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Nature – based solutions for hillslope stability. A systematic review

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Dedicatoria

Dedico este trabajo de titulación, y en sí toda esta maestría a mi esposa. Con ella inicié esta aventura y gracias a ella la he terminado. Está dedicado a su corazón, su paciencia, y su espíritu que son el motor de mi esfuerzo diario.

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Resumen

La inestabilidad de laderas representa un riesgo significativo para actividades humanas y procesos naturales, acentuada por el cambio climático. Para prevenir deslizamientos superficiales y movimientos de masa, y sus consecuencias, las Soluciones basadas en la Naturaleza (SbN) aparecen como una nueva alternativa a la infraestructura gris. El término SbN ha ganado importancia en los últimos años, cubriendo tópicos que incluyen estrategias de mejoramiento en el manejo de recursos naturales y reducción de riesgo de desastres. Para la estabilidad de laderas, las acciones de SbN más comunes usan propiedades de la vegetación, para incrementar la cohesión del suelo en las raíces y regulación hidrológica. En este estudio, realizamos una revisión sistemática de literatura usando bases de datos científicas (Scopus y Web of Science) para recolectar información acerca de implementación de SbN para estabilidad de laderas a nivel mundial. Encontramos la ubicación de las SbN, los tipos de SbN usados, las especies de plantas comúnmente aplicadas y los métodos para evaluar el desempeño de las SbN. La mayoría de los estudios recuperados fueron publicados en los últimos dos años. Descubrimos que Europa tiene el mayor número de estudios y mundialmente existen 36 tipos de SbN para estabilidad de laderas (p. ej. vallas vivas). Adicionalmente, identificamos 55 especies de plantas usadas (p. ej. Chrysopogon sp.) y 17 métodos que evalúan el desempeño de las SbN (p. ej. mediciones del comportamiento mecánico del suelo, fertilidad y crecimiento de las plantas). Nuestro estudio busca presentar un resumen actualizado del estado del arte de

SbN para la estabilidad de laderas, y así acrecentar el interés sobre el tema en investigadores y tomadores de decisiones, y consecuentemente ampliar su estudio, implementación y evaluación. Esto último contribuirá con alternativas a la infraestructura gris para la estabilidad de laderas, mejorando la gestión de los recursos naturales.

Palabras clave

Ecosistemas de montaña, movimientos de masa, laderas, sostenibilidad.

Abstract

Hillslope instability represents a significant risk for human activities and natural processes, accentuated by climate change. To prevent shallow landslides and mass movements, and their consequences, Nature–based Solutions (NbS) appeared as a new alternative to grey infrastructure. The term NbS has gained importance in the last years, covering topics that include strategies for improving natural resources management and disaster risk reduction. For hillslope stability, the most common NbS actions use vegetation properties to increase soil cohesion in the roots and hydrologic regulation. In this study, we conducted a systematic literature review using scientific databases (i.e. Scopus and Web of Science) to collect information on NbS worldwide implementation for hillslope stability, finding their locations, the types of NbS used, plant species commonly applied and methods used to assess the NbS performances. Most of the studies collected were published in the last two years. We found that Europe has the greatest number of studies and worldwide there are 36 different NbS for hillslope stability types (e.g. live cribwalls). In addition, we identified 55 plant species used (e.g. *Chrysopogon sp.*) and 17 methods that evaluate the NbS performance (e.g. measurements of soil mechanical behavior, fertility and plant growth). Our study aims to present an updated state-of-the-art summary of the NbS implemented for hillslope stability, to increase the interest of researchers and decision-makers in this topic, and consequently enhance their study, implementation and evaluation. The latter will contribute with alternatives to grey infrastructure for hillslope stability, improving natural resources management.

Keywords

mountain ecosystem; mass – movements; steep slope terrain; sustainability.

Introduction

Hillslope instability is one of the main concerns of disaster risk reduction, especially landslides that are more prone to occur in mountainous terrains (Gonzalez-Ollauri et al., 2021). The shear forces that become bigger than the strength forces of a slope cause this phenomenon. It could cause biodiversity loss, soil mass wasting, erosion, cumulation of sediments, poor quality of water bodies, damage to human life and infrastructure, economic losses, and shortening reservoir lifespan by decreasing reservoir storage capacity, among others (Gabet & Dunne, 2002; Gonzalez-Ollauri et al., 2021). One of the principal trigger factors that cause landslides or hillslope instability is the intensity of rainfall, especially under extreme precipitation events (Sidle & Ochiai, 2006). The rainfall infiltrates soil on a slope, and subsequently suction decreases, leading to a strength reduction and possible failure (Stokes et al., 2014). Additionally, after a rain event, water tends to accumulate on the hillslope toe, generating positive pore-water pressures and increasing the instability of the slope. Unfortunately, climate change has accentuated the occurrence of hillslope instability, due to the increase of extreme rain events and more are expected to occur in the future (IPCC, 2023). Although grey infrastructure exists to control hillslope instability; a more sustainable way to address the hillslope instability problem recently appeared: Nature-based Solutions (NbS). Grey infrastructure is costly and needs continuous restoration interventions (Stokes et al., 2014). Instead, NbS uses vegetation and soil for its application (WWAP & UN-Water, 2018); furthermore, the systemic interventions of NbS are locally adapted and resource-efficient (Maxwald et al., 2020). However, a specific project could need hybrid solutions (Maxwald et al., 2020).

There is no official consensus on how NbS must be defined (Gonzalez-Ollauri, 2022); however, this term was first used in the 2010s by the International Union for Conservation of Nature (IUCN) stated that NbS are “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). In 2015, a group of European experts promoted NbS in their continent, supported by the HORIZON 2020 projects focused on NbS for urban environments. Later, more efforts appeared like OPERANDUM, PHUSICOS and RECONECT projects (Preti et al., 2022). Additionally, the fields of climate change, water security, water pollution, food security, human health, and disaster risk management present various challenges where NbS could influence beneficially (Mickovski, 2021). Even though NbS for hillslope stability is not a widespread concept for science and executors it has become an umbrella term due to its huge scope of action, sponsoring various fields that fall under its line (Cohen-Shacham et al., 2016). There are various fields under the NbS framework: urban sustainability, ecological engineering, climate adaptation, ecosystem-based management approaches like ecosystem-based adaptation and ecosystem-based disaster risk reduction, green/blue infrastructure, hydraulic engineering, water science, plant ecology, geotechnical engineering, environmental psychology, ground/soil bioengineering, urban forestry, watershed management, biogeomorphology (Gonzalez-Ollauri et al., 2021; Preti et al., 2022; Tröger et al., 2022), among others. Before NbS for hillslope stability became a more known concept, certain approaches actually pertain to the field of NbS. For instance, soil and water bioengineering (SWBE) is one of the NbS approaches for hillslope stability, especially soil bioengineering (SBE), as it studies the dynamic between vegetation and hillslope stability.

Generally, vegetation helps to dry and drain the excess water through the root system and canopy (Gonzalez-Ollauri & Mickovski, 2020); therefore, it is used for controlling natural hazards (Mickovski, 2021), such as landslides. Vegetation intervenes on the first soil strata, reducing surface mass movements, like shallow landslides. The shallow landslides are the more superficial, about two meters in depth (Rickli & Graf, 2009), whose behaviour depends on the interaction of the soil-atmosphere that influences slope stability (Kalsnes & Capobianco, 2022). Two principal vegetation mechanisms provide stabilization of a hillslope: hydrological and mechanical (Kalsnes & Capobianco, 2022). On the hydrological approach, interception through the canopy reduces infiltration rates, and evapotranspiration reduces soil moisture (Naghdi et al., 2013). On the other hand, the mechanical effects of roots provide additional cohesion to the soil depending on the tensile strength and root density (Kalsnes & Capobianco, 2022). Vegetation used for stabilization purposes does not always have successful results. The altitude and weight of the trees combined with the wind could cause a soil mass movement (Guo et al., 2020). Furthermore, water infiltration within the soil profile could change, due to hydrological effects of vegetation on the hillslope. The macropores created by roots increase the infiltration rate causing slope failures during rainfall (Simon & Collison, 2002). Despite that, the benefits of NbS for hillslope stability overcome their disadvantages when implemented properly, and therefore they are of increasing interest to researchers and decision-makers (Gonzalez-Ollauri & Mickovski, 2020).

