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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.

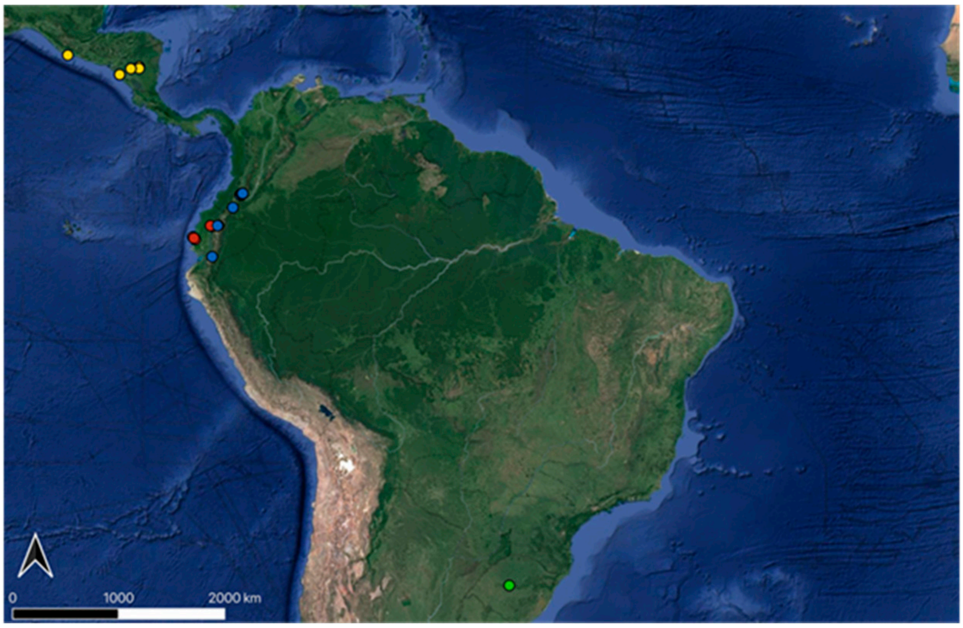

Figure 1. Locations of described soil and water bioengineering constructions.

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).

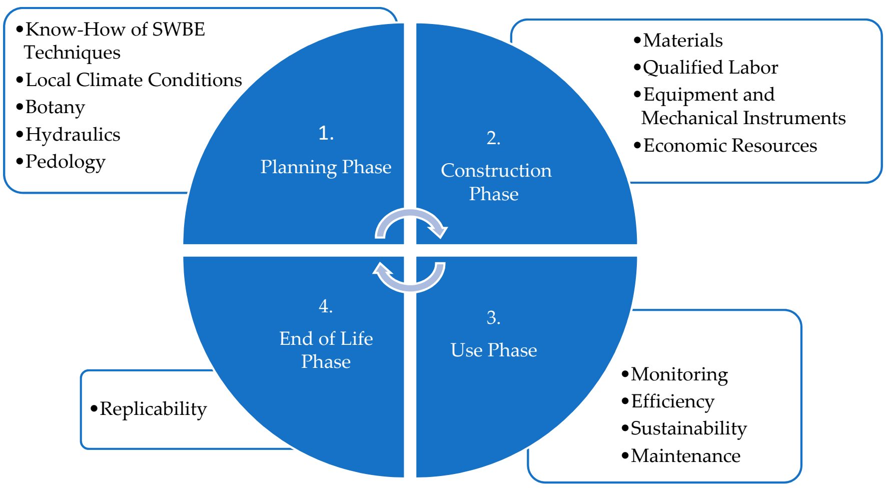

Figure 12. Structure of step 4 of the transferability analysis for soil and water bioengineering.

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 penduliflors*	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.

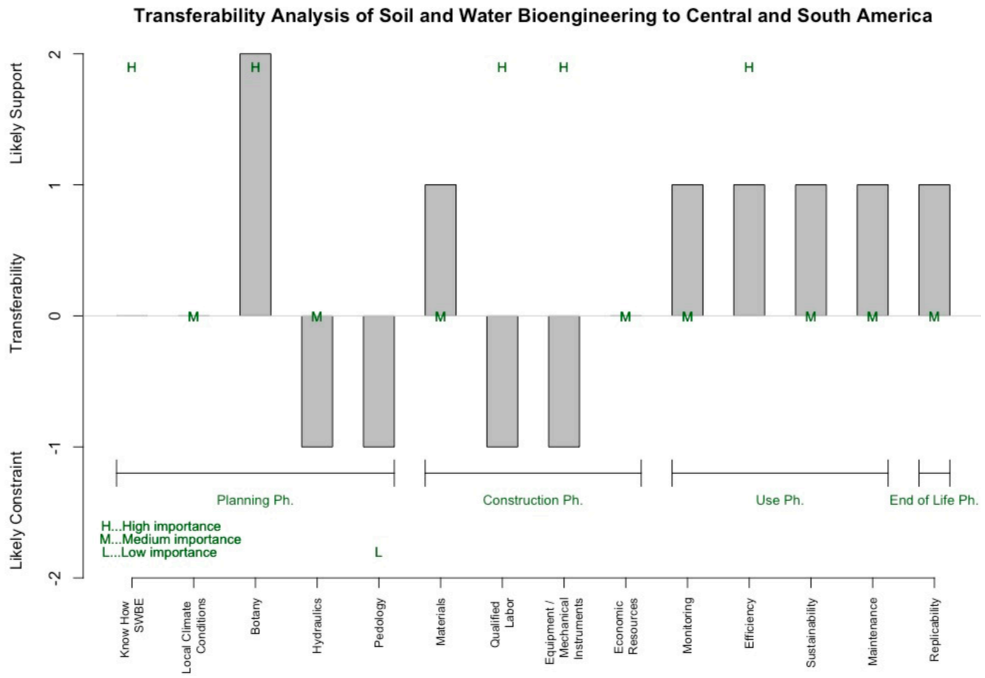

Figure 15. Comparison of level of importance and assessment value of the components.

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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