statt Beton 2. völlig überarbeitete u. erweiterte Auflage September 2012. PATZER VERLAG GmbH & Co, Berlin.

Franceschelli M, Leoni L, Memmi I, Puxed M (1986) Regional distribution of Al-silicates and metamorphic zonation in the low-grade Verrucano metasediments from the Northern Apennines, Italy. J Metamorph Geol 4:309–321. https://doi.org/10.1111/j.1525-1314.1986.tb00353.x

García-Comendador J, Fortesa J, Calsamiglia A, Calvo-Cases A, Estran J (2017) Post-fire hydrological response and suspended sediment transport of a terraced Mediterranean catchment. Earth Surf Process Landforms 42:2254–2265. https://doi.org/10.1002/esp.4181

Girona-García A, Vieira DCS, Silva J, Fernández C, Robichaud PR, Keizer JJ (2021) Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis. Earth-Science Rev 217: 103611. https://doi.org/10.1016/j.earscirev.2021.103611

Granath G, Moore PA, Lukenbach MC, Waddington JM (2016) Mitigating wildfire carbon loss in managed northern peatlands through restoration. Sci Rep 6:1–9. https://doi.org/10.1038/srep28498

Granged AJP, Zavala LM, Jordán A, Bárcenas-Moreno G (2011) Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: A 3-year study. Geoderma 164:85–94. https://doi.org/10.1016/j.geoderma.2011.05.017

Grangeon T, Vandromme R, Cerdan O, De Girolamo AM, Lo Porto A (2021) Modelling forest fire and firebreak scenarios in a Mediterranean mountainous catchment: Impacts on sediment loads. J of Env Manag. 289:112497. https://doi.org/10.1016/j.jenvman.2021.112497

Greenbaum N, Wittenberg L, Malkinson D, Inbar M (2021) Hydrological and sedimentological changes following the 2010-forest fire in the Nahal Oren Basin, Mt. Carmel Israel–a comparison to pre-fire natural rates. Catena 196:104891. https://doi.org/10.1016/j.catena.2020.104891

Giorgetti G, Goffé B, Memmi I, Nieto F (1998) Metamorphic evolution of Verrucano metasediments in northern Apennines: new petrological constraints. Eur J Mineral 10:1295–1308. https://doi.org/10.1127/ejm/10/6/1295

Kampf SK, Brogan, DJ, Schmeer S, MacDonald LH, Nelson PA (2016) How do geomorphic effects of rainfall vary with storm type and spatial scale in a post-fire landscape? Geomorphology 273:39–51. https://doi.org/10.1016/j.geomorph.2016.08.001

Köthe H (2003) Existing sediment management guidelines: An overview. What will happen with the sediment/dredged material? J Soils Sediments 3:139–143. https://doi.org/10.1065/jss2003.08.082

Larsen IJ, MacDonald LH, Brown E, Rough D, Welsh MJ, Pietraszek JH, Libohova Z, de Dios Benavides-Solorio J, Schaffrath K (2009) Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing? Soil Sci Soc Am J 73:1393–1407. https://doi.org/10.2136/sssaj2007.0432

Lucas-Borja ME, González-Romero J, Plaza-Álvarez PA, Sagra, J, Gómez ME, Moya D, Cerdà A, de las Heras J (2019) The impact of straw mulching and salvage logging on post-fire runoff and soil erosion generation under Mediterranean climate conditions. Sci Total Environ 654:441–451. https://doi.org/10.1016/j.scitotenv.2018.11.161

Mastrolonardo G, Hudspith VA, Francioso O, Rumpel C, Montecchio D, Doerr SH, Certini G (2017) Size fractionation as a tool for separating charcoal of different fuel source and recalcitrance in the wildfire ash layer. Sci Total Environ 595:461–471. https://doi.org/10.1016/j.scitotenv.2017.03.295

Mayor ÁG, Bautista S, Bellot J (2011) Scale-dependent variation in runoff and sediment yield in a semiarid Mediterranean catchment. J Hydrol 397:128–135. https://doi.org/10.1016/j.jhydrol.2010.11.039

Mayor ÁG, Bautista S, Llovet J, Bellot J (2007) Post-fire hydrological and erosional responses of a Mediterranean landscape: Seven years of catchment-scale dynamics. Catena 71:68–75. https://doi:10.1016/j.catena.2006.10.006

Moody JA, Martin DA (2009) Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. Int J Wildl Fire 18:96–115. https://doi.org/10.1071/WF07162