In this study, we pretend to summarize the NbS strategies for hillslope stability management, the plant species and the methodologies to evaluate NbS applications. To our knowledge, an updated state of the art on NbS for hillslope stability is lacking. For that reason, we summarized the information about this topic by using a Systematic Literature Review (SLR) method.

The main goals of this research are to identify the places around the world where NbS to hillslope stability were applied, the types of NbS, the plant species used and the methodologies for evaluating the performance of NbS in different cases.

Methodology

A Systematic Literature Review (SLR) method helps to obtain information about NbS applied to hillslope stability. A SLR collects and assesses, in a systematic way, the vast majority of scientific documents about the topic. We based our methodology on the PRISMA protocol. (Haddaway et al., 2017; Page et al., 2021).

We identified keywords to develop the Boolean codification to search literature in the Scopus and Web of Science (WoS) databases. We use hillslope, slope, mountain, landslide, mass movement, nature-based solution, NbS, soil and water bioengineering, SWBE and vegetation. The literature included studies published until December 2022, thus peer-reviewed scientific articles and grey literature (found through exploration on the Google search engine).

Figure 1 shows the initial search code. Afterwards, we made a more specific search of Soil and Water Bioengineering (SWBE). This topic is a widely applied practice in NbS for hillslope stability. It is more common to find the term SWBE in the literature referring to the use of vegetation for hillslope stability. The search codes chosen were: TITLE-ABS-KEY ((hillslope OR slope OR landslide) AND ("nature-based solutions" OR "nature-based solutions" OR "NBS" OR "soil and water bioengineering" OR "SWBE"))). We collected 424 studies on Scopus. We applied the corresponding search code for the WoS database: ALL=((hillslope* or slope* or landslide*) and ((nature and based and solution*) OR (nature-based and solution*) OR (NBS*) OR (soil and water and bioengineering*) OR (SWBE*))), and collected 312 studies. After removing duplicates (283), we had a sample of 453 scientific articles.

Later, we selected the articles using the following inclusion and exclusion criteria: no limit of publication time was applied as well as geographical limits and language; we included articles that describe the implementation of NbS for hillslope stability, even if they do not explicitly call the strategy an NbS (e.g. vegetation as hillslope stabilizer (Naghdi et al., 2013; Rickli & Graf, 2009).

We exclude conference papers due to the limited information they offer. In addition, the articles should include the implementation of NbS strategies for hillslope stability in the field, excluding articles that compare or analyze NbS theoretically. With the same inclusion and exclusion criteria, we selected 78 papers after the title/abstract assessment and then, after reading the text, we selected 40 scientific articles as a final sample (Annex 1). We extracted the following information from each article: title, authors, year of publication, study area, study period, methodology of slope stability analysis, NbS type, species of plants, and monitoring performance of NbS. Eventually, not all the articles had the complete information for the table. Later, we created figures and other specific tables from the extracted information to study our objectives. We have focused the figures, tables and discussion on the types of NbS, the sites of implementation, common plant species used and the methods to evaluate the hillslope stability with an NbS approach.

We grouped NbS types according to their principal characteristics, e.g. structure design (walls with wood) or construction material (stakes, wood, seeds) and also based on LARIMIT classification (Kalsnes & Capobianco, 2022). In that way, we formed eight groups with the NbS, live planting, live stakes (live poles), live crib walls, living palisades, live fascines, grating, brush layering and afforestation.

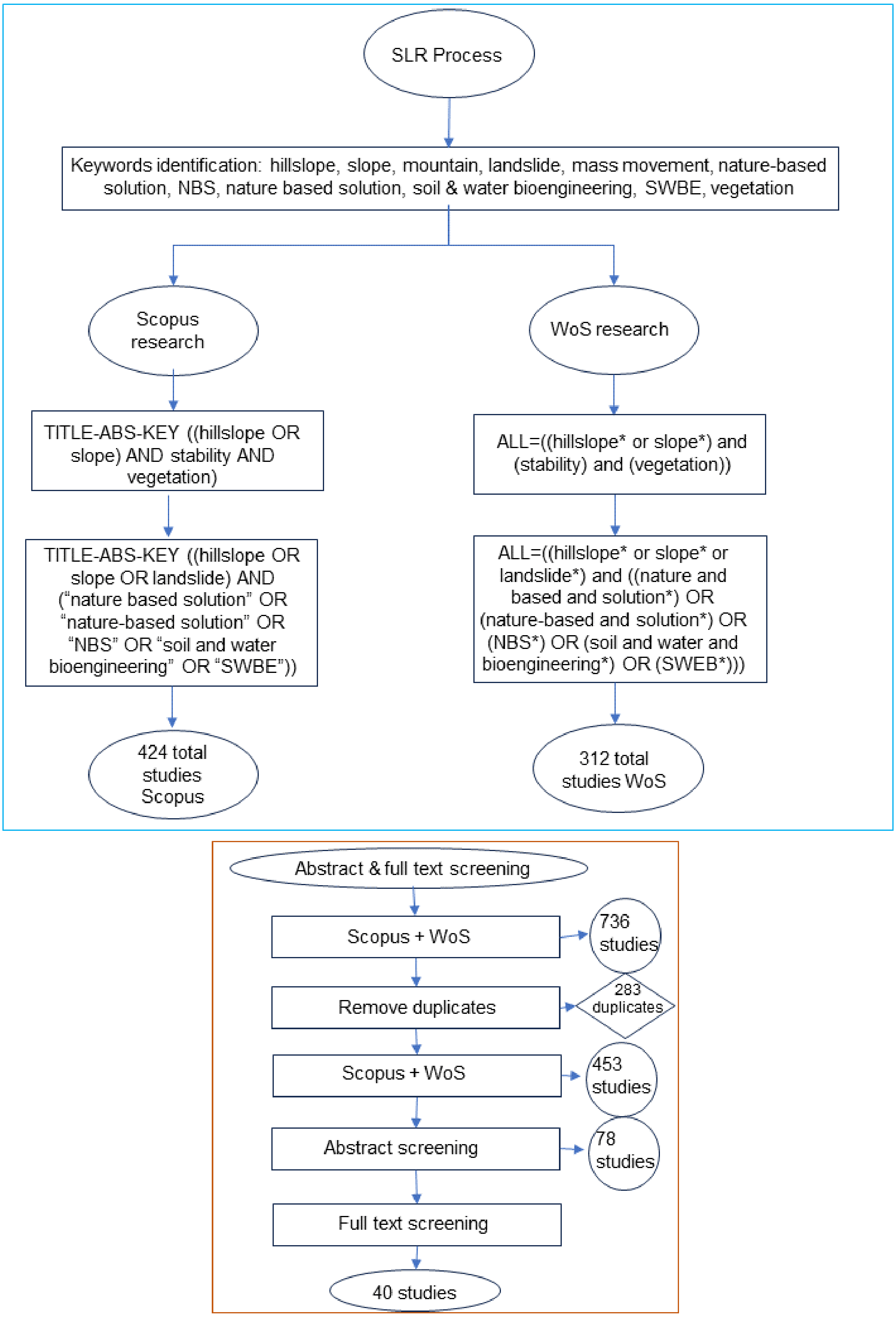

Figure 1. Systematic Literature Review methodology process

Results

We found that 48% of the studies mention “NbS”, and 52% have NbS implicitly. Even though “NbS” are not mentioned in the studies, their approaches can be considered NbS. Those approaches are vegetation to protect hillslopes or interventions related to the benefits of roots and plants to avoid landslides. Nearly half of the studies do not mention NbS directly. 74% of studies were published from 2018 to 2022, and 50% in the last two years, 2021-2022, pointing to an increasing interest in NbS.

Geographical distribution of NbS for hillslope stability

There are 18 documents that assess NbS in the European territory, eight in South America, five in Asia and four in North & Central America. Table 1 shows that seven studies took place in the United Kingdom (UK), being the country with more work developed, followed by Italy, Brazil, Ecuador and China with four, three registered NbS in Norway, two in Spain and Nicaragua; and one in Germany, France, Netherlands, Chile, Colombia, Nepal, USA, Mexico, Guatemala and Costa Rica. More specifically, Table 1 indicates five studies in Catterline in the UK, three studies in Rio Grande do Sul in Brazil, two studies in Quito and Santo Domingo in Ecuador and two in the Loess Plateau in China.

Table 1. Study sites where NbS for hillslope stability have been implemented.

Continent	Country	Study site	# studies
Europe – 18 studies	Italy – 4 studies	Portofino	1
		Serchio River Basin	1
		Campania region (Southern Italy)	1
		Italy	1
	Germany – 1 study	Lahn River. Hesse	1
	Norway – 3 studies	Gudbrandsdalen	1
		Norway	1
		Åserud ravine in Nes municipality	1
	United Kingdom – 7 studies	Catterline. Northeast Scotland	5
		Dundee City. Scotland	1
		Cumbria	1
	France – 1 study	Pyrenees	1
	Spain – 2 studies	Pyrenees	1
		Catalonia	1
	Netherlands – 1 study		1
South America – 8 studies	Brazil – 4 studies	Rocinha. Rio de Janeiro	1
		Río Grande do Sul	3
	Ecuador – 4 studies	East of Loja	1
		Río Chanchán	1
		Las Maravillas	1
		Santo Domingo	2
		Quito	2
		Jipijapa	1
		Membrillal	1
	Chile – 1 study	Patagonia	1
	Colombia – 1 study		1
Asia – 5 studies	China – 4 studies	Nanling National Nature Reserve	1
		Loess Plateau	2
		Liaohe River protected area	1
	Nepal – 1 study	Panchase Region. Central–Western hills	1
North & Central America – 4 studies	USA – 1 study	Guam Island. Ija watershed	1
	Mexico – 1 study	Community of Jacomulco province Veracruz	1
	Nicaragua – 2 studies		1
		Río Blanco. Matagalpa	1
	Guatemala – 1 study	River Coyolate. Santa Odilia. Nueva Concepción	1
	Costa Rica – 1 study	Llano Bonito	1

NbS for hillslope stability types

We found 36 different types of NbS in the SLR (see Annex 2), with similar characteristics, although they were described slightly different in the scientific articles. We grouped them in eight NbS types. We called recurrence to the number of times that a certain NbS type was implemented. In that way, the recurrence of live planting was fourteen, as the more implemented NbS type, followed by live stakes eight times, live crib wall with seven, living palisades four, live fascines or grating with three times each one and brush layering and afforestation with two. The description of each type of NbS is in Table 2.

Plant species for NbS for hillslope stability

In total, we found 55 plant species for NbS approaches (see Annex 3). We grouped plant species that pertain to the genus *Chrysopogon sp*., *Erythrina sp* and *Pinus sp*. The results of the recurrence of species show seven times *Chrysopogon sp*., *Salix sp*. five times, *Erythrina sp*. two and *Phyllanthus sellowianus* Müller Arg two times. Not all papers describe the types of NbS and the species used; nevertheless, there are a couple of studies that included this information, as described in Table 2.

We summarized the types of NbS, their recurrence, plant species used and the countries of implementation (Table 2). Although the use of plant species is geographically differentiated, this list aims to state the plant species used to enlighten about their performance and provide options for implementations, considering that native species should be preferred for replication in other study areas (Maxwald et al., 2020). The most common species used for live planting are *Salix sp*., *Phyllanthus sellowianus* Müller Arg. and *Chrysopogon sp*. Live planting was implemented in China, Guam Island, Nepal, UK, Ecuador, Colombia and Brazil. Figure 2 shows NbS types and the sites where they were implemented.

Table 2. NbS for hillslope stability types, plant species used and countries where they have been implemented.

Types of NbS/ Recurrence		Description	Plant species used	Countries where the NbS was implemented	References
Live planting	14	This technique is used for planting woody vegetation (shrubs, plants, trees) along slopes. The main goals are reducing the erosion and reinforcing the soil.(Norwegian Geotechnical Institute, 2023).	*Salix sp*., *Phyllanthus sellowianus* Müller Arg., *Chrysopogon sp*.	China, Guam Island, Nepal, Scotland, Ecuador, Colombia, UK, Brasil	(Li et al., 2021), (Patil et al., 2021), (Vorpahl et al., 2013), (Devkota et al., 2019), (Anderson et al., 2022), (Turconi et al., 2020), (Donn et al., 2014), (Gallotti et al., 2021), (Capobianco et al., 2022), (Maxwald et al., 2020), (Lupp et al., 2021), (Gonzalez-Ollauri & Mickovski, 2020), (Hankin et al., 2021), (Rauch et al., 2014).
Live stakes (live poles)	8	Live stakes or live poles are live, woody vegetation cuttings inserted directly into the soil. (Norwegian Geotechnical Institute, 2023).	*Salix sp*., *Phyllanthus sellowianus* Müller Arg.	Scotland, China, Brasil	(Anderson et al., 2022), (Capobianco et al., 2022), (Maxwald et al., 2020), (Sorolla et al., 2021), (H. Zhang et al., 2020), (Preti & Petrone, 2013), (Rauch et al., 2014), (Maffra et al., 2019).
Live cribwalls	7	Live crib walls are a particular form of gravity-retaining structures made of on-site fill material, timbers and layers of live branch cuttings aimed to provide linear and/or spatial slope stabilization. (Norwegian Geotechnical Institute, 2023).	*Salix sp., Erythrina sp.*	Scotland, Nicaragua, Guatemala, Ecuador, Colombia, Brasil, Spain	(Gallotti et al., 2021), (Anderson et al., 2021), (Capobianco et al., 2022), (Maxwald et al., 2020), (Gonzalez-Ollauri et al., 2021), (Sorolla et

Types of NbS/ Recurrence		Description	Plant species used	Countries where the NbS was implemented	References
					al., 2021), (Petrone & Preti, 2010).
Living palisades	4	Palisades are barriers made from live wood cuttings or bamboo installed across a slope following the contour in order to trap debris moving down the slope, to armour and reinforce the slope, and to increase the infiltration rate. (Shrestha et al., 2012).		Nicaragua, Ecuador, Colombia, Brasil, México	(Maxwald et al., 2020), (Petrone & Preti, 2010), (Preti & Petrone, 2013).
Live fascines	3	Live fascines are long tubular bundle structures made of cuttings of living woody plant material, placed in trenches across the slope of a bank and fastened with wooden stakes. (Norwegian Geotechnical Institute, 2023).		Norway, Nicaragua, Ecuador	(Solheim et al., 2022), (Maxwald et al., 2020), (Petrone & Preti, 2010).
Grating	3	Vegetated slope gratings are made of wooden frame constructed where the slope has failed and backfilled and revegetated to provide an additional support. Gratings may be done by using live cuttings, such as cottonwood posts, by obtaining an additional reinforcement through the development of root network from the cuttings. (Norwegian Geotechnical Institute, 2023).	Salix sp.	Scotland	(Anderson et al., 2021), (Capobianco et al., 2022), (Gonzalez-Ollauri et al., 2021).
Brush layering	2	Consists of live cut branches and rooted plants placed in layers into excavated terraces and filled with compacted soil material. (Norwegian Geotechnical Institute, 2023).		Nicaragua, Ecuador, Brasil	(Capobianco et al., 2022), (Rauch et al., 2014).
Afforestat ion	2	Afforestation is the establishment of a forest or stand of trees in an area where there was no forest. (Norwegian Geotechnical Institute, 2023).		Scotland	(Anderson et al., 2022), (Gallotti et al., 2021).