Neary DG (2019) Forest Soil Disturbance: Implications of Factors Contributing to the Wildland Fire Nexus. Soil Sci Soc Am J 83:228–243. https://doi.org/10.2136/sssaj2018.12.0471

Panagos P, Borrelli P, Poesen J, Ballabio C, Lugato E, Meusburger K, Montanarella L, Alewell C (2015) The new assessment of soil loss by water erosion in Europe. Environ Sci Policy 54:438–447. https://doi.org/10.1016/j.envsci.2015.08.012

Parks SA, Dillon GK, Miller C (2014) A new metric for quantifying burn severity: The relativized burn ratio. Remote Sens 6:1827–1844 https://doi.org/10.3390/rs6031827

Parsons AJ, Brazier RE, Wainwright J, Powell DM (2006) Scale relationships in hillslope runoff and erosion. Earth Surf Process Landforms 31:1384–1393. https://doi.org/10.1002/esp.1345

Parsons A, Robichaud PR, Lewis SA, Napper C, Clark JT (2010) Field Guide for Mapping Post-Fire Soil Burn Severity.

Pausas JG, Llovet J, Rodrigo A, Vallejo R (2008) Are wildfires a disaster in the Mediterranean basin? A review. Int J Wildl Fire 17(6):713-723 https://doi.org/10.1071/WF07151

Poesen JWA, Hooke JM (1997) Erosion, flooding and channel management in Mediterranean environments of southern Europe. Prog Phys Geogr 21:157–199. https://doi.org/10.1177/030913339702100201

Powlson DS, Whitmore AP, Goulding KWT (2011) Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. Eur J Soil Sci 62 :42–55. https://doi.org/10.1111/j.1365-2389.2010.01342.x

Prats SA, Abrantes JRCB, Coelho C, Keizer JJ, de Lima JLMP (2018) Comparing topsoil charcoal, ash, and stone cover effects on the postfire hydrologic and erosive response under laboratory conditions. L Degrad Dev 29: 2102-211. https://doi.org/10.1002/ldr.2884

Preti F (2013) Forest protection and protection forest: Tree root degradation over hydrological shallow landslides triggering. Ecol Eng 61:633–645. https://doi.org/10.1016/j.ecoleng.2012.11.009

Preti F, Forzieri G, Chirico GB (2011) Forest cover influence on regional flood frequency assessment in mediterranean catchments. Hydrol Earth Syst Sci 15:3077–3090. https://doi.org/10.5194/hess-15-3077-2011

Robichaud PR, Wagenbrenner JW, Lewis SA, Ashmun LE, Brown RE, Wohlgemuth, PM (2013) Post-fire mulching for runoff and erosion mitigation Part II: Effectiveness in reducing runoff and sediment yields from small catchments. Catena 105:93–111. https://doi.org/10.1016/j.catena.2012.11.016

Robichaud PR, Wagenbrenner JW, Pierson FB, Spaeth KE, Ashmun LE, Moffet CA (2016) Infiltration and interrill erosion rates after a wildfire in western Montana, USA. Catena 142:77–88. https://doi.org/10.1016/j.catena.2016.01.027

Robinne F, Hallema DW, Bladon KD, Flannigan MD, Boisramé G, Bréthaut CM, Doerr SH, Di Baldassarre G, Gallagher L, Hohner AK, Khan SJ, Kinoshita AM, Martin D, Mordecai R, Nunes JP, Nyman P, Santín C, Sheridan G, Stoof CR, Thompson MP, Waddington JM, Wei Y, (2021) Scientists' warning on extreme wildfire risks to water supply. Hydrol Process e14086:1-10. https://doi.org/10.1002/hyp.14086

Rulli MC, Rosso R (2007) Hydrologic response of upland catchments to wildfires. Adv Water Resour 30:2072–2086. https://doi.org/10.1016/j.advwatres.2006.10.012

Rulli MC, Bozzi S, Spada M, Bocchiola D, Rosso R (2006) Rainfall simulations on a fire disturbed mediterranean area. J Hydrol 327:323–338. https://doi.org/10.1016/j.jhydrol.2005.11.037

Ryan SE, Dwire KA, Dixon MK (2011) Impacts of wildfire on runoff and sediment loads at Little Granite Creek, western Wyoming. Geomorphology 129:113–130. https://doi.org/10.1016/j.geomorph.2011.01.017

Shakesby RA (2011) Post-wildfire soil erosion in the Mediterranean: Review and future research directions. Earth-Science Rev 105:71–100. https://doi.org/10.1016/j.earscirev.2011.01.001