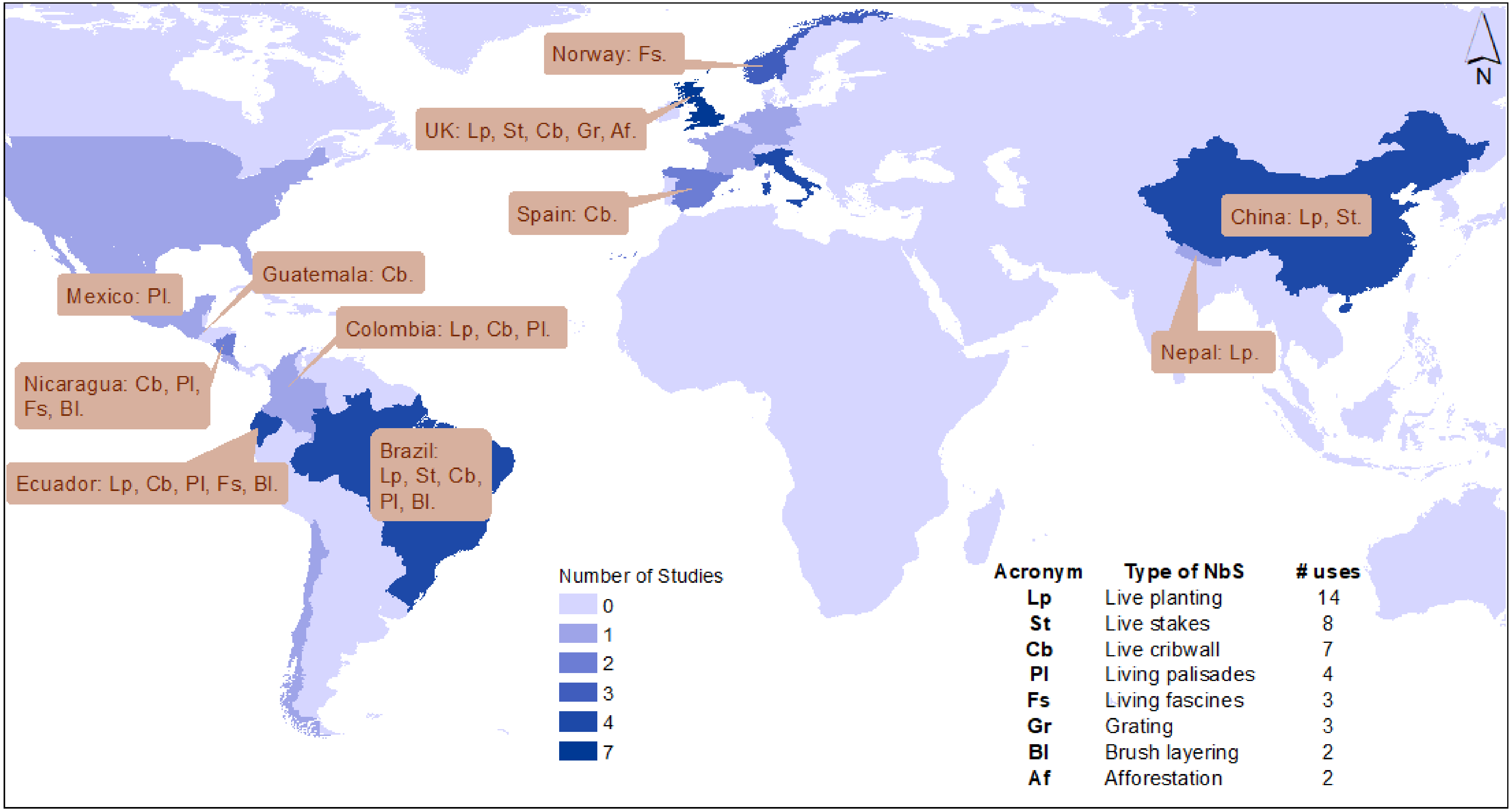

Figure 2. Geographical distribution of NbS for hillslope stability applications, including the number of studies on each place, the types of NbS and the number of implementations per NbS type.

Methods used to evaluate NbS performance

We collected the following information from 14 articles that mention specific methods used to evaluate the performance of NbS applications (Table 3). Evaluation of NbS allows timely correction, improvement, and replication (Gonzalez-Ollauri et al., 2021); in addition, it serves to demonstrate the benefits of a specific NbS for hillslope stability applications.

Table 3. Methods and Measurements to evaluate the performance of NbS for hillslope stability.

ID	Methods	References
1	On-site inspection	(Li et al., 2021)
2	Visually estimated	(Devkota et al., 2019)
3	Geographic Information Systems (GIS)	(Gong et al., 2021; Ronchi & Arcidiacono, 2019)
4	Field surveys	(Vorpahl et al., 2013)
5	Lab analysys	(Badhon et al., 2021; Cazzuffi et al., 2014; Ng et al., 2016)
6	In situ pullout tests on roots embedded in soil	(Cazzuffi et al., 2014)
7	Back analysis of collapsed slopes after storms	(Cazzuffi et al., 2014)
8	Visiting, taking photos, assessing the reasons why the plants growth or not, visits after instability occasions	(Maxwald et al., 2020)
ID	**Measurements**	**References**
1	Pore water pressure	(J. Zhang et al., 2022)
2	Factor of safety	(J. Zhang et al., 2022)
3	Root–shoot biomass (dry) estimation	(Devkota et al., 2019)
4	Measurements of soil mechanical behavior, fertility and plant growth	(Donn et al., 2014)
5	Shear strength and the consolidation degree	(Tröger et al., 2022)
6	Hydraulic measurements	(Capobianco, Cascini, et al., 2021)
7	Survival rate	(Petrone & Preti, 2010)
8	Length of terminal shoot	(Petrone & Preti, 2010)
9	Diameter at the base of terminal shoot	(Petrone & Preti, 2010)

Methods to assess hillslope stability

This section aims to guide the evaluation of hillslope stability when implemented NbS. Table 4 lists the methods used to assess the hillslope stability. In addition, we present a description of each method in Annex 4. The methods are general models, specific tools, software, computer systems, lab analysis, projects, fields and others. Furthermore, in Table 4, we detail the NbS approaches implemented and references related to the methods used.

Table 4. Methods to assess hillslope stability

	Method	NbS evaluated	Reference
General Models	Physical landslide model LAPSUS_LS	Planting* (implicit)	(Rossi et al., 2017)
	Stability Index Mapping model (SINMAP)	Already established vegetation	(Gong et al., 2021)
	Transient Rainfall Infiltration and Grid-based Regional Slope Stability (TRIGRS) model	Already established vegetation	(J. Zhang et al., 2022)
Specific tools	Trace infiltration	Planting* (implicit)	(Li et al., 2021)
	Direct shear tests	Planting* & already established vegetation	(Patil et al., 2021; Yildiz et al., 2019)
	Soil Water Retention Curve (SWRC)	Already established vegetation	(Patil et al., 2021)
	Centrifuge tests	Planting*, even though was a lab experiment.	(Ng et al., 2016)
	Infinite slope analysis	Planting*	(Yildiz et al., 2019)
	Receiver Operating Characteristic Curve (ROC)	Already established vegetation.	(Gong et al., 2021)
	Finite element method	Planting*. Already established vegetation	(Patil et al., 2021; Yildiz et al., 2019)
	Monte Carlo simulations	Planting*	(Yildiz et al., 2019)
	FLAC 3D (Fast Lagrangian Analysis of Continua 3D) simulation (slope safety factor)	Planting* (implicit)	(Li et al., 2021)
	RipRoot model (cohesion)	Already established vegetation	(Gong et al., 2021)
Software	InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software	Already established vegetation	(Ronchi & Arcidiacono, 2019)
	Geotechnical finite element software PLAXIS 2D	Planting*, even though was a lab experiment.	(Badhon et al., 2021)

	Method	NbS evaluated	Reference
	Landslide Risk Mitigation Toolbox. LARIMIT	Not mentioned on paper. Is a general tool for a variety of NbS.	(Capobianco et al., 2022; Solheim et al., 2022)
Computer systems	(HYROP) system	Already established vegetation	(Patil et al., 2021)
	WP4C instrument	Already established vegetation	(Patil et al., 2021)
Lab analysis	Laboratory shear strength test	Planting* (implicit)	(Li et al., 2021)
	Extensive laboratory tests	Not mentioned on paper. Is a general tool for a variety of NbS.	(Badhon et al., 2021)
Field	Open-Air Laboratories—OALs	Live cribwalls and afforestation.	(Gallotti et al., 2021)
	Comparison vegetation cover	Planting* (implicit)	(Tröger et al., 2022)
Others	Economic efficiency (EPP Dollars: Equal Purchasing Power)	Live fascine, live palisade, live crib wall, vegetative covering, biotextile.	(Petrone & Preti, 2010)

*Planting (live planting & live stakes).

Discussion

This study aimed to summarize NbS implementations for hillslope stability and research gaps. It shows places with NbS applied to hillslope stability, types of NbS, plant species used and tools to evaluate the NbS performance. Our research includes the geographical location of NbS approaches. UK has the biggest number of NbS implementations (seven). In general, Europe has more studies about NbS for hillslope stability. In addition, we found that South American countries, such as Ecuador and Brazil, have implemented several NbS for hillslope stability (11 study cases in the latest years). The United States has one study in their territory; the worst case for the entire African continent and West Asian continent with no studies.

There are striking research opportunities to compare, quantitatively, the effectiveness of grey and NbS measures to control landslides or hillslope stability. The NbS approaches are discussed at a descriptive and conceptual level instead of the results of study cases in depth (de Jesús Arce-Mojica et al., 2019). One possibility is to improve modelling tools to help transform the actual overseen way the stakeholders consider NbS (Kalsnes & Capobianco, 2022). We found that there is still the need to evaluate quantitatively the performance of vegetation to stabilize hillslopes, to demonstrate its importance and to facilitate replication (Gonzalez-Ollauri, 2022). Meteorological data help assess the dynamics between plants, soil and the atmosphere to open opportunities for finding indicators that evaluate the hydrological performance of vegetation in NbS projects (Gonzalez-Ollauri & Mickovski, 2020). In that way, to prove a successful intervention of NbS, Gonzalez-Ollauri et al. (2021) defines repositories of key performance indicators (KPIs) and metrics. These indicators assess the engineering performance and the provision of ecosystem functions and services of the NbS implementations to control landslides. Their research focuses on the monitoring phase of projects, looking to encourage the upscale of NbS, even though recent studies have not applied those tools yet. This study exemplifies the way to evaluate NbS performance.

The lack of information about the effectiveness of NBS for hillslope stability, in part, is due to the considerable amount of time that the monitoring of NbS applications requires. It relates to the slow vegetation growth (Rey et al., 2019). The World Bank began to talk about NbS in 2008 (MacKinnon et al., 2008). In 2014, the European Commission started programs of NbS for climate change risks, including landslides (EC, 2017) and a vast number of studies analyzed the first stages of plant growth (Weissteiner et al., 2019).

The use of native plant species for landslides is a well-known practice. Native species are adapted to the conditions of the specific sites, facilitating their development. Comparisons between plant species in similar study sites are required, considering the role of ecosystems (de Jesús Arce-Mojica et al., 2019). This comparison would base on the ability for root growth, bending capacity or vegetative reproduction (Maxwald et al., 2020).

The Larimit tool shows the most complete source of information about NbS types for hillslope stability (Capobianco et al., 2022). In this study, we classified these NbS types, according to their intrinsic characteristics; however, these classifications need to be evaluated on future efforts. Furthermore, for an NbS intervention it is recommended to analyze previous efforts and case studies, since each type of NbS needs a framework to be successfully developed. Some aspects to consider include: 1) the spatial and temporal scale of the NbS action (Gonzalez-Ollauri et al., 2021), 2) species of plants must be adaptable to the study site (Maxwald et al., 2020), 3) information on future climate conditions at a local spatial scale (i.e. downscaling methods that calculate local climate indicators and/or trends) (Gallotti et al., 2021). Additionally, the communities near to the intervention have a pivotal role (Gonzalez-Ollauri et al., 2021), knowing the existing sociopolitical system could facilitate the implementation of the NbS actions. In that way, it is important to consider: 1) supportive governance model, political commitment and intersectoral communication and 2) in-depth stakeholder involvement from the beginning of the action (Lupp et al., 2021) to construct the NbS approach with the community.

NbS implementations can contribute to many global and local aspects, such as global agendas on disaster risk reduction, climate change adaptation or mitigation and sustainable development (Martin et al., 2021). NbS has a crucial role towards climate resilience development, it helps to mitigate climate change (i.e. the use of vegetation instead of grey infrastructure reduces the greenhouse gases emissions and increases the carbon capture), especially if the NbS methods proposes are applied worldwide (Gonzalez-Ollauri, 2022). In that sense, there is the need to do life-cycle assessment of materials used by NbS, to understand their environmental impact in comparison with with grey-infrastructure (Gonzalez-Ollauri et al., 2021).

Through this SLR we have encountered a lack of knowledge on the following topics: negative effects of vegetation used for hillslope stability, (de Jesús Arce-Mojica et al., 2019), the residual risk of hillslope stability with vegetation or SBE, i.e. the acceptable risk that is the tolerated level of damage to people or systems (Bischetti et al., 2021), comprehensive studies on ecosystem dynamics before, during and after landslides (Meng et al., 2014), the impact of different vegetation in shallow landslides under the same climate conditions (Guo et al., 2020), monitoring of soil moisture content, pore pressure, stress-strain, sediments transfer and other variables that help to understand the interaction among the soil-plant-atmosphere system (Stokes et al., 2014) and the growth dynamics of plants (Rey et al., 2019). The absence of large-scale and long-term projects, about experiments on hillslopes under different treatments, types of vegetation, soils, landslides or restorations (Stokes et al., 2014) demonstrates the importance of encouraging companies and universities to implement experimental and in situ experiences (Maxwald et al., 2020).

NbS is a new and wide field that is emerging. This study can be used as a tool to identify previous efforts on NbS implementations for hillslope stability around the world. It exposes the geographical areas where NbS are used, the types of NbS, the plant species used, the monitoring methods and the hillslope stability assessing methods. Therefore, it aims to contribute to the improvement of natural resources management.

Conclusions

NbS for hillslope stability is emerging as a new field of study, opening opportunities for research and better management of natural resources. They have been studied all over the world except certain regions like Africa or west Asia. Furthermore, there are an interesting variety of NbS types for hillslope stability; however, all of them uses vegetation and it could be applied with grey interventions also. Despite of the important diversity of plant species for NbS applications, especially for hillslope stability, the best ecological practice must be using native species.

Among the 17 methods and measurements for assessing NbS performance, we found that the more common are measurements of soil mechanical behaviour, fertility and plant growth, which are related to the development and implantation of vegetation. On the other hand, we found 23 methods to assess the hillslope stability, such as direct shear tests and the landslide risk mitigation toolbox. The last serves as a tool that recently includes the NbS for hillslope stability. Generally, there is still a lack of information about NbS for hillslope stability performance on long-term time evaluations and comparative studies about NbS types and plant species selection.

There is a need for studies about ecosystem dynamics and landslides, the impact of different vegetation in shallow landslides under climate scenarios, and the interaction among the soil-plant-atmosphere system.

NbS for hillslope stability needs interdisciplinary research groups that monitor the ecosystems prior to, during and after the implementation of NbS with appropriate methods that evaluate their performance, followed by the publications of results that enable restructuring the implementations and replication at other sites.

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Annexes

Annex 1. List of final eligible studies

#	Title	Authors	Publication year
1	A Regional Landslide Stability Analysis Method under the Combined Impact of Rainfall and Vegetation Roots in South China	Qinghua Gong, Jun Wang, Ping Zhou &Min Guo	2021
2	Accelerating Effect of Vegetation on the Instability of Rainfall-Induced Shallow Landslides	Zhang, Juanjuan;Qiu, Haijun, Qiu H.;Tang, Bingzhe;Yang, Dongdong;Liu, Ya;Liu, Zijing;Ye, Bingfeng;Zhou, Wenqi;Zhu, Yaru	2022
3	Adopting an Ecosystem Services-Based Approach for Flood Resilient Strategies: The Case of Rocinha Favela (Brazil)	Silvia Rochi & Andrea Arcidiacono	2018
4	Bioengineering Solution to Prevent Rainfall-Induced Slope Failures in Tropical Soil	Austin J. Shelton III, Ujwalkumar Dashrath Patil and Edriel Aquino	2021
5	Biotic controls on shallow translational landslides	Peter Vorpahl, Claudia Dislich, Helmut Elsenbeer, Michael Märker, Peter Vorpahl, Claudia Dislich, Helmut Elsenbeer, Michael Märker	2012
6	Centrifuge modelling of the effects of root geometry on transpiration-induced suction and stability of vegetated slopes	C. W. W. Ng I V. Kamchoom I A. K. Leung	2015
7	Contribution of Vetiver Root on the Improvement of Slope Stability	Faria Fahim Badhon, Mohammad Shariful Islam & Md Azijul Islam	2021
8	Design and temporal issues in Soil Bioengineering structures for the stabilisation of shallow soil movements	Gian Battista Bischetti, Giovanni De Cesare, Slobodan B. Mickovski, Hans Peter Rauch, Massimiliano Schwarz, Rosemarie Stangl	2021
9	Framework for Assessment of Eco-Safe Rural Roads in Panchase Geographic Region in Central–Western Nepal Hills	Karen Sudmeier-Rieux, Narendra Man Shakya & Sanjaya Devkota	2019