Shakesby RA, Bento CPM, Ferreira CSS, Ferreira AJD, Stoof CR, Urbanek E, Walsh RPD (2015) Impacts of prescribed fire on soil loss and soil quality: An assessment based on an experimentally-burned catchment in central Portugal. Catena 128:278–293. https://doi.org/10.1016/j.catena.2013.03.012

Shakesby RA, Chafer CJ, Doerr SH, Blake WH, Wallbrink P, Humphreys GS, Harrington BA (2003) Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires. Aust Geogr 34:147–175. https://doi.org/10.1080/00049180301736

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. Earth-Science Rev 74:269–307. https://doi.org/10.1016/j.earscirev.2005.10.006

Scharffenberg B, Bartles M, Brauer T, Fleming M, Karlovits G (2018) Hydrologic Modeling System HEC-HMS User's Manual. U.S. Army Corps of Engineers, Institute for Water Resources. Hydrologic Engineering Center (CEIWR-HEC). Davis, CA, USA.

Soil Survey Staff (2003) Keys to Soil Taxonomy, Ninth edition. U.S. Government Printing Office, Washington, DC.

Soulis KX (2018) Estimation of SCS Curve Number variation following forest fires. Hydrol Sci J 63:1332–1346. https://doi.org/10.1080/02626667.2018.1501482

Stavi I (2019) Wildfires in grasslands and shrublands: A review of impacts on vegetation, soil, hydrology, and geomorphology. Water 11:1042. https://doi.org/10.3390/w11051042

Grangeon T, Vandromme R, Cerdan O, De Girolamo AM, Lo Porto A (2021) Modelling forest fire and firebreak scenarios in a mediterranean mountainous catchment: Impacts on sediment loads. J Environ Manage 289:112497. https://doi.org/10.1016/j.jenvman.2021.112497

Thompson AL, Gantzer CJ, Anderson SH (1991) Topsoil depth, fertility, water management, and weather influences on yield. Soil Sci Soc Am J 55:1085–1091. https://doi.org/10.2136/sssaj1991.03615995005500040032x

Urbanek E, Shakesby RA (2009) Impact of stone content on water movement in water-repellent sand. Eur J Soil Sci 60:412–419. https://doi.org/10.1111/j.1365-2389.2009.01128.x

USDA Forest Service (2006) Burned Area Emergency Response Treatments Catalog. San Dimas, California. United States Department of Agriculture, Forest Service.

Van Der Werf GR, Randerson JT, Giglio L, Van Leeuwen TT, Chen Y, Rogers BM, Mu M, Van Marle MJE, Morton DC, Collatz GJ, Yokelson RJ, Kasibhatla PS (2017) Global fire emissions estimates during 1997-2016. Earth Syst Sci Data 9:697–720. https://doi.org/10.5194/essd-9-697-2017

Vega SP, Williams CJ, Brooks ES, Pierson FB, Strand EK, Robichaud PR, Brown RE, Seyfried MS, Lohse KA, Glossner K, Pierce JL, Roehner C (2020) Interaction of wind and cold-season hydrologic processes on erosion from complex topography following wildfire in sagebrush steppe. Earth Surf Process Landforms 45:841–861. https://doi.org/10.1002/esp.4778

Wilson C, Kampf SK, Ryan S, Covino T, MacDonald LH, Gleason H (2021) Connectivity of post-fire runoff and sediment from nested hillslopes and watersheds. Hydrol. Process. 35: e13975. https://doi.org/https://doi.org/10.1002/hyp.13975

Wagenbrenner JW, Robichaud PR (2014) Post-fire bedload sediment delivery across spatial scales in the interior western United States. Earth Surf Process Landforms 39:865–876. https://doi.org/https://doi.org/10.1002/esp.3488

Weninger T, Filipović V, Mešić M, Clothier B, Filipović, L (2019) Estimating the extent of fire induced soil water repellency in Mediterranean environment. Geoderma 338:187–196. https://doi.org/10.1016/j.geoderma.2018.12.008

Wu J, Baartman JEM, Nunes JP (2021) Comparing the impacts of wildfire and meteorological variability on hydrological and erosion responses in a Mediterranean catchment. L Degrad Dev 32:640-653. https://doi.org/10.1002/ldr.3732

Zaimes GN, Kasapidis I, Gkiatas G, Pagonis G, Savvopoulou A, Iakovoglou V (2020) Targeted placement of soil erosion prevention works after wildfires. IOP Conf Ser Earth Environ Sci 612: 012050. https://doi.org/10.1088/1755-1315/612/1/012050

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