#	Title	Authors	Publication year
10	Geosynthetic Engineering and Vegetation Growth in Soil Reinforcement Applications	Daniele Cazzuffi & Giuseppe Cardile & Domenico Gioffrè	2014
11	Green, hybrid, or grey disaster risk reduction measures: What shapes public preferences for nature-based solutions?	Carl C. Anderson, Fabrice G. Renaud, Stuart Hanscomb, Alejandro Gonzalez-Ollauri	2022
12	Identifying Spatial Patterns and Ecosystem Service Delivery of Nature-Based Solutions	Paulina Guerrero, Dagmar Haase & Christian Albert	2022
13	Implementation of Nature-Based Solutions for Hydro-Meteorological Risk Reduction in Small Mediterranean Catchments: The Case of Portofino Natural Regional Park, Italy	Laura Turconi, Francesco Faccini, Alessandra Marchese, Guido Paliaga, Marco Casazza, Zoran Vojinovic, Fabio Luino	2020
14	Implementing Nature-Based Solutions in Rural Landscapes: Barriers Experienced in the PHUSICOS Project	Anders Solheim, Vittoria Capobianco, Amy Oen, Bjørn Kalsnes, Turid Wullf-Knutsen, Mari Olsen, Nicola Del Seppia, Idoia Arauzo, Eva Garcia Balaguer & James Michael Strout	2021
15	Improved soil fertility from compost amendment increases root growth and reinforcement of surface soil on slopes	Suzanne Donn, Ron E. Wheatley, Blair M. McKenzie, Kenneth W. Loades, Paul D. Hallett	2014
16	Landslide risk reduction through close partnership between research, industry, and public entities in Norway: Pilots and case studies	Anders Solheim, Bjørn Kalsnes, James Strout, Luca Piciullo, Håkon Heyerdahl, Unni Eidsvig and Jardar Lohne	2022
17	Modeling shallow landslides and root reinforcement: A review	Ilenia Murgia, Filippo Giadrossich, Zhun Mao, Denis Cohen, Gian Franco Capra, Massimiliano Schwarz	2022
18	Modelling the effect of forest cover on shallow landslides at the river basin scale	James C. Bathurst, C. Isabella Bovolo, Felipe Cisneros	2010

#	Title	Authors	Publication year
19	On the Management of Nature-Based Solutions in Open-Air Laboratories: New Insights and Future Perspectives	Glauco Gallotti, Marco Antonio Santo, Ilektra Apostolidou, Jacopo Alessandri, Alberto Armigliato, Bidroha Basu, Sisay Debele, Alessio Domeneghetti, Alejandro Gonzalez-Ollauri, Prashant Kumar, Angeliki Mentzafou, Francesco Pilla, Beatrice Pulvirenti, Paolo Ruggieri, Jeetendra Sahani, Aura Salmivaara, Arunima Sarkar Basu, Christos Spyrou, Nadia Pinard, Elena Toth, Silvia Unguendoli, Umesh Pranavam Ayyappan Pillai, Andrea Valentini, George Varlas, Giorgia Verri, Filippo Zaniboni & Silvana Di Sabatino	2021
20	Pinus plantations impact hillslope stability and decrease landscape resilience by changing biogeomorphic feedbacks in Chile	Danny Troger, Andreas Christian Braun, Jana Eichel, Sebastian Schmidtlein, Marco Sandoval Estrada, Ana Valdes Duran	2022
21	Public Acceptance of Nature-Based Solutions for Natural Hazard Risk Reduction: Survey Findings From Three Study Sites in Europe	Anderson, Carl C.;Renaud, Fabrice G.;Hanscomb, Stuart; Munro, Karen E.; Gonzalez-Ollauri, Alejandro; Thomson, Craig S.; Pouta, Eija; Soini, Katriina; Loupis, Michael;Panga, Depy; Stefanopoulou, Maria	2021
22	Recent innovations in the LaRiMiT risk mitigation t ool: implementing a novel methodology for expert scoring and extending the database to include nat ure-based solutions	Vittoria Capobianco · Marco Uzielli · B jørn Kalsnes · Jung Chan Choi · Jam es Michael Strout · Loretta von der Ta nn · Ingar Haug Steinholt ·Anders Sol heim · Farrokh Nadim · Suzanne Lac asse	2022
23	Soil and Water Bioengineering (SWB) is and has always been a nature-based solution (NBS): a reasoned comparison of terms and definitions	Federico Preti, Vittoria Capobianco, Paola Sangalli	2022

#	Title	Authors	Publication year
24	Soil and Water Bioengineering Applications in Central and South America: A Transferability Analysis	Melanie Maxwald, Cesare Crocetti, Roberto Ferrari, Alessandro Petrone, Hans Peter Rauch & Federico Preti	2020
25	Stakeholder Perceptions of Nature-Based Solutions and Their Collaborative Co-Design and Implementation Processes in Rural Mountain Areas—A Case Study From PHUSICOS	Gerd Lupp, Joshua J. Huang, Aude Zingraff-Hamed, Amy Oen, Nicola Del Sepia, Alberto Martinelli, Massimo Lucchesi, Turid Wulff Knutsen, Mari Olsen, Trine Frisli Fjøsne, Eva-Maria Balaguer, Idoia Arauzo, Anders Solheim, Bjørn Kalsnes and Stephan Pauleit	2021
26	Sustainable Use of Nature-Based Solutions for Slope Protection and Erosion Control	Alejandro Gonzalez-Ollauri	2022
27	Telling a different story: The promote role of vegetation in the initiation of shallow landslides during rainfall on the Chinese Loess Plateau	Wen-Zhao Guo, Zhuo-Xin Chen, Wen-Long Wang, Wen-Wang Gao, Ming-Ming Guo, HongLiang Kang, Peng-Fei Li, Wen-Xin Wang, Man Zhao	2020
28	The 'Rocket Framework': A Novel Framework to Define Key Performance Indicators for Nature-based Solutions Against Shallow Landslides and Erosion	Alejandro Gonzalez-Ollauri *, Karen Munro, Slobodan B. Mickovski, Craig S. Thomson and Rohinton Emmanuel	2021
29	The Effect of Soil-Vegetation-Atmosphere Interaction on Slope Stability: A Numerical Study	Elahe Jamalinia, Philip. J. Vardon, Susan. C. Steele-Dunne	2019
30	The Effect of Willow (Salix sp.) on Soil Moisture and Matric Suction at a Slope Scale	Alejandro Gonzalez-Ollauri* and Slobodan B. Mickovski	2020
31	Using micro-catchment experiments for multi-local scale modelling of nature-based solutions	Barry Hankin, Trevor J. C. Page, Nick A. Chappell, Keith J. Beven, Paul J. Smith, Ann Kretzschmar, Rob Lamb.	2021
32	Wetting-Drying Response of an Unsaturated Pyroclastic Soil Vegetated with Long-Root Grass	Vittoria Capobianco, Leonardo Cascini, Sabatino Cuomo, Vito Foresta	2021

#	Title	Authors	Publication year
33	Improvement of the Plantation Success in a Crib Wall in a Mediterranean Hydro-Meteorological Risks Scenario—Practical Results	Albert Sorolla, Eduard Piera, Bet Mota-Freixas, Gina Sorolla Salvans, Inma Rueda, Adrian Lochner Prats & Clara Unzeta	2021
34	Quantitative evaluation of soil anti-erodibility in riverbank slope remediated with nature-based soil bioengineering in Liaohe River, Northeast China	Hongling Zhang, Zhifang Zhao, Guofeng Ma, Lina Sun	2020
35	Soil bioengineering for risk mitigation and environmental restoration in a humid tropical area	A. Petrone and F. Preti	2010
36	Soil bio-engineering for watershed management and disaster mitigation in Ecuador: a short-term species suitability test	Federico Preti, Alessandro Petrone	2013
37	Installation of a Riparian Forest by Means of Soil Bio Engineering Techniques—Monitoring Results from a River Restoration Work in Southern Brazil	Hans Peter Rauch, Fabricio Sutili, Stephan Hörbinger	2014
38	Evaluation of Live Cuttings Effect on Slope Stability	Charles Rodrigo Belmonte Maffra, Rita dos Santos Sousa, Fabrício Jaques Sutili, Rinaldo José Barbosa Pinheiro	2019
39	Sensitivity of the landslide model LAPSUS_LS to vegetation and soil parameters	L.M.W. Rossi, B. Rapidel, O. Roupsard, M. Villatoro-sánchez, Z. Mao, J. Perez, I. Prieto, C. Roumet, K. Metselaar	2017
40	Hydro-Mechanical Effects of Several Riparian Vegetation Combinations on the Streambank Stability—A Benchmark Case in Southeastern Norway	Vittoria Capobianco, Kate Robinson, Bjørn Kalsnes, Christina Ekeheien and Øyvind Høydal	2021

Annex 2. List of all NbS types registered

#	NbS Type	Description
1	Already established vegetation cover	Vegetation that exists on the study site without an antropic intervention (e.g. the cases that assess the influence of pristine or native vegetation on the hillslope). Vegetation are already established on the site, it works as hillslope stabilizer.
2	Green roofs	Roofs covered with vegetation placed over waterproofing material with drainage and irrigation systems. For peri urban environments. To avoid floods and landslides.
3	Cool roofs	Roofs that reflects solar radiation. For peri urban environments. To avoid floods and landslides.
4	Green permeable paving	Consists of pre-cast blocks made of concrete or hard plastic with voids created by styrene void formers. Such modular systems reduce sub-base depths, eliminate kerb edges, can withstand gross vehicle weights of over 40 tonnes and optimise drainage capacity. For peri urban environments. To avoid floods and landslides.
5	Urban gardens	Terracing systems to retain soil and counter flooding or mass movements.
6	Planted vegetation	Vegetation planted after an afforestation plan. To stabilice hillslope.
7	Live stakes	Live stakes or live poles are live, woody vegetation cuttings inserted directly into the soil. (Norwegian Geotechnical Institute, 2023).
8	Live poles	Live stakes or live poles are live, woody vegetation cuttings inserted directly into the soil. (Norwegian Geotechnical Institute, 2023).
9	Cuttings	Live stakes or live poles are live, woody vegetation cuttings inserted directly into the soil. (Norwegian Geotechnical Institute, 2023).
10	Root suckers	Shoots of a pre-existing plant species. Vegetation that works as hillslope stabilizer
11	Saplings	A young tree, especially one with a slender trunk. Vegetation that works as hillslope stabilizer
12	Live planting (seeds)	This technique is used for planting woody vegetation (shrubs, plants, trees) along slopes. The main goals are reducing the erosion and reinforcing the soil.(Norwegian Geotechnical Institute, 2023)
13	Afforestation	Afforestation is the establishment of a forest or stand of trees in an area where there was no forest. (Norwegian Geotechnical Institute, 2023).
14	Live planting (seddlings)	This technique is used for planting woody vegetation (shrubs, plants, trees) along slopes. The main goals are reducing the erosion and reinforcing the soil. (Norwegian Geotechnical Institute, 2023)
15	Live fascines	Live fascines are long tubular bundle structures made of cuttings of living woody plant material, placed in trenches across the slope of a bank and fastened with wooden stakes. (Norwegian Geotechnical Institute, 2023).
16	Live cribwalls	Live crib walls are a particular form of gravity-retaining structures made of on-site fill material, timbers and layers of live branch cuttings aimed to provide linear and/or spatial slope stabilization. (Norwegian Geotechnical Institute, 2023).

#	NbS Type	Description
17	Live ground anchor systems	Use of branches, woody seedling and cuttings. Vegetation that works as hillslope stabilizer
18	Live drainage systems	Use of branches, woody seedling and cuttings. Vegetation that works as hillslope stabilizer
19	Grating	Vegetated slope gratings are made of wooden frame constructed where the slope has failed and backfilled and revegetated to provide an additional support. Gratings may be done by using live cuttings, such as cottonwood posts, by obtaining an additional reinforcement through the development of root network from the cuttings. (Norwegian Geotechnical Institute, 2023).
20	Geotextiles	Rolled erosion control products. Hillslope stabilizer
21	Drainage blankets	Drainage blanket is a very permeable material used to remove water or to control groundwater seepage from cut slopes or beneath fills. Hillslope stabilizer
22	Live gully breaks	It is used in gullies to control water flow and to prevent the intiation of debris torrenting. Usually live cutting are placed high in the channel to control the initiation of torrents rather than attempting to control the torrent once it gets moving. Hillslope stabilizer.
23	Vegetated gabions	Vegetated gabions are specific gabion walls with incorporated vegetation for a better integration with the surrounding environment. Hillslope stabilizer.
24	Brush layering	Consists of live cut branches and rooted plants placed in layers into excavated terraces and filled with compacted soil material. (Norwegian Geotechnical Institute, 2023).
25	Living palisades	Palisades are barriers made from live wood cuttings or bamboo installed across a slope following the contour in order to trap debris moving down the slope, to armour and reinforce the slope, and to increase the infiltration rate. (Shrestha et al., 2012).
26	Pile wall	Vegetated structure for hillslope stabilization.
27	Sod slabs	Vegetation that works as hillslope stabilizer
28	Wooden contour structures	Vegetated structure for hillslope stabilization.
29	Terracing techniques	Supportive estructure to improve the establishment of vegetation to stabilize sediments. Vegetated structure for hillslope stabilization.
30	Green infrastucture	Interconnected network of green spaces that conserves natural systems and provides assorted benefits to human populations
31	High-density coir logs HDCL	Vegetated structure for hillslope stabilization.
32	Nonwoven fabric + live stakes slope protection technique	Live stakes or live poles are live, woody vegetation cuttings inserted directly into the soil. (Norwegian Geotechnical Institute, 2023).
33	Fiber roll + live stakes slope protection technique	Live stakes or live poles are live, woody vegetation cuttings inserted directly into the soil. (Norwegian Geotechnical Institute, 2023).
34	Metallic net and biotextile coupled with a live palisade made of bamboo	Palisades are barriers made from live wood cuttings or bamboo installed across a slope following the contour in order to trap debris moving down the slope, to armour and reinforce the slope, and to increase the infiltration rate. (Shrestha et al., 2012).

#	NbS Type	Description
35	Vegetated riprap	A layer of stone and/or boulder armoring that is vegetated, optimally during construction, using pole planting, brushlayering and live staking techniques. Hillslope stabilizer.
36	Anchorage with wooden poles and steel wires	Vegetated structure for hillslope stabilization.

Annex 3. List of all plant species used of NbS for hillslope stability approach

#	Species	#	Species	#	Species
1	*Agrostis capillaris*	20	*Erythrina fusca*	39	*Picea abies*
2	*Ailanthus altissima*	21	*Erythrina poppigenea*	40	*Pinus kwangtungensis*
3	*Artemisia gmelii*	22	*Eulalioipsis binate*	41	*Pinus massoniana*
4	*Artemisia scoparia*	23	*Euphorbia cotinifolia*	42	*Platycladus orientalis*
5	*Ateleia glazioveana* Baill	24	*F. rubra subsp. commutata*	43	*Punica granatum*
6	*Bauhinia forficate* Link	25	*Fagus longipetiolata*	44	*Rhodomyrtus tomentosa*
7	*Betula pubescens*	26	*Festuca rubra*	45	*Robinia pseudocacia*
8	*Bothriochloa ischaeum*	27	*Gliricidia sepium*	46	*Rosa xanthina* Lindl
9	*Brugmansia versicolor*	28	*Inga marginata Willd*	47	*Saccharum spontaneum*
10	*Calliandra brevipes* Benth	29	*Lespedeza bicolor*	48	*Salix sp.*
11	*Cannabis indica*	*30*	*Lolium perenne*	49	*Schefflera heptaphylla*
12	*Chirysopogon gryllus*	*31*	*Malvaviscus penduliflorus*	50	*Sophora viciifolia*
13	*Chrysopogon zizanioides*	*32*	*Melastoma sanguineum*	51	*Tabebuia rosea*
14	*Coffea arabica*	*33*	*Musa spp*	52	*Thysanalana maxima*
15	*Cunninghamia lanceolata*	*34*	*Nothofagus pumilio*	53	*Trichanthera gigantea*
16	*Cymbopogon microtheca*	*35*	*Panicum virgatum L. (*Pangrass*)*	54	*Yushania basihirsuta*
17	*Elaeagnus pungens* Thunb	*36*	*Penniseluim purpurreum*	55	*Ziziphus jujuba*
18	*Elytrigia elongata L. (*Elygrass*)*	*37*	*Periploca sepium*		
19	*Eragrostis curvala Nees (*Eragrass*)*	*38*	*Phyllanthus sellowianus* Müller Arg		

Annex 4. Methods to evaluate slope stability, related with NbS and their references

	Method	Description	NbS evaluated	Reference
General Models	Physical landslide model LAPSUS_LS	Models slope stability at the catchment scale. Combines a hydrological model with a Limit Equilibrium Method model, and calculates the factor of safety of individual cells based on their hydrological and geomorphological characteristics.	Planting (implicit)	(Rossi et al., 2017)
	Stability Index Mapping model (SINMAP)	Deterministic model based on landslide physics processes, widely used to predict the spatiotemporal stability of shallow landslides. Based on the following: a DEM, a coupled steady-state hydrological model, and an infinite slope stability model.	Already established vegetation	(Gong et al., 2021)
	Transient Rainfall Infiltration and Grid-based Regional Slope Stability (TRIGRS) model	TRIGRS model, as a grid-based regional slope-stability physical deterministic model of transient rainfall infiltration, has been widely used in slope stability analysis. The TRIGRS model software, which takes into account rainfall-triggered events that determine slope stability conditions, as well as, environmental characteristics such as topography, lithology, soil mechanics, and hydrology, is used to assess the slope susceptibility.	Already established vegetation	(Zhang et al., 2022)
Specific tools	Trace infiltration	Tracer experiments can show preferential flow paths in soil.	Planting (implicit)	(Li et al., 2021)
	Direct shear tests	Direct shear tests are one of the most common geotechnical tests performed to characterize the shear strength of soil. Shear tests usually consist of a shear-box in which the soil samples are placed, typically with a square or circular shape in plan view. (Giadrossich et al., 2017)	Planting & Already established vegetation	(Yildiz et al., 2019), (Patil et al., 2021)
	Soil Water Retention Curve (SWRC)	Is a critical soil hydraulic property to schedule irrigation, and other soil and land management endeavors. It determines water availability and aeration for growing plants. (Bar-Tal et al., 2019; Wraith & Or, 2001)	Already established vegetation	(Patil et al., 2021)

	Method	Description	NbS evaluated	Reference
	Centrifuge tests	Centrifuge model test enables small-scale physical slope models to be tested at the stress levels identical to those experienced by much larger prototypes and under much better controlled test conditions than is possible in field experiments. This technique has been commonly used to study slope stability problems (Take et al. 2004; Wang and Zhang 2014). The fundamental principle of centrifuge modelling is to recreate stress conditions, which would exist in a prototype.	Was a lab experiment, but it was implicit in the paper that they plant various species of plants. So planting.	(Ng et al., 2016)
	Infinite slope analysis	Infinite slope analysis is still used as a guide to quantifying slope stability, especially for slope susceptible to shallow landslides with certain slope length to soil thickness ratios (Wu and Sidle, 1995)	Planting	(Yildiz et al., 2019)
	Receiver Operating Characteristic Curve (ROC)	Is used to analyze and evaluate the model results under rainfall conditions	Already established vegetation.	(Gong et al., 2021)
	Finite element method	It is a numerical method for solving engineering problems. It has been applied to slope stability analysis. Non-linear finite element models using elastic-perfectly plastic material strength formulations have been used to determine factors of safety. (Hammah et al., 2004)	Planting. Already established vegetation	(Yildiz et al., 2019), (Patil et al., 2021)
	Monte Carlo simulations	Used in geotechnical engineering to estimate failure probability, safety factors are calculated by running a model simulation numerous times using various soil parameter sets generated from the known or assumed probability density function. (Tsai et al., 2015)	Planting	(Yildiz et al., 2019)
	FLAC 3D (Fast Lagrangian Analysis of Continua 3D) simulation. (slope safety factor)	The software can well build slope models and input related parameters, and the potential sliding surface can be calculated and estimated by implementing strength reduction, and the FoS can be obtained. This method can analyze the change and the whole process of soil stress and strain. FLAC3D software is used to simulate the slope safety factor	Planting (implicit)	(Li et al., 2021)

	Method	Description	NbS evaluated	Reference
	RipRoot model (cohesion)	The RipRoot model considers different root system tolerances and the process of gradual root system destruction, and it therefore provides a more reasonable root system and associated enhancement of soil strength.	Already established vegetation	(Gong et al., 2021)
Software	InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software	InVEST is an ES-based geographical, economic and ecological accounting tool for regional and urban planning in terms of restoring and conserving the soil natural capacity to provide ecosystem services	Already established vegetation	(Ronchi & Arcidiacono, 2019)
	Geotechnical finite element software PLAXIS 2D	Not mention directly on the papers. But what they use on their studies are samples with the soil of the study site and take measures.	Was a lab experiment, but it was implicit in the paper that they plant various species of plants. So planting.	(Badhon et al., 2021)
	Landslide Risk Mitigation Toolbox. LARIMIT	Web-based toolbox for prioritizing and choosing optimal mitigation measures, including Nature Based Solutions, improved early warning systems and mitigation measures for slope instability. To assist planners and others, from public entities at all levels to private businesses, in their work on risk reduction. The LaRiMiT pilot is a web tool and corresponding database, providing a technical service for problem owners such as municipalities and infrastructure owners.	Not mention on paper. Is a general tool per a variety of NbS.	(Solheim et al., 2022), (Capobianco et al., 2022)
Computer systems	(HYROP) system	Computer-controlled hydraulic property analyzer. HYROP is a computer-controlled equipment that has suction sensors to collect numerous high resolution continuous data points in the wet-end of the Soil Water Retention Curve (SWRC).	Already established vegetation	(Patil et al., 2021)
	WP4C instrument	WP4C dewpoint potentiometer was used to obtain the high suction points (dry end) on the Soil Water Retention Curve SWRC curve.	Already established vegetation	(Patil et al., 2021)

	Method	Description	NbS evaluated	Reference
Lab analysis	Laboratory shear strength test	Using remodeled soil samples. A strain-controlled direct shear apparatus is used to determine the shear strength of the sample	Planting (implicit on the paper)	(Li et al., 2021)
	Extensive laboratory tests	Extensive laboratory tests were performed to characterize the behavior of soil-root matrix. Laboratory direct shear tests were performed on reconstituted root mixed soil samples and also on undisturbed rooted soil samples.	Not mention on paper. Is a general tool per a variety of NbS.	(Badhon et al., 2021)
Field	Open-Air Laboratories—OALs	Methods for the validations of NBSs to mitigate hydro-meteorological hazards. OALs allow a systematic analysis of the most appropriate mitigation policy, also in terms of cost–benefit analysis. They must not be intended as merely laboratory sites, but locations where real natural hazards are coped with efficient tools. OALs represent the bond between the decision-makers and the scientific community.	These NBSs are live cribwalls and high-density plantations of woody vegetation.	(Gallotti et al., 2021)
	Comparison vegetation cover	Assessment of soil indicators under different vegetation assemblages that express soil stability directly. Influence hillslope stability via conditions for biogeomorphic feedbacks.	Planting (implicit on the paper)	(Tröger et al., 2022)
Other	Economic efficiency (EPP Dollars: Equal Purchasing Power)	Financial analysis of the NbS for hillslope stability. EPP is an artificial dollar whose purchasing power is equal in all countries, as its value corresponds to the weighted average of the world prices of 151 kinds of goods. It is a way of comparing prices paid in different geographic areas and understanding their actual entity.	Drainages with live fascine mattress, a live palisade, a vegetated live crib wall for riverbank protection, a vegetative covering made of a metallic net and biotextile coupled with a live palisade made of bamboo.	(Petrone & Preti, 2010)